BUILDING AND FIRE RESEARCH AT NBS/NIST 1975-2000

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Richard N. Wright

Building and Fire Research Laboratory

NIST
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ABSTRACT

In the last quarter of the 20th Century, building and fire research programs at the National Institute of Standards and Technology, formerly the National Bureau of Standards, provided one of the most significant sources of technology, measurements and standards for the construction and fire safety communities of the world. These communities are of great social and economic importance. The built environment shelters and supports most human activities. Its functionality, safety, environmental quality, aesthetics, and economy are important to everyone's quality of life and productivity. In the United States, new construction, renovation, operation and maintenance of constructed facilities amount to over 1/8 of the Gross Domestic Product, and the costs of fire protection and losses to unwanted fires exceed $200 billion, annually. This history summarizes the technical accomplishments of these programs and their impacts, the existential and management challenges faced by the programs, and the visions and efforts of the staff.

KEY WORDS: Building and fire research, built environment, codes, earthquakes, economics research, environmental systems, fire-hazard assessment, fire simulations and suppressants, life-cycle cost methods, materials, measurements, refrigerants, smoke detectors, standards, structures, test methods, wind.

FOREWORD

In April of 2000 Richard Wright suggested that his colleagues on the staff of the Building and Fire Research Laboratory, current and retired, update the history of the Laboratory. The history of building research would be from 1974 when the last history was produced to 2000. The history of fire research would be from 1968 to 2000. The date 1968 is that of the first of a flurry of legislative actions that ultimately established a separate Fire Research Center (this was the title in the law; NBS always called it CFR) at the National Bureau of Standards. Until 1968 fire research for buildings had been part of the broader program in the Building Research Division. Here we have the result of the efforts of a great many people. Read and enjoy it.

The years 1968 to 1977 or so encompassed the formation and maturation of the independent fire research effort at the Bureau. This was also the time when the consumer movement in the Nation peaked and began to decline, most notably, for CBT and CFR, in terms of appropriated budgets. This lack of budget support was odd in that whenever management needed examples of NBS work done with an impact on society the examples were very often drawn from the building and fire programs.

The budget difficulty became worse for both centers during the Reagan Administration when, at one period of several cycles, the budgets were zeroed out by the Administration. The Congress restored the funds but each time we lost a little more so that at this writing the staff level of the programs is way below what it was in the 1960s.

(However, the Congress is injecting large sums into BFRL, as this is being written, for investigation of the collapse of the World Trade Center in 2001. The nature of this work is not new for the BFRL, only the magnitude of the collapse, and the losses involved.)

Much of the work of the two programs was and is hands-on engineering whether in drafting proposed design standards, developing and proposing methods of test, and, often, investigating disasters. In investigations the centers have been expected to analyze their findings and to draw conclusions as to likely causes and to recommend improved practices. These activities placed the two programs in the thick of controversy over the proper design of structures and the best use of materials and systems. Some of the investigations were done in the spotlight of the news media and under the control of the court system. Examples include the, collapse of the Skyline Plaza complex during construction in 1973, the 1975 study of fire safety in the D.C. metropolitan buses and subway cars, the Harbour Cay condominium (Cocoa Beach) collapse during construction in 1981, and the walkway failure in the Hyatt Regency Hotel at Kansas City in 1981. This building was in service at the time of the failure.

NBS through CBT has responsibilities for earthquake hazard mitigation working with three other Federal agencies and the states. The reports of findings from studies of several major quakes brought CBT and NBS before the Congress and into the media frequently and in a very positive light. CBT also has played a significant role in wind hazard studies; e.g., Hurricanes Hugo and Andrew. These activities are primarily the exercise of professional skills and responsibilities and are not primarily research. NBS has been asked to do this work because of its reputation for even-handed, unbiased work.

A particularly interesting project was the study in 1986-87 of the structural integrity of the newly built and unfinished Moscow chancery building of the United States Embassy complex. A team of specialists went to the USSR in the dead of winter at a time when tensions were high between the two countries. The team climbed all over the structure, both inside and out, and concluded that the structural problems could be repaired for a reasonable sum of money. However there were issues with respect to security that held up the repairs.

The work in standards and codes is less dramatic and garners little publicity outside the trade press. But it is this work that ultimately produces changes in design practices and leads to safer more durable structures, products and systems. Sometimes it will take years or even decades to effect a major change and only an organization with the characteristics of NIST has the funding and the patience to follow through on a proposal. Examples in both fire and building work will be found throughout this history. The fire program, for example, struggled for years to limit the use of a horizontal tunnel test to specific constructions. The test had been incorporated by reference into the building codes throughout the country. It took many years of presentations and argument to make the change. Similarly CBT had studied energy use in buildings before the 1973 oil crisis but many years went by before CBT's conclusions were adopted in the appropriate model codes and standards.

Underlying this work has been a solid program of scientific research. The fire program benefited a very great deal by the Congress' transfer of the package of National Science Foundation grants in the fire area. These were mostly at universities and the transfer brought to CFR a group of distinguished academics. The best-known fire researcher was Professor Howard Emmons of Harvard whose work on modeling fire in enclosures was seminal. The studies of fire deaths and injuries carried out at Johns Hopkins Applied Physics Laboratory provided the basis for NBS' program on the toxicity of fire gases. The fire program had lacked sufficient research; the transfer from NSF at a stroke provided this necessary ingredient.

A second transforming event was the establishment by management and Congress of what we came to call the "NBS Competence Fund." In this effort the Bureau was allowed to invest a few millions of dollars a year in projects of scientific research not specified in the appropriation request but decided upon internally. This program was especially beneficial to CBT, which had a small fraction of direct appropriations. Both CBT and CFR benefited. Pay-off from many fundamental programs often takes years. Examples are the fire modeling from first principles by Howard Baum and Ron Rehm; work that was supported early on by the Competence Fund and later was continued by regular funding. This work began in the 1970s and continues to this day. Studies of wind damages and earthquake phenomena have had the same long lives. NBS work on polymer structure vs. thermal stability, originally started in the 1960s in the NBS polymer program, has been extended elegantly in the fire program. CBT carried out fundamental work on details of Portland cement hydration for high-performance concrete. Bruce Ellingwood led a program to introduce into building codes and standards probability-based load criteria for use in structural design. This new concept is now broadly accepted. One last example is Emil Simiu's studies of chaotic dynamics, work supported in part by Competence funding. This phenomenon is best exemplified by the galloping failure of the Tacoma, Washington Narrows Bridge many years ago. The work indicates the conditions under which this phenomenon is likely to occur and guides the designer away from the danger zone.

The reader who was there during these times will enjoy the refreshing of his or her memories; for those who were not there, this history is full of interesting stories that will increase their appreciation of the role these two programs play in our National life.

John W. Lyons
Director (Ret), National Institute of Standards and Technology

REPORT CONTRIBUTORS

Many persons contributed to the preparation of this history. Without them, this account could not have been possible. The following persons made substantial contributions to this history.

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Chapter 7	Belinda Collins and Richard Wright
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Chapter 13	James Pielert, Jonathan Martin, Walter Rossiter, Mary McKnight, and Geoffrey Frohnsdorff
Chapter 14	James Gross, James Pielert, Robert Dikkers, and Richard Wright
Chapter 15	Bruce Ellingwood, Nicholas Carino, Emil Simiu, John Gross, and Richard Wright

As with all histories, important facts and key people are inadvertently omitted from the account. For the missing content and failure to recognize human resources during this 25-year History, the author regrets the omissions.

Noel Raufaste edited and formatted the History for publication, and worked with contributors to identify text and to prepare the many illustrations. In addition, he made great career contributions to the History. For example, the general interest documents, Project Summaries, and Publications reports that he prepared over the years of the History were vital sources of information for its preparation.

Disclaimer

Certain trade names and company products are mentioned in the text or identified in an illustration that helped adequately specify the experimental procedure and equipment used. In no such case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products are necessarily the best available for that purpose.

CONTENTS

1. INTRODUCTION

1.1 OBJECTIVES

Constructed facilities (which include buildings of all types and their service systems, and public works and utilities for transportation, power, communication, water supply, and waste disposal) shelter and support most human activities. They are a principal element of the Nation's wealth, valued at about $20 trillion in year 2000 dollars, with the approximately $1 trillion annually invested in new construction and renovation amounting to about one-eighth of the Gross Domestic Product. Their quality is vital to industrial productivity and everyone's quality of life. Their safety from unwanted fires and other natural, accidental and willful hazards is critical for life safety, avoidance of injuries, protection of property, and national security.

Building and fire research programs seek to provide knowledge bases for decisions supporting functionality, economy and safety at all stages in the life cycle of constructed facilities. The relevant spectrum of knowledge is broad, almost unbounded. Fire phenomena include ignition, growth and suppression of fires, the effects on individuals of fires and combustion products, and the effects on society of fire losses and investments in fire safety. The aspects of performance of constructed facilities include structural stability, durability of materials and equipment, environmental control for building occupants, functionality for the intended purpose of the facility, the costs of construction, operation, maintenance and renovation, and all other social and environmental effects. Therefore, building and fire research involves physical, engineering, life and social sciences. Moreover, this knowledge must be expressed in practices useful to owners, occupants, designers, constructors, maintainers of constructed facilities, and fire services and building regulatory officials responsible for public safety.

Because of the importance of constructed facilities and fire safety to the Nation, the National Institute of Standards and Technology (NIST), formerly the National Bureau of Standards (NBS), has been active in building and fire research almost from its founding in 1901 [1, 2]. Building and fire research at NBS/NIST have been challenged to respond as effectively as possible to these needs with severely constrained human, laboratory and financial resources. This history describes the challenges, opportunities, accomplishments and impacts of the NBS/NIST programs of building and fire research since 1968 for fire research and since 1974 for building research. It follows from earlier histories covering building and fire research through 1968 [2] and building research from 1968 through 1974 [3]. NBS/NIST-wide histories [1, 4, 5, 6] provide selected information on building and fire research and their place in NBS/NIST's evolving Organic Act (authorizing legislation).

The objectives of this history are:

1. To provide a convenient reference on the principal NBS/NIST programs and activities in building and fire research in the last quarter of the 20th century.
2. To recognize the contributions of building and fire research staff and of collaborators elsewhere.
3. To help current and future staff understand the background of their work and to provide perspectives on successes and failures both technical and managerial.
4. To show the societal importance and technical challenge of building and fire research.
5. To provide perspectives on the needs for and benefits of building and fire research to NIST and higher management, industry and Congress.

The organizational units treated here are the Center for Building Technology (CBT), 1975-1990; the Center for Fire Research (CFR), 1975-1990; and the Building and Fire Research Laboratory, 1991-2000.

1.2 ORGANIZATION

The following chapters are in two groups. First the Management chapters treat in chronological order the policy and planning issues affecting the building and fire research programs: 2. Center for Fire Research in the 70s, 3. Center for Building Technology in the 70s, 4. Center for Fire Research in the 80s, 5. Center for Building Technology in the 80s, and 6. The Building and Fire Research Laboratory. These chapters note accomplishments and awards that were managerially significant.

Second, the Technical chapters describe the most significant work and its effects. These are organized by research areas, ordered alphabetically to avoid any inferences of relative importance, and each, because of the inherent continuity of technical work, covers the entire period of this history. These chapters are: 7. Architecture, Psychology, and Acoustics, 8. Construction Integration and Automation, 9. Economics, 10. Environmental Systems, 11. Fire Safety Engineering, 12. Fire Science, 13. Materials, 14. Standards and Codes, and 15. Structures.

The management chapters describe the environment and context for the technical work. There are real differences between management issues and technical accomplishments. Often, program planning and development efforts were frustrated by inability to obtain resources needed to pursue the planned work. In contrast, some very important accomplishments involved little management attention as researchers well linked to peers and customers produced very valuable results. A researcher with good reputation and ideas could obtain funding from external sources ("soft money") to pursue investigations extensive in size and duration. In these instances, management's role could be limited to assuring that the scope of work was appropriate for NBS/NIST and that the quality of work reflected well on NBS/NIST.

1.3 TOP ACCOMPLISHMENTS

This writer's subjective view of the top accomplishments in this period of building and fire research is provided to highlight the detailed coverage of accomplishments contained in following chapters. All of the top accomplishments arose from outstanding technical work in the programs. Most resulted from world-class scientific and technical leadership of the fire and building researchers and skillful collaborations with industry and other federal agencies to achieve beneficial implementations. The encouragement, even insistence, of NBS/NIST management on world-class scientific and technical leadership, and collaborations with other NBS/NIST laboratories, played a large role in these accomplishments.

1. The wide adoption of residential smoke detectors in U.S. homes, facilitated and driven by CFR research (section 11.5), led to early accomplishment of CFR's challenge goal to halve fire deaths in a generation.
2. Fundamental research on the properties of refrigerants and fire suppressants, and the performance of heat pumps, air-conditioners, and fire suppression systems, facilitated world leadership of U.S. industry in developing and marketing alternatives to environmentally harmful refrigerants and fire suppressants (sections 10.9 and 12.9).
3. Investigations of the performance of structural and fire safety systems in important accidents and disasters provided confidence in the efficacy of up to date structural and fire safety standards and practices, and/or identified needs for their improvement (sections 11.4, 15.1 and 15.2).
4. Improved test methods for the seasonal efficiency of space heating and cooling equipment, major appliances, and insulation have provided the basis for national energy labeling programs that have resulted in roughly doubling the efficiency of equipment, appliances and insulation in the marketplace (sections 10.1 and 10.4).
5. Standard information exchange protocols for building automation allow open systems for controls so that owners can: specify desired performance, not be tied to a single vendor, and update automation systems as demands change or better products come into the marketplace (section 10.8).
6. Reliable and predictable performance (including functionality, safety and durability) of materials and systems based on advanced, probabilistic modeling of environments and resistance (sections 10.7, 10.11, 11.8, 13.2, 13.6, 15.3, 15.6).
7. Economical fire test methods for small specimens that relate rationally to the materials' contributions to the severity of fires and the toxicity of combustion products (sections 12.2 and 12.3).
8. Standard life cycle cost economic methods to guide investments in building and fire safety products and practices (sections 9.3, 9.4 and 9.6).
9. New generation of scientifically-based fire simulations that provide the basis for the world's transition to performance-based fire standards (sections 11.9 and 11.10).
10. Development with industry of the concept of sacrificial, energy-absorbing joint materials to allow pre-cast, pre-stressed, concrete frames to be used safely and economically for tall buildings in high seismic zones (section 15.9).

1.4 TOP DISAPPOINTMENTS

Aspirations have been high for building and fire research, so the top accomplishments can be balanced with top disappointments. Since the writer's role was a manager, the top disappointments focus on managerial issues, which are covered in chapters 2-6, rather than on the conduct of research.

1. Inconsistent alignment of CBT/CFR objectives with those of NBS/NIST often led to a lack of support of NBS/NIST for CBT/CFR initiatives. Principally, this occurred when NBS/NIST primarily valued advances in measurement science and practice, and CBT and CFR were pursuing increasing the usefulness, safety and economy of constructed facilities, and reducing fire losses with whatever technologies would be most effective. By the 90s, BFRL management understood and accommodated the focus of NIST on measurements, standards, and technologies for support of U.S. economic growth, and NIST showed greater respect for potential economic and societal impacts.
2. Partnerships with other federal agencies, which would provide mission, funding and delivery mechanisms for CBT/CFR research, became an Institute for Applied Technology strategy for program growth in the 60s and was relied upon throughout the 70s. Indeed, NBS also relied upon this strategy, and, except for the initial funding of CFR, was unwilling, through the 70s, to request new, directly appropriated funding for CBT or CFR for mandates such as energy conservation and earthquake hazard reduction. This gave other agencies

undue control over CBT/CFR programs and left CBT/CFR vulnerable to other agencies' retrenchments in the 80s.

3. When NBS was pressured by the Administration in 1981 to offer cuts in its programs, it offered to eliminate CBT and CFR. The rationale seemed to be that losses of CBT and CFR would not greatly weaken the remaining parts of NBS, and that CBT and CFR were very defensible because of high, tangible benefits to industry and the public. Indeed, both centers were defended successfully by industry, and NBS continued to offer them up for seven more years. Why change a successful strategy? However, the freeze on direct appropriations and reductions in support from other federal agencies caused severe attenuation of the programs and the uncertainties led to losses of some of the most productive staff. CBT/CFR productivity remained high through this period, but losses of staff and reductions of program scope had long term detrimental effects.
4. CFR strove to achieve close collaborations with the fire services, and both CFR and CBT sought strong collaborations with consumer organizations. Neither of these collaborations were as fruitful as expected. Fire services seemed more attracted to conflicting collaborations with the tobacco industry, and consumer organizations seemed unappreciative of the values of building and fire measurements and standards.
5. Both CBT and CFR appreciated the need for and value of human factors and architectural research to achieve their objectives. But NBS was reluctant to invest scarce, directly appropriated funding where it lacked a track record for world class results, and patient funding from other agencies became scarce in the 80s. Therefore, CBT and CFR terminated architectural and human factors research, and BFRL did not find the resources for renewing such efforts in the 90s. Architectural and human factors research remains important for achieving BFRL's objectives, and continues to be lacking.
6. CBT and BFRL sought to support industry in all important, economically significant areas of building and construction technology, but the program constriction of the 80s required termination of important areas of research: acoustics, electrical systems, geotechnical engineering, plumbing, and roofing in addition to architecture and human factors as noted above.
7. Fire grants to external experts in universities and industry have contributed greatly to the fire program. The nation's best talent has been focused on program objectives and highly qualified researchers have been attracted to work at CFR/BFRL. However, the fire grants program has been attenuated severely by budget cuts of the 80s and inflation, and BFRL has not obtained additional, directly appropriated funding to maintain the fire grants program and to create similar programs in other areas.

1.5 ACKNOWLEDGEMENTS OF STAFF

The contributions of the managerial and research professional staff of CFR, CBT and BFRL are cited directly in the chapters that follow. It is important to acknowledge here, both generally and with specific citations, the great and essential contributions of support and administrative staff and technicians to the laboratory's accomplishments.

1.5.1 SUPPORT STAFF

The laboratory's work has been conducted in close collaboration with other federal agencies, industry, standards and professional organizations, universities, and other NBS/NIST units. Much of the work has attracted substantial press and public attention. The laboratory's secretaries, administrative assistants and other support staff have performed admirably in providing friendly and helpful interfaces for collaborators and other interested parties, as well as in supporting production of research results.

Many of the laboratory's support staff began work with CFR, CBT or BFRL as young women fresh out of high schools in the small towns and rural areas west and north of Gaithersburg. They have been notable for their helpfulness, intelligence, ability to learn new skills as office automation technologies have advanced, commitment to their work, and loyalty to the laboratory through good and hard times. The loyalty to and enthusiasm for the laboratory seem to come both from their character and their identification with the goals of the laboratory. Among those meriting specific attention are:

- Linda Beavers joined the Building Research Division as a teenager and grew with it to become secretary to the deputy director of CBT in the 80s. Her team spirit and great personal productivity were extremely valuable in the years that CBT's existence was threatened by the Administration.
- Sheilda Bryner served as secretary of the Building Environment Division during the 1990s and did a wonderful job of supporting the Division and the Division Chief for some major outside responsibilities. The Division was asked to manage a three-year focused program on advanced refrigeration technology for the new NIST Advanced Technology Program for which she took administrative responsibility. In addition, the Division Chief served one year as President of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers and she managed all arrangements effortlessly and error-free for more than 55 of his trips during that year.
- Mary Chandler was the secretary for the founding director of CFR and continued as his secretary as he oversaw CFR, CBT, and then BFRL as director of NEL and NIST. Her helpfulness, understanding, and calm under pressure were a constant resource for CFR, CBT and BFRL.
- Deborah Cramer has been secretary for the chief of the Fire Safety Engineering Division, director of CFR and deputy director of BFRL. She has supported intensive verbal and written information flows and maintained friendly, cooperative relationships with external and internal collaborators, organized numerous meetings and conferences, and maintained contacts with former and retired staff members.
- Gail Crum has provided wonderful support and institutional memory as secretary to the founding director of CBT, the founding director of BFRL and his successor. She is personally productive and develops strong collaborations within the laboratory and with other organizations as the Laboratory conducts leading roles in interagency programs.
- Wanda Eader was a secretary in the NBS director's office before becoming secretary to the chief of the CBT Structures Division in the late 70s and early 80s. Her organizational abilities and skill in dealing with external and press inquiries were extremely valuable to the conduct of high visibility structural failure investigations.
- Nancy Fleegle was a strong producer in CBT's word processing center in the late 70s and early 80s, and then became secretary to the Structures Division for CBT and BFRL. Her compassion, good cheer and steady support have been great resources for fast-paced failure and disaster investigations and in times of financial stringency.
- Carolyn Flood was secretary for the Office of Housing Technology, Building Economics and Regulatory Technology Division, and deputy director of CBT. In these roles she very efficiently handled complex external collaborations, managed office activities and mentored and developed younger staff.
- Barbara Horner joined CBT in 1978 and became Secretary of the Building Materials Division in 1981. She was a highly valued member of the Division management team and was meticulous in monitoring project expenditures and solvency, and producing solvency reports and effectively worked with international materials experts in providing high quality support services in planning and organizing conferences where she received compliments from senior level researchers and managers. In 1985, Horner was awarded a Bronze Medal for "outstanding contributions to the Building Materials Division and international committees and conferences."
- Laurene Linsenmayer was the primary secretarial support for the Office of Applied Economics (OAE) for 18 years prior to her retirement in 1997. She carried out her normal secretarial duties with great efficiency and tact. In addition, she was very skillful in editing and preparing reports for publication, and extremely helpful in making the OAE's Life-Cycle Cost Workshops

run smoothly for both our staff and the many international students taking our classes. Her affable, helpful manner won her many friends at all levels of NIST, while her commitment to excellence and timeliness earned her the professional respect of all.

- Katherine Panagos began her career at NIST as the secretary to the Cement and Concrete Reference Laboratory (CCRL). She later became secretary to the Construction Materials Reference Laboratory, which consisted of CCRL and the AASHTO Materials Reference Laboratory. She was very effective in handling the many facets of these NIST Research Associate Programs requiring close coordination with the sponsoring organizations, AASHTO and ASTM.
- Flora Parsons joined NBS and served as secretary to both the Computer Integrated Construction Group and the Solar Equipment Group. As the secretarial demands in both of these Groups increased, she worked exclusively for the Solar Equipment Group. During her eight years of service, Mrs. Parsons performed in an exemplary manner, providing outstanding secretarial and editorial support. Her productivity and team spirit greatly enhanced the efforts of the Building Environment Division.
- Mary Reppert was secretary for the Building Environment Division in the early years of CBT during the height of the energy crisis. She showed inspiring enthusiasm for and loyalty to her division and great editorial support for its work.
- Paula Svincek became the Heat Transfer Group's secretary in 1996 after providing several years of support to NIST's Advanced Technology Program. Mrs. Svincek was largely responsible for packaging, distributing, and making available on the intranet the simulation model MOIST, used to predict moisture movement within homes. Through her own initiative, she acquired the skills and developed the first web site depicting the research related to building integrated photovoltaics. Additionally she has embraced and provided leadership in the implementation of office automation throughout the Building and Fire Research Laboratory.
- Jennifer Wright joined the Building Research Division as a teenager and grew with it to become secretary of the chief of the Building Environment Division before becoming administrative assistant to the chief of the Public and Business Affairs Division of NIST. Her productivity, excellence in collaborations and knowledge of the building community have been a great resource for BFRL.

1.5.2 ADMINISTRATIVE STAFF

The administration of CFR, CBT and BFRL always has been complicated by the need to manage other federal agencies' and industry funds as well as those provided directly by NBS/NIST. Numerous external audits have been conducted, not always with friendly intent, and never were significant problems encountered. Personnel matters also have been challenging with diverse disciplines represented, many reductions in force required, and performance-based adverse actions made when needed. CFR, CBT and BFRL have been renowned in NBS/NIST for excellent and responsive administration. Among the key people responsible for this were:

- Pearl Bowman Kaetzel joined CBT from the NBS Budget Office and became administrative officer for CBT and an administrative officer for BFRL. Her technical skill and knowledge of NBS were great resources for CBT, she was adept at problem solving, and her kindness helped all the staff.
- Lynn Castle was administrative officer for the Division of Building Research and the first years of CBT. She handled complex financial arrangements with sponsoring federal agencies, faultlessly tracked the flows of funds, and educated novice managers in fiscal matters.
- Karen Perry joined CBT when she completed high school and has grown to become BFRL's senior management advisor. Her competence, excellent interpersonal skills and unstinting extra efforts in times of crisis have been great resources for the laboratory.
- Michael Schmitt was administrative officer of CBT in years when it operated mostly on external funding and when it was required to make substantial reductions in staff and

programs. His competence, wisdom and fresh ideas made him an effective member of the Management Council and caused NEL management to transfer him to the Manufacturing Engineering Laboratory that had even greater administrative challenges.

- Kathryn Stewart became the founding executive officer for BFRL after serving CFR as administrative officer. Her administrative skills were complemented by a concern for people that was very helpful to BFRL management.
- Mike Stogsdill began his long career in administration in the fire technology area, became Administrative Officer of the CFR when it was formed, and later of the National Engineering Laboratory. He has continued to serve with distinction in various capacities at NIST to this day.

1.5.3 TECHNICIANS

CFR, CBT and BFRL have been laboratory-based organizations. The quality and efficiency of laboratory work have been made possible by excellent and dedicated technicians. While many are cited for their professional contributions to the research in the chapters that follow, it is appropriate to cite some outstanding technicians here:

- Jim Allen played an instrumental role in the testing of solar energy systems. Allen was largely responsible for setting up the facilities needed at the NIST Annex to evaluate the various components of solar energy systems. His in-depth knowledge of electronics greatly assisted the project engineers in designing numerous data acquisition systems used to measure the performance of solar devices.
- Bill Bailey headed up a team of technician specialists to conduct large-scale fire tests, first at the Connecticut and Van Ness site and later at Gaithersburg. He was responsible for outfitting and commissioning Building 205, a special facility dedicated to large-scale fire work. He and his crew performed this dangerous work flawlessly year in and year out.
- Donn Ebberts assisted in the fabrication, testing, and the data reduction associated with the development of ASHRAE test procedures for liquid and air solar thermal collectors, thermal storage systems, and solar hot water systems. Ebberts assisted in the construction and instrumentation of a passive solar energy home at the NBS Annex used to evaluate various passive solar energy systems.
- Frank Rankin was the lead structural technician throughout the years of CBT and in the early years of BFRL. In field and laboratory studies he developed and mentored young technicians and young engineers with strong attention to safety and efficient conduct of research.
- Willard (Bill) Roberts was a lead technician for the calibration, maintenance, and use of the instruments in the Building Material Division's Analytical Laboratory from the mid-1970s to the mid-90s. Among his contributions he performed testing that provided the foundation for drafting test methods to evaluate the performance of materials used in fabricating solar collector systems for residential use that became the technical basis of standards to support the Nation's solar energy program and the acceptance of solar collector systems.
- Charles Terlizzi provided the technician support needed to develop test procedures for solar thermal hot water systems. Terlizzi conducted numerous experiments to compare the performance of solar hot water systems tested under outdoor conditions, and indoors using a solar and thermal simulator. His diligent efforts resulted in an ASHRAE Standard that is currently used to rate all solar water heating systems sold within the United States.
- Dave Ward provided outstanding technician support in the area of refrigerant mixture measurements and in the development of a test rig for determining refrigerant flammability.

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2. CENTER FOR FIRE RESEARCH IN THE 70s

2.1 CREATION OF THE CENTER FOR FIRE RESEARCH

Until the latter half of this century, the U.S. Congress had not shown much interest in the unwanted urban fire problem. (Unwanted fires denote those caused by accidental, natural and willful hazards, as distinguished from those desired and under control such as a fireplace fire to warm and cheer a room.) Then, beginning with passage of the Flammable Fabrics Act in 1953, this changed. During the next two decades, peaking in the Nixon years (1969-75), a number of pieces of legislation were enacted aimed at improving consumer health and safety, including fire safety. Notable among these were the Occupational Health and Safety Act, The Environmental Protection Act, the Consumer Product Safety Act, and three acts relating to a Federal role in reducing the losses due to unwanted fire. These three Acts - the amendments in 1967 to the 1953 Flammable Fabrics Act, the Fire Research and Safety Act of 1968 (PL 90-259), and the Federal Fire Prevention and Control Act of 1974 (PL93-409) constitute a considerable effort on the part of Congress to do something about fire losses in the United States. Each called for a major role for the National Bureau of Standards (NBS) in research and technology. So why this sudden attention to a problem that had traditionally been left to state and especially local governments?

Until the middle of the nineteenth century protection from the ravages of fire had been the province of private fire companies and insurance underwriters. As larger fractions of the populations moved into the cities and people were more crowded together, fires became a greater problem. In the big cities the fire companies were taken over by the city governments. Well-engineered water systems were placed so as to provide adequate pressure for fire fighting, and ordinances were passed concerning separations or fire barriers between buildings. These measures, taken mostly by city governments, were directed to preventing conflagrations that could and did involve large sections of cities - even, sometimes, entire cities.

Concern gradually shifted to preventing the loss of large, individual buildings. Still mostly city governments' work, building codes came into being, tests for fire worthiness were devised and required, organizations such as the National Fire Protection Association, the Underwriters' Laboratories, the American Society for Testing and Materials were established. The NBS was created in 1901 and one of its early experiences with fire standards came after the great Baltimore fire of 1904 in which it was found that fire hose couplings from different cities and towns could not attach to the Baltimore Fire Department's fire hoses and hydrants. NBS, working in collaboration with other organizations, created standards for fire hose couplings and for many years kept standard artifacts for adapters for the many different hydrants in the country.

For the first 50 years or so of NBS' history there was a steady progression of field and laboratory work on fire endurance. Fire endurance denotes the ability of building components to maintain their load bearing and separation functions for prescribed time periods when exposed to fire. Burnout tests were conducted in rooms and buildings to measure the temperatures produced in fires and their durations. Laboratory tests were developed and perfected for use in building codes. Many of these were for evaluating prolonged resistance to the stresses from prescribed fire exposures, usually in the form of standard time-temperature relationships, in a large furnace. The furnaces could be configured to test columns, floors, walls roof assemblies and ceilings. The code could then specify, according to occupancy and location in the building, a particular duration; e.g., 1/2, 1, 2, or even 4 hour ratings. Thus the lower structural members of a tall office building might be expected to resist fire exposure for 4 hours, giving the fire service time to gain control without collapse of the building. By the 1960s this work was mature and the Nation's building codes controlled fire safety in large buildings very well. Indeed, it was by then possible to say that in the United States we no longer lost towns and cities or large buildings when they were built and maintained according to code. Nearly all conflagrations or large building fires causing multiple deaths and major monetary loss could be attributed to "out-of-code" construction or use or to large natural disasters.

This seems no longer valid following the events of September 11, 2001. The disaster at the World Trade Center in New York City involved both severe impacts and severe fires ending with collapse of both towers. There now is concern that then applicable and current codes may not require sufficient evaluation of beam-column ensembles and beam to column connections. There also is concern that current temperature-time relations for fire testing do not adequately represent all potential fire exposures. New research is expected to improve test methods and code requirements.

Still, the fire losses in this country had become large and politically sensitive. America Burning [1] cited annual deaths approaching 12,000 and annual costs conservatively exceeding $11 billion. What had happened? Review of the fire loss data suggested that, to make further reductions in our losses, we had to shift focus from large commercial and multi-occupancy buildings to residences and from fire spread to ignition. We also had to think of preventing individual life loss. Thus we had to look at the products brought into the residence and their behavior both as ignition sources and as agents for the growth and spread of fire within the space of fire origin.

2.1.1 THE FLAMMABLE FABRICS ACT

One of the early expressions of concern by the Congress was passage of the Flammable Fabrics Act in 1953. This Act was directed to removing from the market certain textile products that became known as "torch sweaters." The material was unusually combustible and a simple vertical flame exposure (in a voluntary standard method of test based on work done at NBS) served as the test. The immediate objective was achieved. By the 1960s, new fabrics and fabric constructions were on the market and studies began to show new problems with flammability. In 1967 the Congress amended the Flammable Fabrics Act and established responsibility among three agencies: the Department of Commerce was to establish test standards and requirements, the Department of Health, Education, and Welfare was to investigate reports of fire injuries and deaths, and the Federal Trade Commission was to enforce the Act. The Commerce Secretary assigned the standards development work to NBS. A Flammable Fabrics Section was set up under James Ryan and subsequently an Office was established under the Institute for Applied Technology (IAT) at NBS.

2.1.2 THE FIRE RESEARCH AND SAFETY ACT OF 1968

In 1968 the Congress expanded its concerns to all sources of losses from unwanted fire and enacted the Fire Research and Safety Act. This Act authorized a new National Commission to see why the U.S. had such high fire losses and what might be done to reduce unwanted fires and to mitigate the effects of those that do occur. The legislation further enhanced the technical role of the NBS by setting up a second office called the Office of Fire Technology. This group was charged with looking at ways to utilize modern technology both in fighting fires and in assisting the fire fighter by improving the tools and equipment available. So by the end of the decade NBS found itself with three essentially independent entities, all looking at some aspect of unwanted fire: the fire section in the Division of Building Research, the Office of Flammable Fabrics, and the Office of Fire Technology. The division and both offices were under the direct supervision of the Institute of Applied Technology.

2.1.3 THE AD HOC PANEL ON FIRE RESEARCH AT NBS - THE NATIONAL RESEARCH COUNCIL

This somewhat fragmented situation caused NBS management to request of the National Research Council (NRC), an ad hoc Panel on Fire Research specially chartered to evaluate fire research at NBS and to make recommendations on how to improve the quality of work product. This panel, chaired by Professor Howard Emmons of Harvard University and made up of an eclectic mix of professional interests drawn from around the country, made an in-depth study of what NBS was doing and wrote, in 1972, a detailed review with 34 numbered recommendations. The report called for a careful analysis of the National needs followed by a selection of those challenges that NBS could appropriately handle - a comprehensive plan. The report emphasized the need to think about the fire problem in a fundamental way and urged that fundamental work at NBS be expanded. It also urged that NBS' work on fire be tightly coordinated. The succeeding 1973 NRC report praised NBS efforts to pull fire research together, urged creation of a fire dynamics group, worried about hazards from new materials; e.g., plastics, and said that the work on smoke and toxic gases needed strengthening. The panel felt studies of smoke and fire detectors were going well. The need for better large-scale fire test facilities was emphasized. The ad hoc panel was converted to a regular, recurring panel soon thereafter and reported annually.

2.1.4 THE FEDERAL FIRE PREVENTION AND CONTROL ACT OF 1974

This legislation created the National Fire Prevention and Control Administration, the National Fire Academy, and a Fire Research Center at NBS. The intent was to come to grips with the National fire problem and to define a Federal role to work in tandem with the States and municipalities and the various groups in society already at work. Some NBS functions for fire fighter's equipment and training were transferred to the newly created U.S. Fire Administration and the U.S. Fire Academy. The new Consumer Product Safety Commission was just getting under way at this time and NBS transferred part of the effort on flammable fabrics, retaining the standards development work but transferring the evaluation of fire data on burns. Thus the area of work for the NBS was made clear. In fact it was spelled out in more detail than any other part of the Bureau.

The Act of 1974 amended the organic act of the NBS to establish the Fire Research Center. It authorized a long list of research areas that were included in the organic act by amendment. These are:

"(1) basic and applied research for arriving at an understanding of the fun-

damental processes underlying all aspects of fire. Such research shall include scientific investigations of -

- *(A) the physics and chemistry of combustion processes;*
- *(B) the dynamics of flame ignition, flame spread, and flame extinguishment;*
- *(C) the composition of combustion products developed by various sources and under various environmental conditions;*
- *(D) the early stages of fires in buildings and other structures, structural subsystems and structural components in all other types of fires including, but not limited to, forest fires … with the aim of improving early detection capability;*
- *(E) the behavior of fires involving all types of buildings and other structures and their contents, … and all other types of fires, including forest fires … oil blowout fires …;*
- *(F) the unique fire hazards arising from the transportation and use, in industrial and professional practices, of combustible gases and materials;*
- *(G) design concepts for providing increased fire safety consistent with habitability, comfort and human impact in buildings and other structures; and*
- *(H) such other aspects of the fire process as may be deemed useful in pursuing the objectives of the fire research program;*

"(2) research into the biological, physiological, and psychological factors affecting human victims of fire and the performance of individual members of fire services, including -

- *(A) the biological and physiological effects of toxic substances encountered in fires;*
- *(B) the trauma, cardiac conditions, and other hazards resulting from exposure to fire;*
- *(C) the development of simple and reliable tests for determining the cause of death from fires;*
- *(D) improved methods of providing first aid to victims of fires;*
- *(E) psychological and motivational characteristics of persons who engage in arson and the prediction and cure of such behavior;*
- *(F) the conditions of stress encountered by firefighters, the effects of such stress, and the alleviation and reduction of such conditions; and*
- *(G) such other biological, psychological, and physiological effects of fire as have significance for purpose of control or prevention of fires; and*

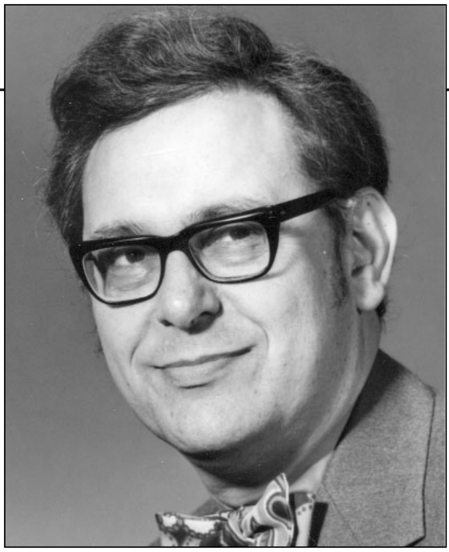
"(3) operation tests, demonstration projects, and fire investigations in support of the activities set forth in the section.

"The Secretary [of Commerce] shall insure that the results and advances … are disseminated broadly. He shall encourage the incorporation … in building codes, fire codes … test methods, fire service operations and training and standards. …"

John W. Lyons, a physical chemist, had been hired in 1973 to head the newly consolidated fire program. He arrived before the legislation was passed and became the founding director of the Center for Fire Research (CFR). Irwin Benjamin, an expert in uses of structural steel and the leader of the fire section within the Center for Building Technology's (CBT) Structural Division, joined CFR to become leader of its fire safety engineering work. Benjamin's personal commitment to fire safety, vision, skill in recruiting and mentoring his staff, insight into the best opportunities to improve fire safety, and knowledge of how to get improved practices accepted and applied in the fire safety community were key in CFR's achieving its goal to halve fire losses in a generation. Lyons hired Robert Levine from NASA to lead CFR's fire science activities. Levine came to CFR as a leading rocket scientist. He made strong contributions to CFR through his knowledge of combustion science and peer scientists worldwide, and his enthusiasm for good work in both fire science and fire safety engineering. Frederic Clarke, an organic chemist, joined CFR as assistant to the director.

CFR was established on October 29, 1974, when President Ford signed the Federal Fire Prevention and Control Act of 1974. NBS had anticipated this action and had in place a Programmatic Center for Fire Research headed by John Lyons and involving 110 federal employees.

John Lyons, founding director, Center for Fire Research during 1973 to 1977 when he became founding director of NBS's National Engineering Laboratory. Lyons' experience in industry, expertise in fire science and its applications, delight in strong technical work, and concern for people provided a strong start for CFR. His talents led to his promotions in 1978 to become the founding leader of the National Engineering Laboratory, and in 1990 to become director of the National Institute of Standards and Technology until 1993.



Irwin Benjamin, initial leader of Fire Safety Engineering.

Robert Levine, initial leader of Fire Science.

2.1.5 A LONG-RANGE PLAN FOR NBS FIRE RESEARCH - FIRE SCENARIOS AND INTERVENTION STRATEGIES

The detailed listing of the 1974 Act would seem to leave nothing to chance; it certainly authorized NBS staff to study whatever seemed necessary. However the list was only authorized, not mandated. Given the resources then available or likely to be, a host of choices had to be made to plan and execute the actual research program. Soon after the legislation was signed into law, the director of NBS requested of the director of the Center for Fire Research a detailed long-range research plan with a rationale for the proposed work [2]. In response the managers of CFR and some of the key research staff spent much time meeting together to develop an approach that took into account what was then known about the etiology of unwanted fires, the sequences by which the fires moved from ignition to growth and spread, and the ultimate cause of the losses through death, injury and destruction of property [3]. They called these sequences fire scenarios.

The NRC reports had prepared the way for carrying out the subsequent provisions of the Federal Fire Prevention and Control Act of 1974. The report of the Federal Commission on Fire Prevention and Control (1972) had declared that it should be possible to reduce the Nation's fire losses by half in about 14 years. The CFR planners took the 50 percent figure but stretched the timing to some two decades and then sought to define the technical work that would be needed to underpin the various interventions that would be required in those key scenarios that accounted for most of the fire losses. The goal for CFR became:

> *To insure the development of the technical base for the standards and specifications needed in support of the National goal to reduce fire losses by 50 percent over the next generation.*

The CFR staff took it as their responsibility not only to conduct and publish the technical work but also to see to it that the results were widely promulgated and adopted by the community at large. There was some concern by some staff that such objectives went beyond the ability of the staff to control outcomes. While this was certainly true we felt strongly that the Congress was funding the work for the change in fire losses, not for publications, however important.

2.1.6 TECHNICAL CHALLENGES FOR FIRE RESEARCH

A large number of technical challenges faced CFR.

Challenges deemed important by management were:

1. **Lack of tests that are scientifically based to meet legal challenges to imposing tests in regulations and codes. For instance, one cannot test at one irradiance if one wants to take into account the heat from the material's combustion in addition to that from the exposing flame or source; the use of a simple flame or single exposure is useful only for ignition tests.**
2. **Lack of tests at bench scale that correlate closely to performance in full-scale fire tests - hence the costly need to "build it and burn it."**
3. **Lack of mathematical models good to within 10 percent or so for predicting key events: e.g., flashover, toxic levels of gases. Fires are turbulent, reacting, buoyant flows with low symmetry - no two fires are the same.**
4. **Lack of first principles models to provide credibility for simplifying assumptions in zone models.**
5. **Lack of thermo-chemical and thermo-physical data on modern materials and composite structures for input to mathematical models.**
6. **Dearth of information on toxicity of combustion products - the predominant cause of death in fires: no standard test for toxicity, no tie between testing for toxicity and for ignition, spread, and growth.**
7. **No reference materials for calibration of instruments.**
8. **Lack of understanding of the molecular details of combustion such as soot particle formation and its effect on flame radiation and heat transfer.**
9. **Lack of rugged, calibrated instruments for looking into fires, and thermal lag in thermocouples.**

2.1.7 ORGANIZING THE RESEARCH

After transferring those pieces of the work that more properly fit the missions of the Consumer Product Safety Commission and the Fire Administration, there remained the task of putting together the new Fire Research Center, or in NBS custom, the Center for Fire Research (CFR). The programs involving fire then in the Center for Building Technology were moved into CFR and combined with the remaining parts of the flammable fabrics work and the fire research and safety functions. The several analyses and plans referred to above led easily to a new emphasis on the fundamentals and the creation of the Fire Science Division in which were chemistry, physics and dynamics, and an office of information and hazard analysis. In a short time chemistry became chemistry and toxicology, and a few months later this group split into two groups emphasizing the growing importance placed on the toxicity of combustion products. The engineering-oriented work was placed in a Fire Safety Engineering Division with groups on fire prevention - products (flammable fabrics and related ignition work), fire control in construction, fire control in furnishings (growth and spread of fire), fire detection and control (detectors and sprinklers), and new design concepts. This two-division structure worked well for a number of years. There were some permutations and the transfer of the National Science Foundation's fire research grants to CFR caused some adjustments.

The organization and key people as of 1975 became:

Fire Science Division, *R. Levine, Chief*
- *Project Manager for Arson, B. Levin*
- *Office of Information and Hazard Analysis, B. Buchbinder*
- *Program for Chemistry, C. Huggett*
- *Program for Toxicology of Combustion Products, M. Birky*
- *Program for Physics and Dynamics, J. Rockett*

Fire Safety Engineering Division, *I. Benjamin, Chief*
- *Program for Fire Prevention-Products, J. Winger*
- *Program for Fire Control-Construction, D. Gross*
- *Program for Fire Control-Furnishings, S. Davis*
- *Program for Fire Detection and Control Systems, R. Bright*

2.1.8 CFR ACQUIRES NSF'S FIRE RESEARCH PROGRAM

In the late 1960s and early 1970s the National Science Foundation (NSF) program called Research Applied to National Needs was managing a set of research grants awarded primarily to universities, but also to private and commercial research institutions with close ties to universities. NSF had about $2 million a year invested in fire related research. The program was of the highest quality. The Congress decided that a better place for this effort was at the CFR; thus in 1975 they transferred the authority and budget to NBS. This move caused some concern at the Bureau. Some thought it a poor idea to mix in-house work with management of grants or contracts externally. The belief was that the added management role would dilute attention to NBS' laboratory work and that perhaps both would suffer. (This argument returned again both under the Carter Administration, when centers for cooperative technology development were proposed to be located at NBS with major components from the private sector, and later when the Advanced Technology Program, the Manufacturing Extension Program, and the Baldrige National Quality Award were in fact enacted and given to NBS to manage.) However, the choice to accept the NSF grants or not was not NBS' and we went forward with the transfer. The decision was a good one.

A key decision was to assign the oversight of the external work to the individual research groups in CFR. Thus the dynamics work at Harvard/ Factory Mutual, California Institute of Technology, Notre Dame etc was closely followed by the fire physics and dynamics group at CFR and the toxicology work was overseen by the CFR toxicology group. Recommendations as to changes in the work or renewals came from the in-house group leaders. This internal management was made possible through the use of cooperative research agreements as opposed to grants or contracts. The cooperative agreements had recently been authorized by Congress to enable closer cooperation and integration between in-house and extramural work throughout government. In CFR's experience the mechanism worked effectively. It was not long before the interactions became very close and we could consider all of the work - in-house and extramural - as one large integrated program. The benefits to all were great.

2.1.9 1975 ACCOMPLISHMENTS

Accomplishments in 1975 included:

- The pilot implementation of the National Fire Data System was completed and turned over to the National Fire Prevention and Control Administration.
- A relationship was established between flammability limits in premixed and diffusion flames.
- The capability was developed for measuring particle size distribution and mass concentration in smoke.
- A proposed standard for the flammability of upholstered furniture was developed and recommended to the Consumer Product Safety Commission.
- The fire safety of interior components of AM General buses and Metro subway cars was evaluated for the Washington Metropolitan Transit Authority.
- Reduced scale and analytical modeling techniques were developed and tested for predicting fire growth in rooms.
- Recommended performance standards for single-station smoke detectors were adopted and published by Underwriters' Laboratories, Inc.

2.2 EVENTS AND PROGRESS THROUGHOUT THE 70S

In the early 1970s some disastrous fires had been occurring in rooms lined with fire retardant treated cellular plastics. These plastic foams had been deemed to be fire-safe by the bench scale fire tests in use at that time and also by the ASTM E84 tunnel test that is the standard test for interior finishing materials. As a result, the Products Research Committee (PRC) with John Lyons as its chairman, was created in 1974 as a free standing charitable trust in an agreement to a consent order signed between the U. S. Federal Trade Commission and 25 manufacturers of cellular plastics.

Thus, a large investigation was launched to determine: 1) why the existing tests failed; 2) if they could be fixed; and 3) if new tests needed to be developed for these materials. The Products Research Committee members came from industry, testing agencies, government and academia. The committee supported relevant research in a number of organizations including NBS. The funds were provided by the cellular plastics industry.

This work showed that thermal radiation reinforcement by the enclosure was a critical factor in the growth of fire in a room. The building codes now require that cellular plastics be covered by safer materials, or pass a standard room fire test with a substantial ignition source in one corner. A standard room fire test was developed in the civil engineering department at the University of California on a research grant from CFR. William Parker, the project monitor from CFR, worked with Brady Williamson at UC on the design and incorporation of an oxygen consumption system for measuring the heat release rate in the room fire.

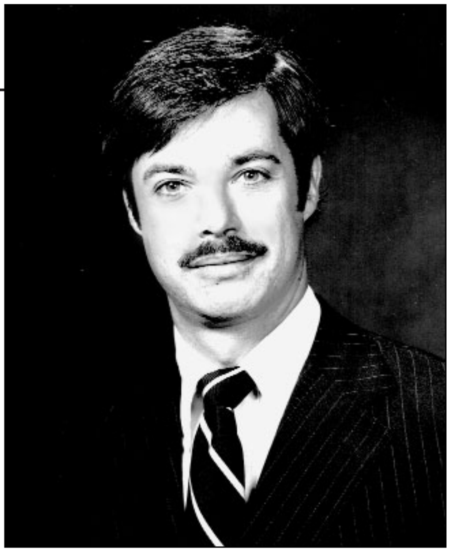
John Lyons, beginning in October 1977, organized and directed the new National Engineering Laboratory (NEL). NEL replaced the Institute for Applied Technology (IAT) as the parent organization for CFR and CBT. Frederic Clarke, who had served as Lyons' special assistant for planning and communications, became acting director of CFR and its permanent director in October 1978. Clarke, still in his 30s, showed outstanding scientific and analytical skills, commitment to CFR's goal, and strong interpersonal skills.

The report of the September 1978 Annual Conference on Fire Research [4] summarized the major activities and accomplishments of CFR in fiscal year 1978.

Benjamin Buchbinder's Program for Information and Hazard Analysis described, with the example of upholstered furniture, how Decision Analysis provided the analytical framework for combining loss and cost estimates for alternative strategies for addressing particular fire problems and selecting the most cost effective strategy. The Fire Research Information Services (FRIS) was described as one of the world's foremost collections of fire research documents.

Richard Gann's Program for Chemistry was seeking a scientifically based susceptibility index for spontaneous ignition, and determining the fire potential of dielectric fluids that could be substituted for the environmentally harmful polychlorinated biphenyls (PCBs) that had been banned as insulating fluids for transformers and capacitors by the Environmental Protection Agency. Oxygen depletion by combustion was shown to be a sound quantitative measure of rate of heat release, and mass spectroscopy was showing valuable capabilities for studying temperatures and chemical processes in flames.

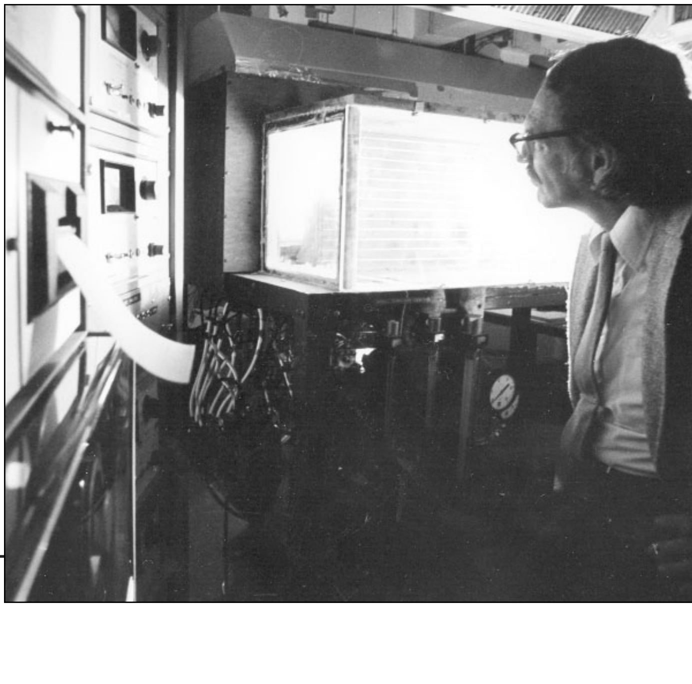
John Rockett's Program for Physics and Dynamics progressed with zone models for the spread and growth of fires and computational fluid dynamics models for flow phenomena in fires. James Winger's Product Flammability Program worked for the Department of Energy to develop methods and procedures to assure adequate fire safety when wood is used for a fuel in residences. William Parker's Construction Materials Program produced a new heat release rate calorimeter and worked on fire hazards of insulations in residential occupancies for the Department of Energy.



Frederic Clarke, 2nd director of the Center for Fire Research.

Edward Budnick's Fire Detection and Controls Program worked on test methods for smoke and fire detectors and performance of detection systems in health care facilities and mobile homes. Laboratory studies were conducted on the performance of sprin-

John Rockett, leader of Physics and Dynamics, is performing an experiment to model smoke growth and flow in corridors. Rockett had played a leading role in NBS's fire research since the 60s and contributed strongly to the development of CFR.



klers in health care facilities and in open stairways.

Harold Nelson's Program for Design Concepts worked on closing the gap between scientific data and models and the "use system" of standards and codes. Fire safety evaluation systems were under development for health care facilities, group homes and multi-family housing.

Merrit Birky's Program for Toxicology of Combustion Products drafted, in consultation with experts from industry, government and academia, a test method for the identification of materials that produce unusually toxic combustion products. It involved measuring the mid-lethal concentration of combustion products for exposed rats. NBS management was very uncomfortable with on-site animal testing, but a major goal of this work was to reduce needs to conduct animal testing to determine the combustion toxicity of products.

The Third Annual Conference on Fire Research held on August 22-24, 1979, [5] does not describe management issues and cites few major accomplishments. James Winger's Program for Product Flammability Research reported a review of literature, model codes and tests for the fire safety of wood burning appliances in residents and small industries. Standards were recommended to the Consumer Product Safety Commission for cigarette ignition of upholstered furniture and for flammability of general apparel, and to the Federal Aviation Administration for flammability of flight crew uniforms.

The Fire Safety Engineering Division participated with ASTM in the introduction of new test methods and in the improvement of existing ones. These included:

1. Flooring Radiant Panel E 648 for Carpet Flame Spread.
2. Critical Radiant Flux for Flame Spread on loose fill insulation.
3. Smoldering Ignition test.
4. Mobile Home Project: factors affecting life safety given a fire in a mobile home and mitigation of the worst hazards.
5. New time-temperature curve for fire endurance of walls and floor assemblies in residential occupancies. Basement recreation rooms were especially dangerous because of the short time to flashover.
6. Smoke movement in high-rise buildings.
7. The Lateral Ignition and Flame Spread Standard Test (LIFT) apparatus to measure ignition flux and flame spread.

In addition, heat release rate (HRR) was recognized as a most important fire property of materials.

CFR issued its updated Research Plan in August 1979 [6]. The goal of CFR was expressed as:

> *The goal of the Nation is to reduce fire losses by 50 percent by 1995. The goal of the Center for Fire Research is to provide the needed knowledge for making rational and cost-effective choices among alternative strategies for this loss reduction, and to reduce fire as an obstacle to meeting of other national needs.*

The strategy for CFR was:

1. The Center research program will take several simultaneous approaches to reducing fire losses.
2. The Center's approach to improved fire safety is one grounded in an understanding of the fundamentals of fire science.
3. The Center's responsibility includes the conversion of research results into implemented fire safety measures.

Planning was based on the scenarios for fire losses [6] that related fire deaths in the U.S. to occupancy, item ignited and ignition source. Technical issues were identified to address the scenarios and from these action items were identified for fire research:

1. Improved standard test method for smoke detectors.
2. More economical design criteria and performance specifications for sprinkler operation and installation to the National Fire Protection Association (NFPA).
3. Design criteria for optimum use of smoke control/HVAC systems to NFPA and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE).
4. Take systematic approach to achieve given level of fire risk with lowest cost combination of fire protection elements.

5. Standard test methods to ASTM International, NFPA for flame spread and rate of heat release of interior finishes.
6. Standard test methods to ASTM, NFPA, and Consumer Product Safety Commission (CPSC) for flame spread, rate of heat release of furnishings.
7. Proposed standards to reduce likelihood of ignition by electrical and heat producing products to Underwriters Laboratories Inc. (UL), Factory Mutual, and the Institute of Electrical and Electronics Engineers, Inc (IEEE).
8. Recommended practices to assess combustion product toxicity as component of life safety hazard.
9. Modeling design decisions to minimize full-scale assembly testing.
10. Design and formulation guide for improving ignition or smolder resistance of composite materials.
11. Specific structural fire resistance requirements based on experimental evidence.
12. Design requirements based on actual human behavior and needs.
13. Standard test method for detectors to NFPA, UL, which identifies detector capability to resist false alarms.
14. Arson detection methods for the National Fire Academy, state arson laboratories through US Fire Administration (USFA).

The Plan then established the objectives for CFR. The Plan was developed just before CFR moved into an extremely difficult decade with unstable funding and funding cuts. Yet, this history will show excellent accomplishment of the objectives.

For Existing Resources

1. To develop a set of performance based design recommendations for automatic suppression systems, with submission of recommended design changes for automatic sprinkler systems to the appropriate authorities in 1983.
2. Develop performance guidelines for the design of both fire detection and smoke control systems; including recommendations regarding whether or not to develop a revised full scale protocol for smoke detection by 1980, and the development of an initial Mechanical Engineers Smoke Control Manual based on state of the art technology by 1981.
3. To identify the importance of combustion product toxicity as part of the overall fire hazard and to provide the test methods and recommended practices for predicting and reducing the hazard, with the development of a toxicity hazard assessment methodology by 1983.
4. To develop test methods for the fire properties of materials and products which can be related to fire hazard; with procedures for ignitability, flame spread, and rate of heart release for upholstered furniture to be completed by 1983.
5. To develop the capability to predict the effects of a fuel's physical characteristics and chemical composition on its fire behavior, with a mechanistic model for radiant ignition developed by 1982.
6. Develop technical background to support measures to reduce the likelihood of unwanted ignitions associated with the generation, distribution, and use of electrical energy and use of heat producing equipment or processes with recommendations to reduce ignitions from residential electrical power systems in 1983.
7. To develop a validated, physically based predictive method for describing the growth of fire in a building, with a documented validated room fire model by 1983.
8. To provide the full-scale fire test data needed to verify the physical and analytical fire growth models, to support the development of standard fire test and to assess the hazards of materials as exemplified by the development of a correlated reduced scale room fire test by 1981.
9. Develop and apply methodology for evaluating alternative strategies for reducing fire losses based on cost benefit considerations, with an initial analysis of residential fire loss reduction strategies by 1982.
10. Synthesize fire research, fire protection engineering, and human behavior technology into systematic technically based approaches to fire safety design, with the issuance of initial approaches to comprehensive design evaluation and cost effectiveness systems by 1983.

11. Establish by 1983, a battery of analytical methods and procedures for use in the field and laboratory detection of arson.
12. To transfer information on both fire research and the interpretation of fire research to various publics: e.g., designers, fire researchers, fire services, and standards organizations. An example of this transfer will be the incorporation of the NBS developed Fire Safety Evaluation System into the 1980 edition of the Life Safety Code.

For New Resources (which were not received)

1. To publish a home fire safety design manual and curriculum by 1985.
2. To develop the instrumental capability and technical competence to define the role(s) of oxygen in the various modes of fire-related combustion, with a model of the oxygen involvement in oxidative pyrolysis by 1982.
3. To exploit the mechanics of smoke and aerosols, and new fire detection sensor principles to eliminate false alarms by 1985.
4. To improve existing knowledge of the physiological effects of fire and to recommend methods of treatment by 1985.
5. Develop, by 1983, the competence to analyze and identify methodologies for controlling fire losses associated with storage and transportation of hazardous materials.

The Department of Commerce provided strong recognition for CFR's accomplishments in its awards of Gold and Silver medals:

- Gold to Alexander Robertson in 1976 for career accomplishments in improvements of fire safety standards.
- Gold to John Lyons in 1977 for leadership of CFR.
- Silver to Richard Bright in 1976 for his work in improving the performance of residential smoke detectors.
- Silver to John Rockett in 1977 for advances in fire modeling.
- Silver to Clayton Huggett in 1978 research in flame inhibition.
- Silver to James Winger in 1978 for research in fabric and furniture flammability.
- Silver to Irwin Benjamin in 1979 for the development and adoption in standards of the Fire Safety Evaluation System.

The National Bureau of Standards conferred its Rosa Award on Alexander Robertson in 1978 for development of standard flammability test methods.

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3. CENTER FOR BUILDING TECHNOLOGY IN THE 70s

3.1 BACKGROUND FOR 1975

Fiscal year 1975 began on July 1, 1975, which serves as a convenient starting point for coverage of building research in this history. The prior history [1] covers building research from 1968 through 1974. The sections of this chapter are organized by years, approximately fiscal years, which through fiscal year 1976, began on July 1 of the prior calendar year, and thereafter began on October 1.

The Nation was in political turmoil with President Nixon nearing his resignation of August 6, 1974. The industries of construction were depressed (volume in constant dollars down 11 percent) because of higher interest rates imposed to curb inflation caused by increases in energy prices. However, CBT's building research was growing because of increased funding for research for energy conservation and solar energy. The National Bureau of Standards (NBS) had a dynamic young director, Richard Roberts, who had been director only since February, 1973, and emphasized closeness of NBS programs to their customers and effective representation of NBS work to policy makers and the public.

NBS's Institute for Applied Technology (IAT) was the parent unit for CBT and the home for most of the other engineering programs of NBS. IAT's director was F. Karl Willenbrock, an electrical engineer and physicist, who had led IAT since 1970. Willenbrock was passionate and inspiring for the potential of engineering research to improve quality of life, and for strengthening engineering programs at NBS in both their technical quality and their influence on practices and public policy. James Wright, chemist and founding director of CBT, since February 1974, had been deputy director of IAT. He complemented Willenbrock's leadership with his own enthusiasm for more effective programs and strong leadership in improving management practices in the Institute. Willenbrock focused much of his efforts on external representation of the Institute to develop collaborations with leaders in government and industry, but maintained active interest in good technical ideas within the institute. Wright concentrated on addressing organizational and management problems within the

F. Karl Willenbrock, director, Institute for Applied Technology 1970-1976. Willenbrock was passionate and inspiring for the potential of engineering research to improve quality of life, and for strengthening engineering programs at NBS in both their technical quality and their influence on practices and public policy.

Richard N. Wright, director CBT and BFRL 1974-1999.

James Wright, founding director of CBT 1972-74 and chief of Building Research Division 1967-72 (former CBT); in 1975 he became deputy director, Institute of Applied Technology.

Institute and improving its working relations within NBS, continued a founder's interest in the development of CBT, and remained active in leadership of the International Union of Testing and Research Laboratories for Materials and Structures (RILEM).

At its founding in 1972, the mission of CBT was expressed as:
The Center for Building Technology shall consult with industry, government agencies, professional associations, labor organizations, consumers, and such organizations as the National Conference of States on Building Codes and Standards in developing test methods for evaluating the performance of buildings, including their materials and components, the support and stability characteristics of their elements and systems, the effects of new design strategies, their fire safety and environmental characteristics, and their service and communication systems; shall formulate performance criteria for building design and urban systems; and shall perform research (including research on safety factors) in the systems approach to building design and construction, improving construction and management efficiency, in building materials characteristics, in structural behavior, and in building environmental systems.

The Center was organized by divisions, which conducted the laboratory work, and offices, which provided program management and some technical work. These units and their leaders were:

- Headquarters was led until February 1974 by James Wright, with Deputy Director Harry Thompson. Wright's enthusiasm for effective programs and leadership in improving management practices contributed strongly to CBT and all other units of IAT. Thompson, an architectural engineer, had fifteen years of experience in federal design and construction programs and six years in the Bureau of the Budget dealing with public buildings. Thompson's warmth and kindness built rapport within the Center, Bureau and among other agencies.

- In June, 1974, Richard Wright became the director of the Center. Wright, a civil/structural engineer, had been professor of civil engineering at the University of Illinois at Urbana-Champaign, and had experience at NBS as chief of the Structures Section from June 1971 to July 1972, and deputy director-technical of the Center from July 1972 to August 1973. He was drawn to CBT by its potential for interdisciplinary problem solving and research addressing the functionality, safety and economy of constructed facilities.

- Office of Building Standards and Codes Services led by Gene Rowland a mechanical engineer who had joined NBS after leading the formation of the National

James Gross, leader in service to the standards and codes community

Samuel Kramer, expert in working with federal agencies and Congress.

Paul Reece Achenbach, Chief of the Building Environment Division.

Conference of States on Building Codes and Standards as the building official for the State of Wisconsin. Rowland's enthusiasm, wit and energy focused on improving the Nation's building regulatory system.

- Office of Housing Technology led by James Gross an architectural engineer who had joined NBS after being director of engineering and research for Precast Systems, Inc,. and director of engineering and technology for the Structural Clay Products Institute. Gross pressed for quality and responsiveness to sponsors in the Center's work and usefulness in practice of the Center's results, and expressed continued affection for masonry systems.

- Office of Federal Building Technology led by Samuel Kramer a civil engineer who had joined NBS after four years as an examiner with the Bureau of the Budget and ten years working on design criteria, design and construction with the Corps of Engineers. Kramer's intellectual curiosity, analytical skills, and interest in people extended to all of CBT's programs, and eventually to all of NBS/NIST as he was promoted to deputy director of the National Engineering Laboratory and subsequently to deputy director of NIST.

- Structures, Materials and Safety Division led by Edward Pfrang a civil engineer who joined NBS after faculty appointments at the universities of Nevada and Delaware, to lead the Structures section and then organize the Office of Housing Technology and develop major programs with the Department of Housing and Urban Development. Pfrang was outstanding for his imagination, forcefulness and comfort with conflict where he showed extraordinary ability to think on his feet.

- Building Environment Division led by Paul Reece Achenbach a mechanical engineer who had joined NBS in 1937. Achenbach worked tirelessly with quiet passion to gain knowledge to improve building environmental systems and extended his leadership to the American Society of Heating Refrigerating and Air-Conditioning Engineers.

- Technical Evaluation and Application Division led by Porter Driscoll an architect with extensive experience in private practice, government and industry before joining NBS in 1973. Driscoll was eager to make the Center's work relevant and useful to architects.

For 1974 the Center's funding was \$9.2 million, \$3.4 million directly appropriated and \$5.8 million for sponsored research, and its staffing was 231. Sponsored research funding and staffing had increased substantially over 1973 driven by needs for research on energy conservation.

One major accomplishment of 1974 merits mention to set the stage for this history. In the spring of 1973, the National Conference of States on Building Codes and Standards (NCS-BCS) requested CBT to develop a technical basis for effective, nationally applicable building code requirements for energy conservation in buildings of all types. (Note the major role that CBT's predecessor, the Building Research Division of NBS, had played in the founding of NCSBCS [2].) CBT drew upon its long-term research expertise in the prediction and measurement of building thermal performance and lighting to formulate a technically and economically effective approach to the design of energy conserving buildings. Shortly after the oil embargo in December 1973, the NBS report was available for use.

In January 1974, NCSBCS requested the American Society for Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) to process the NBS report as a national consensus standard. ASHRAE established an extraordinary effort to analyze and refine the NBS report and develop a national consensus standard, which became ASHRAE 90-75 and the basis for the energy conservation building codes of the U.S. A thorough description of this effort may be found in the NBS/NIST Centennial Publication [3]. In summary, it showed how effectively CBT could work with the building community to meet critical national needs.

Major influence on the visions of Karl Willenbrock, James Wright, John Lyons and Richard Wright for building and fire research in the United States had been and continued to be provided by consultant William Allen. Allen, a British architect, was born and educated in Canada, and joined the British Building Research Station (BRS) in 1937 where he became a disciple of Robert Fitzmaurice, principal author of the seminal *Principles of Modern Building*, which was published in 1938.

Their views were that building practices can and should be based on science, a real understanding of the physical and human environments and behaviors that influence the usefulness, safety and economy of constructed facilities. Professional judgment, creativity and aesthetics are celebrated, too, but supported increasingly in improved knowledge from research. Another important perspective was that building and fire research laboratories should be closely linked to leaders in practice, including design, construction, product development and manufacturing. To be successful and supported, a laboratory should be and should be perceived to be valuable to industry. It should anticipate and be responsive to industry's greatest needs for knowledge, deliver this knowledge in useful form to decision makers, and assist in resolution of technical policy issues such as standards, regulations, education, and research priorities.

Allen, in turn, as Chief Architect of BRS was mentor to U.S. architect Ezra Ehrenkrantz, who worked under Allen, prior to returning to the U.S. and leading in introduction of systems building. After NBS's Institute for Applied Technology was created in 1964, its director Donald Schon and deputy director John Eberhard, himself an innovative architect, sought Allen as consultant for NBS's Division of Building Research. Allen had left the Building Research Station in 1961 to become Principal of the Architectural Association School and to form Bickerdike, Allen and Partners, which became a leading architectural practice in London. The relationship with NBS/NIST lasted almost thirty years.

Another, related legacy from the 1960s had profound influence on management's vision for building research at NBS in the 70s. Under the leadership of John Eberhard, as deputy director and director of the Institute for Applied Technology, and James Wright, director of the Building Research Division, building and fire research activities in the late 60s were energized and focused on providing criteria, and measurement, test and evaluation methods for the performance approach in building to building standards and codes [4].

All disciplines of the Building Research Division were involved in a major program, cosponsored by NBS and the Department of Housing and Urban Development (HUD) to explore the hypothesis that, if adequate performance standards for low-income housing could be developed, and if they were

The performance approach demands a statement of performance in terms of function. Since buildings serve people, function is defined by the attributes necessary to serve human requirements. The means of delivering an attribute is left open. It is in this way that the builder or supplier of a building component is invited to innovate. Indeed, the encouragement of innovation is sometimes cited as the reason for the performance approach. In any event, the philosophy of performance begins and ends with - and puts its principal emphasis on - the satisfaction of human needs.

broadly used, an important and fundamental way would be opened to accommodate the introduction of cost-reducing innovations into the design of housing for low income families. The success of this work [5] encouraged the HUD to proceed with Operation Breakthrough to encourage manufactured housing systems to improve housing quality and reduce costs.

CBT staff were greatly involved in Operation Breakthrough in support of HUD in developing performance criteria for the acceptance of innovative housing systems [6], assessing the compliance of the systems through analysis and testing, and performing longer range research to improve the criteria. The rigorous and systematic approach developed for the expression and application of performance criteria set the stage for the national and international move to performance based design in the late 20th century. The performance criteria and the responses of housing systems manufacturers advanced practices in residential smoke detectors, design to avoid progressive structural collapse, thermal insulation, acoustics, plumbing systems and durability. CBT and CFR researchers developed a strong orientation towards improved performance in meeting users' needs for safety, functionality, and durability. While HUD's support for Operation Breakthrough was not sustained sufficiently to greatly increase the U.S. market for industrialized building systems, it did achieve significant and continuing improvements in housing technology.

Simultaneously, the Building Research Division worked with the Public Building Service (PBS) of the General Services Administration to apply the performance concept in the procurement of better performing and more economical government office buildings. These were developed for and applied in the procurement of Social Security Administration payment centers for San Francisco, Philadelphia, and Chicago [7].

The focus of CBT on the performance concept continued after these projects for HUD and PBS were completed. The vision of Karl Willenbrock, James Wright, and Richard Wright for CBT was for it to be the leading laboratory supplying the performance prediction, measurement, test and evaluation methods needed by designers, builders, regulators, manufacturers, owners and occupants to achieve the performance (usefulness, safety and economy) for the buildings or building products and services with which they were concerned.

3.2. 1975

The energy crisis of 1973-1974 resulted in several legislative mandates for CBT:

- PL 93-409, Solar Heating and Cooling Demonstration Act of 1974, which became law on September 3, 1974, directed NBS to assist in determining performance criteria for solar heating and cooling systems, establishing test procedures and evaluating performance of systems demonstrated.
- PL 94-163, Energy Policy and Conservation Act directed NBS to develop test procedures for estimating annual operating costs and measures of energy consumption of energy consuming building equipment.
- PL 94-385, Energy Conservation and Production Act directed NBS to develop efficiency improvement targets for household heating and air-conditioning equipment, and to assist in the development of energy conservation performance standards for new commercial and residential buildings.

Another act influencing the CBT program was P.L. 93-382, The Housing and Community Development Act of 1974, which charged HUD to develop the Federal Mobile Home Construction and Safety Standards. HUD called upon CBT for substantial technical support. The Act also authorized the creation of the non-governmental National Institute of Building Sciences (NIBS) to improve the building regulatory environment, facilitate the introduction of new and existing products and technology into the building process, and disseminate nationally recognized technical and regulatory information. NIBS and NBS/NIST have generally found their roles complementary with NIBS suited to convening all elements of the building community to seek consensus on technical policy issues, and NBS/NIST having the research and laboratory capability to address needs for performance prediction, measurement, test and evaluation methods.

An immediate response was to reorganize CBT to respond effectively to these mandates that drew broadly upon the technical competences in the divisions. In September 1974 the "office" (program management) structure was revised to:

- Create the Office of Energy Conservation led by Jack Snell. Snell, an aeronautical and civil engineer, had joined NBS from a faculty position at Princeton University in 1971, and served successively as chief of the Building Service Systems Section and deputy chief of the Building Environment Division. Snell's personal energy, enthusiasm, broad technical competence and rapport with both policy and technical people qualified him well for this assignment (and many more to come in this history of building and fire research).
- Continue the Office of Building Standards and Codes Services under the leadership of James Gross. Gene Rowland had been called to the parent Institute for Applied Technology to lead its Standards Application and Analysis Division. Thomas Faison became acting chief of the Office of Housing Technology. Faison, who joined NBS as an undergraduate student trainee in 1957, was outstandingly efficient and congenial in dealing with sponsors and researchers to meet commitments on time, on target and within budget.
- Assign Samuel Kramer as acting deputy director with Harry Thompson becoming acting chief of the Office of Federal Building Technology.

The Solar Heating and Cooling Demonstration Act gave CBT 120 days to develop interim performance criteria for heating systems and the dwellings themselves. The criteria, needed as the basis for selecting the systems to be demonstrated, were drafted by November 1, 1974, reviewed in an open meeting at NBS on November 20, 1974, and provided to HUD for use in the demonstration program by the scheduled date of January 1, 1975. Work was planned and initiated to produce Intermediate Minimum Property Standards for Solar Heating and Domestic Hot Water Systems, as a supplement to HUD's Minimum Property Standards, to allow federally insured mortgages for dwellings with solar systems.

In response to the strong national concern for energy conservation, NBS and the Department of Commerce worked to obtain a legislative mandate and directly appropriated funding for energy conservation research. Betsy Ancker-Johnson, Assistant Secretary of Commerce for Science and Technology, Richard Roberts, director of NBS, and Karl Willenbrock, director of IAT, led the efforts in planning and testifying and were supported by Jack Snell and Reece Achenbach of CBT. However, the momentum in the Administration and Congress was to develop the Nation's programs in the Federal Energy Administration and the Energy Research and Development Administration. Increased directly appropriated funding for NBS was rejected in the White House Office of Management and Budget citing the rule that the lead agency would request the funding for NBS's supporting work.

Snell, Achenbach and colleagues worked extensively in support of planning of the Federal Energy Administration and the Energy Research and Development Administration to assist these new agencies address their responsibilities for energy conservation in buildings and industry. The first major output was achieved for the program for energy conservation in industry: the Energy Conservation Program Guide for Industry and Commerce [8].

The CBT Advisory Committee initially was chartered by the Secretary of Commerce for a two-year period (January 1973 to January 1975) to help identify current and emerging issues in building design, construction and materials for study by the Center. Its members represented materials manufacture, design, construction, finance and consumer interests, and the Committee was chaired by Karl Willenbrock.

Jack Snell, founder of the Office of Energy Conservation, possessed energy, enthusiasm, broad technical competence, and rapport with technical and policy leaders that led to success in this assignment and to future leadership of CFR and BFRL.

This guidance was clear endorsement for comprehensive, performance-oriented planning for the Center's program.

The Building Economics section, the Building Environment Division and NBS Public Affairs collaborated to investigate the energy savings potentials and life cycle costs of improvements in housing, and express the results in a form usable to homeowners (9). NBS director Roberts cited *Making the Most of Your Energy Dollars in Home Heating and Cooling* as the Bureau's most significant publication of 1975. However, the publication created some friction with CBT's sponsors in HUD who had commissioned a document of similar purpose but lesser scope. Neither agency had informed the other of its intent until the two documents were published.

Noel Raufaste took on responsibilities for preparing outreach publications for the Center - publications that would inform the building community and others interested in the Center's work what it was doing and producing. A general overview [10], project summaries [11] and publications listing [12] were produced to begin series that would continue through the 90s.

CBT received strong recognition in Department of Commerce Medal Awards. Paul Reece Achenbach received the Gold metal for the study that provided the basis for national standards for energy conservation in buildings. Jack Snell received the Silver Metal for his leadership of NBS's energy conservation program. James Clifton and Robert Mathey received a Silver Metal for their study of coatings to prevent corrosion of reinforcing bars in concretes exposed to deicing salts that led to creation of the epoxy coated reinforcing bar industry.

Richard Roberts resigned as director of NBS at the end of FY 1975. Ernest Ambler, veteran NBS physicist who had been Robert's deputy, became acting director and remained "acting" until confirmed under President Carter in 1977. Ambler was dedicated to hard physical science, a firm and decisive director for internal affairs, and uncomfortable with personal external representation of the Bureau's interests.

The principal recommendations in its June 17, 1975 report were:

- That CBT work toward a systematic understanding of the working of the Nation's building regulatory system;
- That CBT explore the socio-economic impacts of research output;
- That CBT continue to endorse national consensus energy standards based on performance of the building as a whole;
- That CBT identify generally significant environmental factors related to buildings and their uses, and relate intensities of environmental factors to associated human responses;
- That CBT prepare a state-of-the-art report dealing with applications and requirements for further development and research for guidance on future construction community activities in support of the performance concept.

3.3 1976

P.L. 94-168, The Metric Conversion Act of 1975, became law on December 23, 1975. CBT focused substantial efforts on learning from experiences in the metrication of the British Commonwealth to provide technical bases for metrication in U.S. building practices, standards and codes. Hans Milton, who had led in Australia's metrication of building, came to work at CBT to show the U.S. how to benefit from the Commonwealth's experience. The extensive results contributed to ASTM standards and the work of the U.S. Metric Council. CBT also investigated methods to respond to the one-time opportunities for dimensional coordination (effective and efficient families of product sizes) that would arise from "hard" metric conversion (to sizes such as 100, 200 and 500 millimeters rather than 101.6, 203.2 and 508.0 millimeters which correspond to 4, 8, and 20 inches, respectively). Formal catalog optimization approaches looked very interesting, but were not pursued when it became evident that there was not broad enthusiasm in U.S. industry or society for metric conversion. The recommendations of the Advisory Committee, re-chartered for 1975 to 1977, were decisive in not pursuing work in dimensional coordination.

The Advisory Committee's efforts from 1975 to 1977 focused principally on the programs of the Center for Fire Research.

The Center and Institute were much concerned to develop an effective architectural research effort. For guidance, the Center co-sponsored the Architectural Research Roundtable in September 1975, with the American Institute of Architects, the Association of Collegiate Schools of Architecture and the AIA Research Corporation [13]. The Roundtable addressed:

- The opportunities, problems and benefits of architectural research;
- The strategies and methods of architectural research;
- The resources needed to perform architectural research;
- The delivery and application of architectural research.

Another benefit was the associations developed between the Institute's and Center's management and 40 leaders in architectural practice and education, and in industry.

The Institute launched a second effort in the summer of 1976 to identify the knowledge-based problems of those responsible for building design, and to suggest areas in which the Institute should focus its present and future efforts in order to improve building [14]. Francis Ventre, an architectural engineer whose thesis studied the effects of the building regulatory system on innovations, and who was on detail from the Center to the Institute, staffed the study for the Institute. The study was conducted by Ehrenkrantz and Associates with involvement by William Allen, Professor John Habraken of MIT, and Richard Wright, Porter Driscoll, Robert Wehrli and Robert Hastings of CBT. The study's main recommendation was for "the conscious design of a system of inquiry that will better enable CBT to serve the needs of building designers and other members of the building team."

At the request of the Institute for Applied Technology's director, Karl Willenbrock, following several years of initiative by the Institute's deputy director, James Wright, CBT management undertook a substantial effort in organizational development. CBT managers studied Grid Organizational Development for each to gain understanding of team dynamics and the influence of one's own behavior on the quality of a team's work. It seemed that each person had been trained in school, including graduate school, to work alone and be rewarded only for one's own ideas. Such orientation is detrimental to finding and exploiting the best ideas of the team.

The organizational development was facilitated by Paul Buchanan, an ingratiating management psychologist who had taught James Wright at the Federal Executive Institute. Offsite meetings were held on September 3-5, 1975, October 14-16, 1975, and December 11-13, 1975. The first two involved the Management Council (headquarters executives and division and office chiefs) to define our problems and a process to resolve them. The latter involved the Management Group (Management Council plus section chiefs from divisions and program managers from offices).

At the first offsite, the Management Council agreed to merge the offices of Housing Technology and Federal Building Technology into a single Office of Housing and Building Technology with Harry Thompson as acting director. Samuel Kramer continued as acting deputy director of the center.

The Management Council identified 42 "itches" to be dealt with in the organizational development.

The general effect of the organizational development was to generate conscious attention to teamwork in the Management Council and in the conduct of multi-unit projects. CBT also developed a Policy, Procedures and Operating Guide to cover predictable needs for collaboration.

As part of this process, CBT made more concise its mission statement: "To advance the Nation's building technology and facilitate its implementation for the public benefit."

In August 1976, IAT decided to move energy program management to the Institute. Jack Snell transferred to the Institute to lead the Institute-wide program, the CBT Office of Energy Conservation was abolished, and the program managers concerned with energy conservation and solar energy in buildings transferred to the Office of Housing and Building Technology.

In February 1976, Reece Achenbach announced his plans to retire in about three years and his desire that the Center proceed to replace him as Chief of the Building Environment Division. A search committee was appointed to identify the best available successor recognizing that his leadership of the division and profession would be difficult to match.

In September 1976, Karl Willenbrock announced that he would become Dean of Engineering at Southern Methodist University on October 1. His enthusiasm for technical excellence and for beneficial influence on building practices, while generally difficult to satisfy, had been inspiring to CBT.

James Hill received the Department of Commerce Silver Medal for his research to provide consistent test methods for solar collectors. Stephen Petersen received the Silver Medal for his guidance to homeowners on cost effective investments in energy conserving measures in Making the Most of Your Energy Dollars.

NBS felt staffing and budget pressures as part of the Ford administration's efforts to deal with inflation. CBT successfully defended its directly appropriated funding for fiscal year 1977 in August 1975, received a staff ceiling cut of 11 positions in October 1975, and was assigned a $500,000 cut in its directly appropriated funding for fiscal year 1978 in September 1976.

3.4 1977

Earthquake hazard reduction had long been seen as an important area for CBT research. Edward Pfrang organized the U.S./Japan Panel on Wind and Seismic Effects in 1968. In 1971, he led a significant investigation of the San Fernando Earthquake, which showed the value of prompt reporting of structural performance and identification of important opportunities for research and improvement of practices.

Richard Wright in 1971 began collaborations with the National Science Foundation, the Department of Housing and Urban Development and the White House to develop a multiagency program on building practices for disaster mitigation. Charles Thiel of NSF had the initiative and financial resources to be "first among equals" in the collaborations.

Charles Culver in 1972 joined CBT from a faculty position at Carnegie Mellon University to become disaster research coordinator and the manager for the joint NSF/NBS project to work with leaders in research and practice to synthesize nationally applicable seismic design and construction provisions from available knowledge. Culver's energy, efficiency and experience in laboratory and analytical research helped advance this work. In 1977, Congress developed the Earthquake Hazards Reduction Act, and in August 1977 Culver represented NBS on the team developing the Act's implementation plan in the White House Office of Science and Technology Policy.

Led by Jack Snell, NBS had been working with the Energy Research and Development Agency (ERDA) in the planning and conduct of energy conservation research. Snell, Achenbach, and Frank Powell prepared a National

The main concerns seemed to be:

- Lack of trust, respect, commitment and responsiveness
- Poor communications, from overload to lack of feedback
- Unclear priorities, policies, and strategies

Program Plan for Energy Conservation that was used by ERDA and its successor, the Department of Energy, as a resource in program planning. Development of major programs in the National Laboratories required NBS to clarify its role as it became just one of the laboratories in an area in which it had been predominant. The role selected by NBS and recognized by headquarters of ERDA (though never by the National Laboratories) was performance criteria, and evaluation, test and measurement methods. CBT had proposed a systematic approach, using formal optimization techniques, to developing the Congressionally mandated energy budget performance standards for buildings. It was dismissed as too complex and the assignment given to HUD using the AIA Research Corporation in April 1977. Their eventual results were not implemented since opponents could show the lack of sound basis for the recommendations. The basis for the Nation's energy conservation performance standards remained the component performance approach developed by CBT in 1973 and standardized by the American Society of Heating, Refrigerating and Air Conditioning Engineers.

The initial direct influence of the Carter administration on NBS was the requirement to do Zero Base Budgeting - prioritize all activities and eliminate or justify those lowest in priority. The process consumed much time and energy and CBT defended successfully its activities.

The organizational development program of the Institute for Applied Technology reached the stage of teamwork among its units to solve an important mutual problem. Given that limitations on numbers of personnel were inhibiting the hiring of engineers and scientists to conduct available work, the team decided to reduce clerical staffing where it was deemed excessive. CBT was identified to exceed Institute norms for clerical staffing and required to make reductions. This was accomplished by organizing a word processing center to make more efficient the production of reports and other voluminous documents. The process was painful, clerical staff were valued members of their units, but the resulting word processing center was seen as a model for NBS.

Preston McNall was recruited from his position as Director of Engineering for Johnson Controls to replace Reece Achenbach as Chief of the Building Environment Division. McNall's leadership in ASHRAE and expertise in mechanical systems and human comfort qualified him well to match Achenbach's stature. Porter Driscoll was reassigned to manage a new Design and Construction Technology Applications Program to exploit his passion for making knowledge available in useful form to designers. Robert Kapsch, a scholarly and productive civil engineer, became acting chief of the Technical Evaluation and Application Division. At the request of IAT, which had not processed the re-assignments, Harry Thompson resumed the position of deputy director of CBT and Samuel Kramer the position of chief of the Office of Housing and Building Technology.

In September 1977, NBS director Ernest Ambler assigned John Lyons, director of the Center for Fire Research to head the team planning the National Engineering Laboratory that would replace the Institute for Applied Technology. Lyons decided that NEL would not use matrix management so CBT was reorganized to four divisions: Structures and Materials led by Edward Pfrang, Building Thermal and Service Systems led by Preston McNall, Environmental Design Research with Thomas Faison acting director, and Building Economics and Regulatory Technology led by James Gross. Program management responsibilities were divided appropriately among division chiefs; the tension between offices and divisions was ended.

Department of Commerce Silver Medals were received by: Charles Culver for management of the development of tentative provisions for the development of seismic regulations for new buildings, Rosalie Ruegg for development of life cycle cost analysis methods for solar energy systems, and James Pielert and James Gross for analyzing the performance of mobile homes and recommending improvements in mobile home standards.

3.5 1978

Public Law 95-124, The Earthquake Hazards Reduction Act of 1977 was approved on October 7, 1977, to authorize the National Earthquake Hazards Reduction Program (NEHRP). NBS was listed as one of the participating agencies. In April 1978, the White House requested NBS to budget for its role in the program. In the Implementation Plan issued by the President on June 22, 1978, NBS was assigned to assist in continuing the development, testing and improvement of model seismic design and construction provisions suitable for incorporation in local codes, standards, and practices, and research on performance criteria and supporting measurement technology for earthquake resistant construction. However, NBS did not give priority to seeking funding for NEHRP in its fiscal year 1980 budget request. CBT, with NBS approval, reprogrammed funds from building regulatory technology to provide research and technical support for the National Earthquake Hazard Reduction Program.

The Interagency Committee on Seismic Safety in Construction (ICSSC) was established in 1978 to assist the Federal departments and agencies involved in construction to develop and incorporate earthquake hazard reduction measures in their ongoing programs. Richard Wright served as Department of Commerce representative to ICSSC and served on its Steering Committee. CBT provided the technical secretariat, which led by E.V. Leyendecker of the Structures and Materials Division, began work on the assignment to develop seismic design and construction standards for consideration and subsequent application in Federal construction by 1980.

A cooperative research program was developed with the Public Buildings Service of the General Services Administration to address its principal needs for improved building practices. David Dibner, Assistant Commissioner for Construction Management, was the champion for PBS and Noel Raufaste was the coordinator of research for CBT.

A number of management changes resulted from the formation of the National Engineering Laboratory. The name of the Technical Evaluation and Application Division (an epitome of bureaucratic meaninglessness fortunately matched by several divisions at the U.S. Army's Construction Engineering Research Laboratory) was changed to Environmental Design Research Division and Francis Ventre was selected as its chief. However, there is reason in bureaucracy. The clear name made it a target for those who felt NBS should be limited to physical science and hard engineering research. Robert Kapsch went on to a Congressional Fellowship. Samuel Kramer became deputy director for programs of the National Engineering Laboratory.

NBS director, Earnest Ambler, initiated the NBS Competence Building Program to provide multi-year research support to small teams of investigators to develop world leadership in technical areas that would be vital to the future of NBS. Individual investigators initiated proposals, the center and laboratory expressed their priorities, and the Director made his selections. CBT was interested in many competence areas, including behavioral science. Its priority proposal in geotechnical engineering test methods was not successful.

CBT conducted a thorough long range planning process including:

- Assessing societal problems and trends requiring building research;
- Assessing technical problems and trends to identify the technologies needed and the role, considering other organizations, appropriate for CBT;
- Defining goals and objectives for CBT's work over five years.

The goals selected were:

1. Energy Conservation in Buildings;
2. Safety in Construction and Use of Buildings;
3. More Useful and Economical Buildings.

The Plan expressed the mission of CBT as:
to increase the usefulness, safety and economy of buildings through the advancement of building technology and its application to the improvement of building practices.

Needs to obtain the majority of funding from external sponsors and to conduct the work jointly with other organizations complicated the planning and implementation, but the Plan was valuable in focusing CBT's work.

Zero-based budgeting defenses continued to consume much management time. NBS offered to the White House cuts in CBT work in acoustics, materials, and standards and codes.

George Kelly received the Department of Commerce Silver Medal for his research on test methods for energy labeling of heat pumps and air-conditioners.

3.6 1979

The recommendations of the Advisory Committee on Building Technology for its 1977 to 1979 term were supportive of CBT's engineering research, but not of behavioral research or strengthened funding. In light of the desire of the Administration to reduce numbers of advisory committees and the availability of the National Academies, the National Institute of Building Sciences and other sources for program guidance from the private sector, the Advisory Committee was not re-chartered.

Thomas Dillon, deputy director of NBS, discussed informally with Richard Wright the prospects for NBS's support of CBT's long range plan. He doubted that CBT's plan would be supported by NBS. In view of several years of reductions and reprogramming in the CBT program, NBS management decided to assess the program to aid in consideration of further budget actions such as termination, continuation or augmentation.

In April 1979, 50 letters were mailed to building community leaders by NBS Director Ambler, and three letters were sent by Assistant Secretary of Commerce for Science and Technology Jordan Baruch to his counterparts in the Departments of Housing and Urban Development and Energy and in the Occupational Safety and Health Administration. Forty-six responses were received, which in summary stated:

1. The mission and role of CBT are appropriate to NBS and for the building community.
2. The CBT program is well oriented, but materials, regulatory technology, metrication, and building performance criteria issues need attention.
3. The Program's delivery system is well-oriented toward meeting standards, codes and industry needs; but better mechanisms are needed to reach designers and builders.
4. The NBS/DoC should provide a larger proportion of directly-appropriated funding to provide a healthier environment for the program.

National Engineering Laboratory Director John Lyons addressed the issue of whether the Laboratory should develop a world-class competence in behavioral research to support its programs in building technology, fire research, consumer product technology and manufacturing engineering. He did not want NEL to be pursuing programs with which NBS was uncomfortable. A panel of eminent scientists reviewed the relevant NEL programs and program plans and recommended that NEL develop and maintain competence in behavioral research. These recommendations were reviewed with the NBS Executive Board and Assistant Secretary Jordan Baruch. Their decision was that NEL and NBS would not seek to measure fitness to human use without a new and specific mandate in legislation. Behavioral research should be only an incidental part of NBS programs that should not be global, soft or unbounded.

The National Earthquake Hazards Reduction Program, with full involvement of CBT management and in consultation with private sector leaders, decided to assign the role of developing and evaluating recommended seismic design and construction provisions for buildings to the Building Seismic Safety Council operating under the auspices of the National Institute of Building Sciences. This would assure that federal influence on the provisions would not be, or perceived to be, dominant. CBT's role was to participate appropriately in the Council's technical committees and link the Council's work to that of the federal agencies as secretariat of the Interagency Committee on Seismic Safety in Construction. As the research community met to consider the earthquake research agenda, the primarily academic group preferred that engineering research be funded through the National Science Foundation rather than NBS. There was the same preference of NSF over the U.S. Geological Survey for earth science research, but USGS already had its appropriation for NEHRP. The White House Office of Science and Technology Policy requested NBS to budget for increased earthquake engineering research for fiscal year 1981, but again NBS did not give it priority.

The Federal Trade Commission (FTC) became concerned that thick insulations were not correctly labeled for insulating value and that customers might be inequitably treated. Standard test methods traceable to NBS were available only for thicknesses up to 25 mm; much greater thicknesses were in use for energy conservation. FTC, the insulation industry and NBS agreed that NBS would accelerate development of a device for direct measurement of insulating value of thick insulations and make calibration specimens available to industry as an improved basis for insulation labeling. The resulting technical work is described in Chapter 10.

The Senior Executive Service was implemented in 1979 with the Center's director, deputy director and division chiefs becoming members, and developing performance agreements as basis of pay for performance.

Robert Dikkers received the Department of Commerce Silver Medal for his work in developing performance criteria for solar energy systems for buildings.

3.7 1980

In November 1979, representatives of the National Construction Industry Council, which was composed of 28 national trade associations and professional societies involved in all sectors of construction, met with Undersecretary of Commerce Luther Hodges to seek support in:

1. Leveling out extreme cycles in construction that increase costs,
2. Establishing and maintaining a comprehensive program of information for the construction community,
3. Technology for enhancing construction productivity,
4. Revision of government policies, such as regulatory delays, that inhibit productivity,
5. Adoption of a national energy policy sensitive to construction's needs, and
6. Encouraging construction and engineering exports.

Philip Klutznick, formerly a Chicago developer, had become Secretary of Commerce in 1979. He sought to be a builder in Commerce, too, and during 1980 in preparation for the fiscal year 1982 budget, encouraged NBS to propose challenging programs. CBT began by proposing a construction productivity initiative at a level of $3.5 million. The response of Secretary Klutznick was to request definition of a Construction Productivity Program at a level of $100 million annually.

Planning of new work in construction productivity involved most of CBT management. They were assisted by John Eberhard who had joined CBT as a part time consultant after leaving the presidency of the AIA Research Corporation in late 1978 following termination of its project for HUD on Building Energy Performance Standards. CBT took a fresh look at research topics for impact on construction productivity:

Partial support for construction research centers at universities in the fifty states was proposed to assist in research and education, and demonstration programs were emphasized for technology transfer.

The basis in and growth beyond CBT's base program can be seen by comparing topics from its October 1979 long range plan:

Energy Use in Buildings
- Energy conservation in buildings
- Building thermal envelope systems and insulating materials
- Building solar systems technology

Safety in Construction and Use of Buildings
- Structures and foundations performance
- Earthquake hazards reduction
- Building safety

Building Productivity and Performance
- Building rehabilitation technology
- Building and community acoustics
- Building service systems performance
- Lighting technology
- Building economics

The drive for a Construction Productivity Program ended in the election of November, 1980, but the work with industry leaders on productivity needs and the research ideas developed had substantial effects on the evolution of CBT's program. Moreover, it had been transiently refreshing to plan for growth rather than defend against cuts. However, NEL assigned CBT cuts of 20 positions for fiscal year 1981 as part of a transition of NEL and CBT to focus on engineering measurements.

Harry Thompson retired as deputy director in February. Charles Culver rejoined CBT from assignments to the White House and NEL to become deputy director. The Building Thermal and Service Systems division was divided to form the Building Thermal Performance Division, headed by Preston McNall, and the Building Equipment Division, headed by James Hill. Hill, a calm, cheerful, efficient and insightful mechanical engineer had led CBT's solar systems performance research since the early 1970s.

Construction Management Technologies
- Construction project information systems
- Evaluation system for computer-aided design and construction technologies
- Measurement systems for management for productivity
- Equivalency system for regulatory approvals

Construction Site Technologies
- Construction loading criteria
- Shoring and scaffolding systems
- Materials handling systems
- Excavation and soil stabilization
- Concreting operations
- Quality assurance

Performance of Facilities
- Roofing evaluation system
- Wall evaluation system
- Controls evaluation system
- Lighting evaluation system
- Sanitation evaluation system
- Accessibility evaluation system
- Facilities productivity evaluation

The Merit Pay system including performance plans and pay for performance was implemented for NBS supervisors. Much work was required to develop appropriate performance plans, and the system functioned well.

William Cullen received the Gold Medal Award of the Department of Commerce for his research on performance standards for built up roofing systems. Tamami Kusuda received the Gold Medal Award for developing and verifying computer models for the dynamic thermal performance of buildings. Bruce Ellingwood received the Silver Medal Award of the Department of Commerce for leading research to formulate consistent, reliability-based load factors for structural systems using the principal structural materials (masonry, concrete, wood and steel). Steven Petersen, of the Building Economics Group, was selected for the Presidential Executive Exchange. He worked with the Carrier Corporation to develop techniques for evaluating the life cycle costs and benefits of innovative, energy-conserving appliances.

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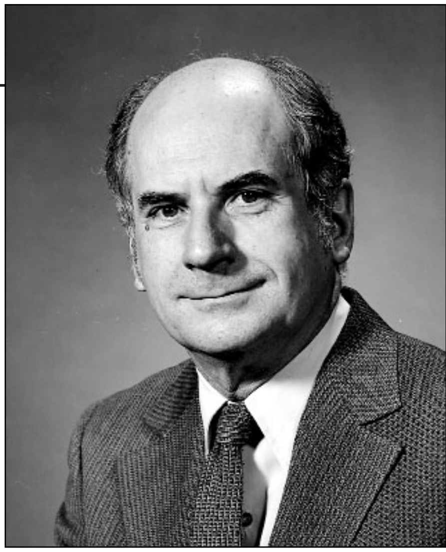
4. CENTER FOR FIRE RESEARCH IN THE 80s

4.1 OVERVIEW

The decade saw the Center for Fire Research survive repeated attempts at its elimination by the Administration. Subsequent budget reductions resulted in staff reductions and a refocusing of the technical program over the period.

The 1974 legislation establishing the Center for Fire Research and the National Fire Prevention and Control Administration (FPCA) in the Department of Commerce called for directly appropriated funding. In 1978 FPCA became the United States Fire Administration (USFA), which was transferred to the newly formed Federal Emergency Management Administration. At the start of FY 1981 almost 72 per cent of the $5.7 million appropriation for the Center for Fire Research came through USFA and the rest came from NBS. Reimbursable funding totaled $3.1 million. In 1982 CFR faced a major financial problem caused by FEMA's proposal to eliminate financial support for CFR for the year 1982 and beyond. After much discussion among the agencies, the White House and with Congress the funding was restored for 1982 and transferred to the NBS budget for 1983. In 1983 the Administration again decided to eliminate CFR. After widespread private sector support accompanied by strong Congressional support, funding was approved for fiscal year 1984. However, Administration efforts to eliminate or severely reduce CFR continued for six more years. Accompanying these budget reduction proposals were proposals to combine CFR with the Center for Building Technology. 1990 was the last year for separate centers for fire research and building technology. Congress authorized their merger in June 1990, and the successor Building and Fire Research Laboratory began to operate at the start of fiscal year 1991.

In 1981 CFR had a staff of 100 directed by Fredrick Clarke. In the summer of 1981 Fred Clarke and Irwin Benjamin, chief of the Fire Safety Engineering Division resigned to form a consulting company, Benjamin Clarke Associates. Clark and Benjamin were replaced by Jack Snell and Andrew Fowell respectively. CFR was then reorganized, with Clayton Huggett continuing as deputy director. Robert Levine headed the Office of Fire Research Resources, Richard



Clayton Huggett, Deputy Director, CFR

Gann became chief of the Fire Measurement and Research Division and Andrew Fowell became chief of the Fire Safety Technology Division. By 1984 the staff had increased to 108 people, with an additional 22 research associates from industry. However, the repeated budget reductions reduced the federal staff to 90 in 1985. Staff remained at about this level for the rest of the 1980s.

Early in the decade the technical program was re directed to address smoke hazards, fire modeling and fire model validation, fire growth and extinction, fire toxicology, and exploratory fire research. The Center continued its fire research grants program supporting research at a number of the country's top universities and research organizations.

Technical products produced by the Center included: HAZARD I, a computer program based on zone fire modeling; a smoke control design manual; a fire safety evaluation system to support the National Fire Protection Association's Life Safety Code; a guide for the safe installation of solid fuel heaters and chimneys; safety guidelines for Navy fire fighter trainers; guidelines for combustion of oil spills at sea and the suppression of oil and gas well fires; and a computerized data base of research documents relating to fire. The decade also saw the commercialization of the Cone Calorimeter, a device developed in the Center for measuring the heat release of materials. Heat release is a key input to fire growth models.

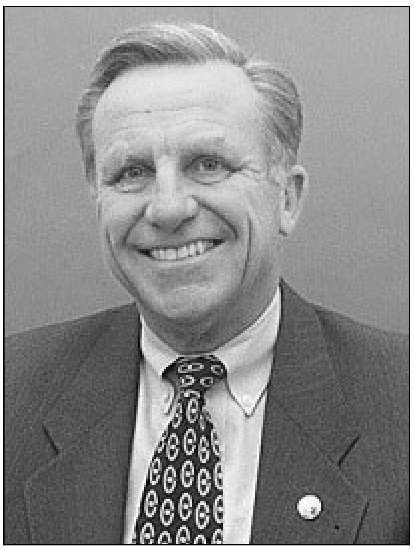
New legislation included the Cigarette Safety Act of 1984, and the Fire Safe Cigarette Act of 1990. The Center carried out a number of fire investigations including the MGM Grand Hotel in Las Vegas, and the DuPont Plaza Hotel in Puerto Rico.

4.2 1981

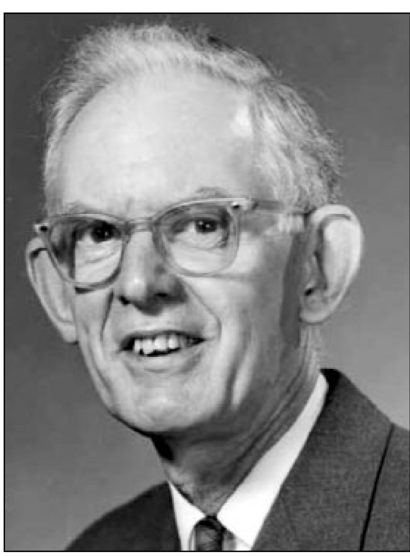
1981 witnessed a change in management and reorganization of the Center for Fire Research. At the beginning of the year Fredrick Clarke was director and Clayton Huggett, deputy director. Huggett was revered as a skillful scientist and manager. The management team was composed of Richard Gann, head, Exploratory Fire Research, Robert Levin, chief, Fire Research Resources Division, Irwin Benjamin, chief Fire Safety Engineering Division, and James Winger, chief Fire Performance Evaluation Division. At the end of 1981 Clarke and Benjamin resigned to form their own consulting company, Benjamin Clarke Associates. Jack Snell, who had been director of the Office of Energy Conservation in the National Engineering Laboratory became the new director. Richard Gann became chief of the new Fire Research Division. Gann's insightful and incisive research and management of programs and people contributed greatly to CFR and BFRL. Andrew Fowell became Chief of the Fire Safety Technology Division. He joined CFR after serving as chief of the Product Performance Engineering Division in the Center for Consumer Product Technology. He worked very effectively externally to the Center to obtain support for research and implementation of its results. Robert Levine became chief of the Office of Fire Research Resources, which directed the Fire Grants program. The total staff numbered 100 and funding totaled $8.8 million. Appropriated funding came from NBS ($1.6 million), and the U.S. Fire Administration ($4.1 million). Reimbursable funds amounted to $3.1 million.

The scientific and technical work of the Center continued to move toward the prediction of fire growth through fire modeling, the development of accurate test methods for fire data collection and the development of practical tools for use by fire safety engineers. The Department of Commerce Silver Medal was awarded to Howard Baum and Ronald Rehm for outstanding progress in developing the large eddy simulation model for fire-driven flows. They and their colleagues also published a number of papers on the development of the method. William Parker published Calculations of the

Richard Gann, Chief, Fire Research Division.



(top) Andrew Fowell, Chief of the Fire Safety Technology Division.
(bottom) Alexander Robertson recipient of ASTM's Award of Merit and Rank of Fellow



Heat Release Rate by Oxygen Consumption for Various Applications, NBSIR 81-2427, which became the basis for the development and worldwide use of the cone calorimeter for measurement of materials' potential contributions to fires. The Fire Safety Evaluation System, a cost-effective approach to achieving fire safety in health care facilities and other occupancies, was adopted by the National Fire Protection Association into the Life Safety Code. The system was developed by Harold Nelson. CFR and the American Iron and Steel Institute constructed a large scale steel building frame, representative of the mid height of a twenty story office building, and measured its response to a severe fire. The results were made available for the testing of computer simulations for structural fire endurance that would become the basis for more rational design of fire resistant steel structures.

In cooperation with the U.S. Fire Administration and the National Fire Protection Association, CFR investigated the fire at the MGM Grand Hotel in Las Vegas, NV. Deaths remote from the actual fire illustrated the hazard of combustion products and the documentation of the fire provided basis for evaluating models for movement of smoke and combustion products in large buildings.

Alexander Robertson received the Award of Merit from ASTM and the rank of Fellow in ASTM in recognition of 25 years of leadership in the development and advancement of national and international standardization of fire test methods for materials, building products and construction assemblies.

4.3 1982

The new long-range plan for CFR expressed its goal more succinctly: *To provide the scientific and technical basis for reducing fire losses and the costs of fire protection by 50 percent.*

The technical program strategy was:

1. To promote the continued advance of fire science.
2. To promote the development and widespread use of scientifically based fire protection engineering practices.
3. To provide technical support for timely resolution of major fire-safety issues/problems.

CFR's new management faced a major financial problem. The Federal Emergency Management Agency (FEMA) proposed to eliminate financial support for CFR for fiscal year 1982 and beyond.

This directly appropriated funding was called for by the 1974 legislation establishing CFR and the National Fire Prevention and Control Administration in the Department of Commerce. When FEMA was founded in 1978, the latter became the U.S. Fire Administration in FEMA. The funding was crucial to the CFR program as 72 percent of its directly appropriated funding, and 47 percent of its total funding in 1981. After much discussion among the agencies, the White House and with Congress, the funding was restored for 1982 and transferred to the NBS budget for 1983 and beyond. However, relief was short lived as the Administration decided in the summer of 1982 to eliminate funding for CFR in fiscal year 1984 and beyond.

Technical work continued productively. John Klote completed work on the Building Smoke Control Systems Design Manual as a joint project between CFR and ASHRAE. Collaborations with the Office of Applied Economics in the Center for Applied Mathematics led to the incorporation of a cost optimization model in the Fire Safety Evaluation System. The Cone Calorimeter was constructed. Barbara Levin and colleagues completed and published the NBS Toxicity Test Method report based on work from 1976-1982.

Harold Nelson received the Department of Commerce Silver Medal for the development of the Fire Safety Evaluation System and James Quintiere received the Silver Medal for leadership in the mathematical modeling of fire growth and spread in buildings. Daniel Gross received the Ingberg Award of ASTM for his contributions to fire standards.

4.4 1983

The Administration recommended that CFR be eliminated. In its hearings for reauthorization of NBS for fiscal year 1984, Congress heard from the communities affected by the CFR programs. Senate hearings were first on February 23, 1983. The Senate received testimony supporting the restoration of funding for CFR from the National Academies' Evaluation Panels for the National Bureau of Standards, the Statutory Visiting Committee of the National Bureau of Standards, the former chairman of the National Fire Prevention and Control Commission, the American Society of Civil Engineers, Factory Mutual Research, the Mineral Insulation Manufacturers Association, the National Fire Protection Association, the National Institute of Building Sciences, the Society of Fire Protection Engineers, the U.S. Chamber of Commerce, and the Wood Heating Alliance. As a precedent for all following hearings on the subject, no private sector organizations supported the Administration's proposal.

House hearings were held on March 22 and 23, 1983. Testimony supporting continuation of CFR was received from Allied Tube and Conduit Corporation, the American Institute of Architects, the American Iron and Steel Institute, the American Society of Civil Engineers, the American Society of Heating Refrigerating and Air-conditioning Engineers, the Asphalt Roofing Manufacturers Association, the Brick Institute of America, the Carpet and Rug Institute, the Council of American Building Officials, the General Electric Corporation, the Man-Made Fiber Producers Association, the Mineral Insulation Manufacturers Association, the National Fire Products Association, the National Fire Protection Association, the National Institute of Building Sciences, the Society of the Plastics Industry, Sheet Metal and Air-conditioning Contractors of North American, the Society of Fire Protection Engineers, the U.S. Chamber of Commerce, Underwriters Laboratories, the Westmoreland County Firemen's Association, United McGill and the Wood Heating Alliance.

The Senate Report [1] recommended:
The administration has proposed the elimination of CFR. Both the testimony received at the hearing and other communications to the Committee confirm the judgment of the Committee that such a step is ill-advised and unwarranted.

The fire research program is the only Federal research effort aimed at reducing annual fire losses, particularly from residential fires. The U.S. continues to be among the leading nations in incidence of building fires and fire-related deaths. Fires in residences account for 46 percent of the dollar losses and 77 percent of the fire-related deaths. Results of the research performed at CFR are used by designers, builders, standards committees and state and local codes officials to prevent fires develop efficient fire-control practices. Through its grants program, CFR provides the link between university research and the needs of fire technology. This role is consistent with the Administration's policy to support education and training in the context of Federally funded research.

The private sector, either in contract research laboratories or in individual corporations, has neither the incentive nor the resources to conduct a comprehensive broad-based fire research program such as exists at NBS. Private efforts, such as those conducted by the Factory Mutual Research Corporation, are mission-oriented and relatively narrow in scope. Factory Mutual, for example, addresses fire protection and loss reduction in industrial buildings. Factory Mutual has stated that its small effort in fundamental fire research would probably cease should CFR be terminated and, in any case, could not be expanded.

The Committee is not convinced that the private sector would assume the role of carrying out primary research in the fire sciences. Moreover, the Committee believes that a credible, neutral source of information such as that found in CFR is essential to protect the public interest as well, since the work performed at CFR affects public health and safety.

The House report [2] recommended:
The Committee strongly supports the continuation of the Center for Fire Research, proposed for elimination in the Administration's fiscal year 1984 budget request. This program provides the scientific and technical basis for the reduction of the Nation's fire losses and the cost of fire protection.

The National Bureau of Standards has been involved in fire research since its inception in 1901, as authorized by the Organic Act. The Center for Fire Research was established by the Federal Fire Prevention and Control Act of 1974 as a direct result of a 1973 Report of the National Commission on Fire Prevention and Control, which stated that there was no existing organization conducting basic fire research.

The program's strategy is to develop the technical basis for fire hazard assessment in order to provide the fire community with new and improved practices for reducing fire hazards. In addition, as an integral part of the program, $2 million is provided annually to about 30 universities and organizations for fundamental fire research. These grants currently represent the only funding source for research through which our Nation's new fire scientists are trained.

The Committee believes that the private sector has neither the incentive nor the resources to conduct a comprehensive broad-based fire research program such as that existing at NBS. Furthermore, the Committee believes that research on subjects protecting the health and welfare of the Nations' citizens is a Federal responsibility and that the Bureau is a source of credible, impartial information in an essential area. The Committee has, therefore, restored funding for the Center for Fire Research in the sum of $6.4 million for fiscal year 1984.

Funding was appropriated for fiscal year 1984 in response to the private sector and Congressional support. However, Administration efforts to eliminate or severely reduce CFR continued for six more years.

Good technical work continued in spite of the budget turmoil. Howard Baum and Ronald Rehm began transient 3-D computer simulations of flows generated by fires in compartments. Harold Nelson and colleagues issued the Fire Safety Evaluation System for Board and Care Facilities. Thomas Ohlemiller completed a major review article on smoldering combustion. Bernard McCaffrey received the Department of Commerce Bronze Medal for pioneering research on the processes underlying large fire plume behavior.

4.5 1984

The Administration again proposed to eliminate CFR, this time for fiscal year 1985 and beyond. Substantial efforts by the fire community and CFR management again resulted in restoration of the budget by Congress.

In August 1984, CFR and the National Fire Protection Association sponsored the first National Fire Research Strategy Conference to develop a coordinated private and public sector national strategy for fire research. CFR was advised to "assume the crucial role of spear-heading and coordinating basic engineering and applied fire research through: independent research within the Center; by provision of grants, fellowships and technical support to independent researchers and universities and similar institutions; and by serving as an objective forum for reviewing and coordinating the national fire research effort."

Recognizing that funding would be constrained for the duration of the Administration, management moved to tighten technical objectives, tasks and

major staff assignments to fit available resources and focus on a central technical objective:
The central technical objective of the Center is to develop means to predict fire safety and to suggest and evaluate ways to reduce risk and hazards of fire.

Research priorities included:
1. Quantitative tools to estimate the hazards of fire such as heat and smoke toxicity.
2. A consistent set of practical models of relevant fire phenomena and their complex interactions.
3. Data and measurement methods to support fire models.
4. "Benchmark" fire and smoke models to check or qualify simpler engineering models.
5. Practical fire protection engineering methodologies and user-friendly application tools.

The Fire Safety Technology Division took on the following four thrusts:

Fire Safety Performance led by Harold Nelson involved the development of practical engineering methods for fire safety design, performance evaluation and analysis of fire risk.

Smoke Hazards led by Richard Bukowski involved the development of research models and associated computer codes to predict smoke transport and smoke hazard development in buildings and the establishment of a data base of material properties, building and people characteristics suitable for use in fire growth and smoke transport models.

Room Fire Modeling led by Leonard Cooper with the aim of developing a room fire computer code for use in research and as a benchmark for fire protection engineering methods and user-friendly computer codes.

Fire Growth and Extinction Research, led by James Quintiere, with the aim of developing fundamental understanding of the elemental processes of fire growth and extinction and develop models and algorithms to characterize their contribution to fire growth and smoke movement.

Fire Measurement and Research Division also took on four thrusts, namely:

Fire Performance and Validation led by Sanford Davis. The goal was to generate the generic methodology for testing and assessing the accuracy and limitations of fire models and measurement methods. The plan was to conduct unique, highly instrumented experiments to establish fire behavior on a realistic scale for aiding the understanding of fire phenomena.

Fire Toxicology led by Barbara Levin who was asked to identify and measure potentially harmful combustion products and quantify their effects on living organisms.

Furnishings Flammability led by Vytenis Babrauskas involved the development of quantitative measures of the ignitability and fire contribution of furniture and furnishings for use in modeling fires and to provide guidance for less hazardous composition.

Exploratory Fire Research led by Walter Shaub included the development of fundamental scientific knowledge of the phenomenology, which underlies incomplete combustion and materials degradation.

The first order toxic hazard model was completed and published by Bukowski in the NFPA Fire Journal. The ISO working group on rate of heat release selected CFR-developed cone calorimeter for international standardization as the technique for heat release rate measurement. William Twilley received the Department of Commerce Bronze Medal for design, construction operation and maintenance of flammability apparatuses including the cone calorimeter.

4.6 1985

The Administration again proposed to eliminate CFR, this time for fiscal year 1986 and beyond. Substantial efforts by the fire community and CFR management again resulted in restoration of the budget by Congress.

The goal of the Cigarette Fire Safety Bill, passed by Congress in 1984, was to reduce the one-third of residential fire casualties caused by cigarettes dropped inadvertently on upholstered furniture and bedding. The Bill's objective was the study the feasibility of producing commercially acceptable cigarettes with significantly lower

Group photograph of CFR staff taken in 1985.

propensity to ignite soft furnishing substrates than the majority of current brands. CFR was charged to understand the mechanism for ignition of soft furnishings by cigarettes with the objective of finding means to reduce cigarette ignition propensity.

Substantial progress was made on improved fire modeling. Walter Jones and colleagues released a second-generation model of the transport of combustion products (FAST V17) in both mainframe and PC compatible versions. The model includes multiple floors, improved modeling of conduction, and a simplified toxicity calculation. To support the use of computer models in fire safety engineering, CFR established the Fire Simulation Laboratory and began conducting short courses in the use of fire simulation programs.

Kermit Smyth and colleagues published a landmark paper on the most detailed and complete chemical structure measurements ever made in any flame [3].

Howard Baum and Ronald Rehm received the Department of Commerce Gold Medal for their unique and highly sophisticated mathematical model, which can accurately describe the evolution of smoke and gases in rooms or enclosures of various shapes. George Mulholland won the Department of Commerce Bronze Medal for his research concerned with the physics and chemistry of smoke particle generation and growth, which resulted in clarification of new and fundamentally important information about the process of soot growth and coagulation in fire environments.

4.7 1986

The Administration's budget proposal for CFR for 1987 and beyond continued to call for elimination of CFR. However, Congress and the Administration arrived at a "compromise" whereby in exchange for a cut of $0.5 million in directly appropriated funding for CFR the Administration would not seek further reductions for the remainder of the Administration (fiscal years 1988 and 1989). The cuts occurred as agreed, but the Administration subsequently reneged on the compromise and proposed large cuts, but not elimination, for the next two budget cycles.

CFR refocused its program to accommodate the cuts. Andrew Fowell moved to deputy director and James Quintiere became chief of the renamed Fire Science and Engineering Division. Its program areas became:

1. Predicting the burning rate of materials.
2. Modeling wall fire growth.
3. Development of a first-order suppression model.
4. Development of a benchmark compartment fire model.
5. Development and dissemination of a comprehensive method for fire hazard analysis.
6. Combustion of oil spills on the seas and suppression of oil/gas well fires.
7. In-flight fire and ventilation characteristics of aircraft cabins, smoke control in buildings, and analog simulation for smoke movement in buildings and ships.

Objectives for Richard Gann's Fire Measurement and Research Division were:

1. Combustion product prediction.
2. Fire model validation.
3. Fire-safe polymers.
4. Cigarette safety.

Hazard I, the first version of the hazard assessment methodology, was completed and made fully operational on desktop computers by Richard Bukowski and colleagues. FIRST, the prototype benchmark compartment fire model computer code, was produced by Leonard Cooper and colleagues. The cone calorimeter, which was adopted by ASTM, was produced by instrument suppliers. Takashi Kashiwagi and colleagues reported on the thermal degradation of polymers.

Vytenis Babrauskas received the Department of Commerce Bronze Medal for his research on the measurement of heat release from burning materials and his development of the cone and furniture calorimeters. Thomas Ohlemiller received the Bronze Medal for his pioneering research in understanding the complex physics and chemistry of smoldering combustion.

4.8 1987

The Administration's budget proposal for CFR for fiscal year 1989 called for a 40 percent reduction, below the amount for 1987 after the "compromise" cut of $500,000, and a merger of CFR with the Center for Building Technology (CBT). Continued strong support from both fire and building communities led to rejection of these proposals and continued funding for CFR and CBT, but without restoration of the cuts of $500,000 each that occurred in 1987 with the "compromise."

The Office of the Inspector General inspected the Center and reviewed three of its grants. Its report was complimentary.

The Center is managed effectively and efficiently, the Center is unique and technically competent, funding uncertainty is a cause for concern, private sector interest in fire science is limited, local government could not do the Center's work, OMB's research parallels ours, the Center has limited success in technology transfer, and the extramural grant program is managed effectively.

The fire hazard assessment method, HAZARD I, began a beta test to be applied to real problems by volunteer participants throughout the fire community. CFR-developed quantitative modeling tools were used to reconstruct the conditions that occurred in the Dupont Plaza Hotel in Puerto Rico, and the results were presented to a Congressional hearing on hotel fire safety.

The studies of cigarette ignition propensity called for by the Cigarette Fire Safety Act of 1984 were completed and reported to Congress. It was shown that thinner cigarettes with less tobacco and less porous paper significantly reduce the chance of igniting soft furnishings.

FIREDOC, the Center's computerized bibliographic database came on line with references, abstracts and key words for more than 8,000 of the 30,000 documents in the Fire Research Information Service. The Center's public access computer bulletin board also came on line with access to FIREDOC, and information on the Center's fire simulation programs, conferences, and recent reports.

Kermit Smyth and Houston Miller completed studies of soot nucleation in methane/air diffusion flames. Fluorescence, multi-photon ionization, Rayleigh-Mie scattering and mass spectroscopy were used to describe chemical structure and the nucleation of soot particles.

Howard Baum and Ronald Rehm developed a mathematical model of combustion in a turbulent eddy based on solutions of the Navier-Stokes equations. The technique allowed three-dimensional simulation of physical and chemical processes in turbulent, reacting flows.

Takashi Kashiwagi and Thomas Ohlemiller studied the gasification of PMMA and developed a new model based on thermally driven rearrangement of the primary polymer radicals which gave better agreement with experimental results than previous models and gave consistent values for degradation kinetic constants.

Daniel Gross received the Rosa Award of NBS and the ASTM Award of Merit for his contributions to national and international standardization organizations over his career at NBS. Kermit Smyth received the Condon Award of NBS for his paper "The Chemistry of

Daniel Gross researcher and leader of standardization efforts.

Molecular Growth Processes in Flames" in Science. Jack Snell received the Gold Medal of the Department of Commerce for technical leadership in fire safety, and Richard Peacock received the Bronze Medal of the Department of Commerce for his research on the fire safety of solid fuel heating appliances and chimneys. Harold Nelson was the first recipient of the Harold E. Nelson Award of the Society of Fire Protection Engineers.

4.9 1988

The Administration's budget proposal for CFR for fiscal year 1990 again called for a merger of CFR with CBT and funding both for a total of $5 million. Continued strong support from both fire and building communities led to rejection of these proposals and continued funding for CFR and CBT with both centers receiving small increases in appropriations.

CFR management realized at the start of the fiscal year that it faced a serious funding shortfall because of the reduction of base funding from the "compromise" funding for fiscal year 1987, the completion in fiscal year 1988 of the cigarette study funded by the Consumer Product Safety Commission, and limited research funds in many government agencies. In response and to focus the program, in-house research on human behavior in fire was terminated to free resources for priority projects. Staff reductions were associated with this move. Supervisory and research staff were encouraged to work with colleagues in other federal agencies to identify their fire research needs and to follow up with research proposals that would complement CFR's research performed with directly appropriated funding. Many of these proposals were funded, often as multi-year projects, to give good prospects for future funding and staff growth.

The technology transfer effort headed by James Winger was upgraded to become an Office of Technology Transfer incorporating the Fire Research Information Service, the Simulation Laboratory and the Computer Bulletin Board.

Full-scale building fire tests were felt to be increasingly important because of the need to verify new generation fire models. Expansion began in fire exhaust capability in Building 205 to gain a calorimeter capable of free burn fires up to 1.5 MW. Planning began for a three-fold increase in the working area for Building 205.

Barbara Levin developed the "N" gas model for toxicity of multiple combustion products to cover four principal gases and exposure times from one minute to sixty minutes.

James Quintiere, Robert Levine and Harold Nelson reconstructed events in a two story residential house fire in Sharon, PA on September 26, 1987, in which smoke and heat from a fully developed kitchen fire killed three residents on the second floor. The fire was reconstructed in the large fire facility. Data showed that current fire models underestimated hazard conditions, particularly carbon monoxide.

James Quintiere, John Klote and Harold Nelson assisted the Los Angeles Fire Department and the U.S. Bureau of Alcohol, Tobacco and Firearms in the investigation of the First Interstate Bank Fire. It completely gutted floors 12-15 of a 62-story building. CFR modeled effects of open landscape office spaces, desktop computer equipment, flame projection from windows, and smoke propagation in vertical shafts.

Mark Nyden produced the first of an important series of computer simulations of heat driven fragmentation of a polymeric molecule. This capability led to better understanding of how more fire-stable polymers can be produced while preserving salient commercial properties.

Richard Gann worked with the U.S. Air Force and the New Mexico Engineering Research Institute to develop an eight-year, $20 million program to develop replacements for halogenated fire suppression agents. These two highly effective agents, (halon 1301, CF_3Br, and halon 1211, CF_2ClBr) are strong contributors to depletion of stratospheric ozone and were being removed from production. Replacement agents must quench flames, be non-toxic and non-corrosive, leave no residue and not deplete ozone. This began a very significant CFR/BFRL program.

Vytensis Babrauskas and William Twilley won an R&D 100 Award for development of the Cone Calorimeter. It measures as a function of radiant exposure, the time to ignition, amount and rate of heat release, amount of smoke produced, and amounts of several toxic gases from small samples of materials. Thus, it provides data needed for rational modeling of the contributions of various materials to the development of large-scale fires. Both ASTM International and the International Organization for Standardization (ISO) were developing standard test methods based on the cone calorimeter and two U.S. manufacturers were producing units for the market.

4.10 1989

The Administration's request to Congress for the fiscal year 1990 budget, the last prepared by the Reagan Administration, again proposed to merge CFR and CBT and fund the combined center at a level of $5 million (half their combined bases of $10 million). The fire community again supported full funding for CFR and Congress again restored funding for the fiscal year 1990 budget. Also, CFR and CBT directors discussed the programs with the new Bush Administration officials in the Department of Commerce and the Office of Management and Budget with the result that the cuts no longer were proposed for the fiscal year 1991 budget.

Jack Snell, recognizing the status of CFR (reduced in real funding and staffing substantially in the 80s with remaining resources focused on hazard and risk modeling) and the recommendations of the National Research Council evaluation panel on CFR, produced a new long-range plan for CFR. It sought major technical innovations or breakthroughs to reduce substantially the losses and cost of fire. An NFPA study estimated these costs as $48 billion in 1986. Current resources were focused on fire prediction methods and technical advances to reduce fire losses and costs by up to 10 percent by 2000. An enhanced funding level was proposed to provide the technical basis for reducing fire losses and costs by 50 percent by 2000-2005.

Five objectives were defined:

1. Quantify and communicate fire risk and hazard.
2. Engineered fire-safe products and materials
3. Sense and communicate risky conditions.
4. Control and extinguish fires.
5. Locate, protect, and remove occupants/people.

Eleven priority projects were established for the current resources for fiscal year 1990:

1. Hazard II led by Richard Peacock: plan and implement a second-generation hazard methodology by 1992.
2. Unified Model of Fire Growth and Smoke Transport led by Walter Jones and Glenn Forney: modify the FAST model to incorporate lessons learned from the consolidated compartment fire model by 1990.
3. Toxic Potency Measurement led by Vytensis Babrauskas: provide an accurate bench scale methodology for combustion toxicity measurement by 1991.
4. Furniture Flammability led by William Parker: develop a test and calculation protocol for evaluating the fire hazard of upholstered furniture by 1992.
5. Wall Fire Spread led by Henri Mitler: develop a method for predicting the rate and extent of fire spread on interior surfaces in a room using the fire properties of the materials involved by 1992.
6. Carbon Monoxide Production and Prediction led by William Pitts: develop a fundamental understanding of the mechanisms of carbon monoxide formation in flames sufficient to produce an estimation model in 1994.
7. Burning Rate led by Takashi Kashiwagi: develop by 1992 glob-

al/detailed models able to predict non-flaming gasification rates and horizontal burning rates for thermoplastics after understanding the polymer gasification process and energy feedback mechanisms.

8. Fire Suppression led by David Evans: develop methods for the prediction of sprinkler system performance by 1995 using measurable system parameters such as spray drop size distribution, heat transfer characteristics, and installation geometry.
9. Turbulent Combustion led by Howard Baum: understand and predict energy release and fuel consumption in turbulent systems.
10. Soot Formation and Evolution led by Kermit Smyth: develop a predictive model for the formation of soot in flames and evolution of smoke components from flames by 1992.
11. Engineering Methods led by Harold Nelson: develop the FPETOOL methodology for practical fire safety evaluation and incident reconstruction by 1990.

HAZARD I and eight example applications were released. These became the basis for a course at Worcester Polytechnic Institute and were marketed by NFPA. An agreement was negotiated with the National Association of State Fire Marshals and the Fire Marshals Association of North America to put a visiting marshal in the Center for a year to work on applying new fire protection engineering methods to typical problems.

The California Bulletin 133 room fire test for upholstered furniture was assessed and a proposal developed for improving the repeatability of ignition conditions. LAVENT, a program to predict actuation of fire vents, was developed under sponsorship of the American Architectural Manufacturing Association using parts of the Consolidated Compartment Fire Model. A cone calorimeter was redesigned to allow burning under reduced oxygen conditions. Burning Douglas Fir at 14 percent oxygen quadrupled CO yields. This suggested that the much larger yields recorded in under-ventilated burns depend on total oxygen available.

Richard Gann was named chairman of the Technical Committee of the Halon Alternatives Research Consortium, which included the Air Force, Navy, Army, Environmental protection Agency (EPA), National Aeronautics and Space Administration (NASA), DuPont, ICI, National Science Foundation (NSF), Great Lakes Chemical, Ansul, the Halon Research Institute and Factory Mutual.

Harold Nelson received the Gold Medal of the Department of Commerce for outstanding contributions to advancing the science of fire protection. John Klote received the 1988 ASHRAE Best Paper Award for "An Overview of Smoke Control Technology." William Walton received the Director's Award of the Society of Fire Protection Engineers for his work as section editor on the first edition of the Handbook of Fire Protection.

4.11 1990

John Lyons was nominated by President Bush on November 22, 1989 to become NIST director, was confirmed by the Senate on February 8, 1990, and sworn in on February 9. Lyons as founding director of CFR, 1974-1978, and founding director of the National Engineering Laboratory, which included CBT and CFR, from 1978-1990, had first hand knowledge of CBT and CFR programs, people and constituents. It was wonderful to have understanding leadership at NIST! However, budget deliberations did not lead to an initiative for fire research for fiscal years 1991 or 1992.

It was clear that fiscal year 1990 was the last for separate centers for building and fire research. Congress authorized their merger on July 30, 1990, the merger was announced to staff on August 30, and the successor Building and Fire Research Laboratory (BFRL) began to operate on October 1, 1990 (the beginning of fiscal year 1991) although the formal reorganization did not take place until January 31, 1991.

The CFR program in 1990 continued its focus on the technical bases for advanced fire modeling and the verification of the models. Need continued for improvements of the large fire testing facility, but funds were not available for enlargements or major renovations.

CFR commissioned studies of the total costs of fire, fire losses plus costs of fire protection measures [4], and impacts of CFR [5]. The former showed an annual cost exceeding $128 billion; it neglected all government fire losses and fire safety expenditures. The latter showed an annual impact of $5-9 billion for CFR in reduction of fire costs and noted virtually every major contribution from the 70s still was providing benefits. These studies guided the focus of the fire program in BFRL.

P.L. 101-352, *The Fire Safe Cigarette Act of 1990*, directed that:

> *"at the request of the Consumer Product Safety Commission, the National Institute of Standards and Technology's Center for Fire Research, shall: (1) develop a standard test method to determine cigarette ignition propensity, (2) compile performance data for cigarettes using the standard test method developed under paragraph (1), and (3) conduct laboratory studies on computer modeling of ignition physics to develop valid, "user friendly" predictive capability."*

Richard Gann was elected chairman of the Technical Advisory Group created in response to the Act, and led the research effort in CFR.

CFR established a memorandum of agreement with the National Association of State Fire Marshals to improve mutual understanding of the technical needs of the fire services and the delivery and implementation of resultant products of CFR. For additional linkages with users, Jack Snell was elected to the Board of Directors of the National Fire Protection Association and appointed to its Long Range Planning Committee, and David Evans was elected to the Board of Directors of the Society of Fire Protection Engineers.

Jack Snell led in the organization of the Forum for International Cooperation on Fire Research, FORUM, comprised of heads of fire research organizations around the world, and became its chairman. At its 1990 meeting, FORUM developed a common strategy for fire resistance testing of materials and furniture that was based primarily on technology developed by CFR.

In a project jointly supported by U.S. and Canadian agencies, CFR participated in a mass fire experiment outside of Chapleau, Ontario. The results were used to compare predicted fire-induced wind velocities with measured values - important information for developing and validating CFR's large fire models and for understanding urban conflagrations.

Vytensis Babrauskas and colleagues established the first relationship between the toxicity of room fire smoke and that measured in the combustion of small samples. Agreement was within a factor of 3, which is acceptable for prediction of life safety in building fires.

Mark Nyden developed a prototype, ab initio, model of thermal degradation and cross linking of polymers which led to understanding of how less flammable chars are formed. Stimulation of char formation was identified as an important fire retardant mechanism.

William Pitts developed a large-scale apparatus and developed novel techniques to measure the turbulent mixing in fire plumes. Unmixedness dominates the formation of smoke and toxic combustion products.

Harold Nelson was awarded the NFPA's Standards Medal for unselfishly contributing to the fire protection community for over 30 years. Richard Bukowski, Walter Jones, Richard Peacock, Cheryl Forney, and Emil Braun received the Department of Commerce Silver Medal for producing the world's first fire hazard assessment methodology. Vytensis Babrauskas was the first recipient of the Interflam Award of the International Conference on Fire Safety for his leadership in the development and implementation of heat release rate measurement.

A number of departures and retirements of founding staff members accompanied the merger of CFR. James Quintiere resigned as Chief of the Fire Science and Engineering Division to become Professor of Mechanical Engineering at the University of Maryland. Retirements included William Parker, Head of the Fire Dynamics Group, Sanford Davis, research chemist, and Maya Paabo, research chemist.

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5. CENTER FOR BUILDING TECHNOLOGY IN THE 80s

5.1 Overview

As Fiscal Year 1981 began on October 1, 1980, the Center for Building Technology (CBT), had a staff of 199 work years, and was preparing, at the request of the Secretary of Commerce, a proposal for a new Construction Productivity Program at a level of $100 million annually. However, management of the National Bureau of Standards (NBS) was concerned about the high proportion (about 40 percent) of CBT's funding from the Department of Energy, and requesting that the energy work be focused on measurement.

As Fiscal Year 1990 ended on September 30, 1990, CBT had a staff of 89 work years, and was about to become part of the new Building and Fire Research Laboratory (BFRL) of the National Institute of Standards and Technology (NIST) as NBS had been renamed in 1987.

The prospects for major growth of building research at NBS ended with the results of the Presidential election of 1980. Reductions of about 30 percent in CBT staff occurred in 1981 to respond to both reductions in other agency funding and Administration requirements for reductions in NBS staffing. The President's budget proposal for fiscal year 1984, which was announced in January 1983, called for elimination of CBT. The rationale was that the program was more properly the role of the private sector and state and local governments. Although Congress restored funding for fiscal year 1984, the President continued to call for elimination of CBT in his budget requests for fiscal years 1985 through 1987. Congress restored funding each year until 1987, when it agreed with the Administration on a compromise cut of $500,000 in CBT to end the attacks. The Administration reneged on the compromise and proposed for fiscal year 1988 to merge CBT and the Center for Fire Research at a level of one-half of their 1986 funding. Congress restored their funding at the reduced 1987 levels and kept the centers independent. The Administration proposals for reductions and the Congressional restorations continued for fiscal years 1989 and 1990.

CBT survived Administration proposals for its elimination because of strong support before Congress from the private sector and state and local governments. Its work on failure investigations, measurements for thermal insulation, quality assurance for construction materials laboratories, and many other topics, was cited as evidence that it fulfilled important needs that could not otherwise be met.

The proposals for elimination or reduction allowed neither cost of living increases nor new initiatives for CBT's directly appropriated funding, and other agency funding was constrained by similar reductions in other agencies' funding. In order to remain effective, CBT responded to the financial constraints by narrowing scope as it cut staff. By 1986, work had been terminated in acoustics, architecture, economics, electrical distribution systems, environmental psychology, foundations, geotechnical engineering, plumbing, and solar energy. However, other programs were increased to respond to important needs: alternatives to the refrigerants threatening the ozone layer, automatic controls of building service systems, computer integrated construction and indoor air quality.

Recruiting new staff, whether entry level or mid-career, was difficult while the Center was under attack by the Administration. Indeed, many valuable people left either voluntarily or involuntarily. But, staff morale stayed strong; people were proud of their work and the public support for it highlighted by testimony in Congressional hearings. Productivity was high and the evident reason for continued existence of the Center.

However, staff attitudes were defensive, and it would require a conscious effort to break away from a "bunker mentality" to take advantage of the opportunities the 90s offered to NIST and its Building and Fire Research Laboratory.

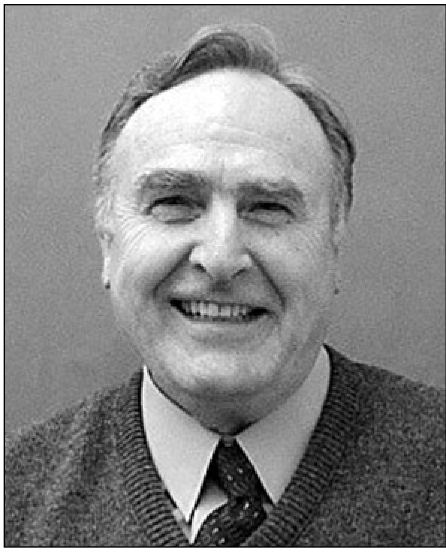
5.2 1981

The National Construction Industry Council, an umbrella organization of trade and professional associations, was strongly concerned with lagging or declining construction productivity, and met with the Undersecretary of Commerce on November 27, 1979, to request support in technology in enhancing construction productivity. In response, CBT focused substantial efforts on technologies for improvement of the productivity of construction and of constructed facilities. Ongoing work in lifecycle costs and benefits, rehabilitation standards, plumbing systems performance and materials durability supported more productive construction, and acoustics and lighting supported more productive buildings. New work was proposed in computer integrated construction, building control systems, productivity measurements, equivalency systems for regulatory approval, concreting technologies, excavation, soil stabilization and materials handling. Although new funding was not received for many years, the productivity need was strong and work was begun, through reprogramming, in computer integrated construction and building control systems.

Even prior to the election of November 1980, NBS requested that five positions be cut in CBT. Subsequent to the election with the preparation of the last Carter Administration budget, the assigned cut grew to 20 positions. When the Reagan Administration assigned reductions to NBS in February 1981, CBT's share grew again to 49. Department of Energy funding was reduced by 1.3 million dollars; major cuts would have been required for fiscal solvency alone. In total, CBT staff was reduced by about one-third.

CBT decided, with direction from NBS and NEL, to reduce its scope so that the remaining programs would be strong. The Environmental Design Research and the Building Economics and Regulatory Technology divisions were abolished. The Building Materials Division was split from the Structures and Materials Division to give CBT four divisions: Structures, Building Physics, Building Equipment and Building Materials. Applied Economics was transferred, with reduced staff, to the Center for Applied Mathematics, and groups in Architectural Research, Building Safety, and Building Rehabilitation Technology ceased to exist.

Geoffrey Frohnsdorff became chief of the Building Materials Division and held this position until his retirement in 2001. His unrelenting focus was to



Geoffrey Frohnsdorff, chief CBT Building Materials Division.

make more predictable the performance of building materials over their life cycle. He overcame much adversity in the initial lack of NBS funding for building materials research by working patiently and effectively with leaders in the scientific community, industry, NBS and other federal agencies to define and fund needed programs of research. He recruited and developed young scientists and engineers to bring his division to international leadership.

NBS director Ernest Ambler was uncomfortable with research in architectural and behavioral sciences areas as remote from the physical sciences and engineering measurements that he felt constituted the core of NBS, and susceptible to imprecision and questionable results that would be harmful to NBS' reputation. John Lyons and both James and Richard Wright had supported these areas of work as important for achieving CBT's objectives, but management's direction was clear. John Eberhard, as a consultant to CBT, was very helpful to staff seeking new jobs, prior to his own move in July 1981 to become executive director of the National Academies' Building Research Advisory Board.

All was not losses. Appliance efficiency staff and Department of Energy projects were transferred to CBT as the Center for Consumer Products Technology was eliminated, and the Construction Materials Reference Laboratory was transferred to CBT from the NEL Office of Engineering Standards.

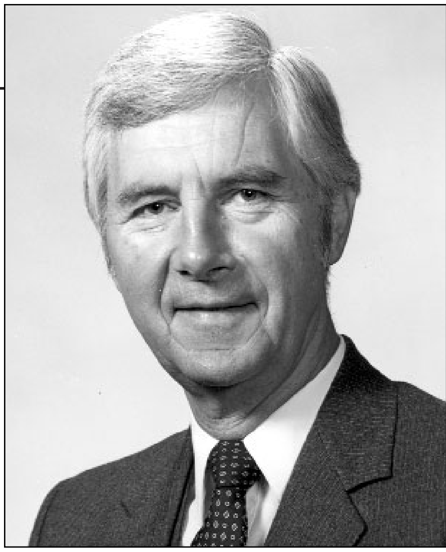
It was vital to inform policy makers in the new Administration of the importance of construction productivity and the need for cooperation between industry and government to achieve it. Charles E. Peck, Executive Vice President, Owens-Corning Fiberglas Corporation, worked with Richard Wright to organize a Conference on Research for Building Construction Productivity on June 2, 1981, with sponsorship of the Construction Action Council of the Chamber of Commerce of the United States [1]. Keynote speakers were Joseph Wright, Deputy Secretary of Commerce, and John Dunlap of Harvard University. Technical presentations were made on measurement of productivity by professors Robert Logcher and David Kresge of MIT, reduction of construction duration by Joseph Newman of Tishman Research Corporation, reduction of risks of failure by Richard Marshall of CBT, computer-integrated construction by professor Steven Fenves of Carnegie Mellon, and productivity in the completed building by architect Ezra Ehrenkrantz.

Consensus was reached on six primary research topics: micro measures of productivity to assist in decision making, macro measures of productivity to assist in understanding industry trends, extending computer applications to all phases of construction decision making, expediting the regulatory process, relating occupant/user productivity to building design, and improving knowledge of the physical properties of buildings. The private sector should take the initiative to formulate and conduct research, with government supporting and conducting some research.

The Conference gave CBT good guidance, industry partners and bases for developing its research program, but, as events would show, did not lead to Administration support. In fact, Joseph Wright became a leader of the President's Office of Management and Budget as it locked into four successive years of proposals for the elimination of CBT, and three more for its halving.

Important results were achieved in spite of the tumult of staff cuts and reorganization. The innovative One Meter Guarded Hotplate went into service to provide reference samples of thick insulations needed by the insulation industry to meet Federal Trade Commission requirements for insulation labeling.

The only specific milestone in the President's plan for the National Earthquake Hazards Reduction Program was met when CBT synthe-



Edward Pfrang, chief CBT Structures Division.

sized and published the Draft Seismic Standard for Federal Buildings. The Life Cycle Costing Manual for the Federal Energy Management Program was published to allow federal agencies to comply with energy conservation legislation and Executive Order 11912.

Arthur Rubin's and Jaqueline Elder's hard cover, attractive *Building for People* was printed in 1981. It was dedicated to Reece Achenbach as "an engineer who designed and created a research environment which nurtured and fostered the growth of a new discipline." Its purpose was to acquaint the practicing architect and student to the potential contributions of the social sciences to the solution of building problems. It focused on the need to understand man/environmental relationships rather than making design recommendations or compiling knowledge. It was poignant to issue this thoughtful manifesto for man/environmental research at the time such research was being eliminated from NBS programs. But as the work notes, the research record did not show clear cut solutions to man/environmental problems.

On July 17, 1981, The Kansas City Hyatt Regency Hotel skywalks collapsed during a dinner dance killing 114 participants. Edward Pfrang, chief of the CBT Structures Division, immediately was sent to Kansas City to begin informally the investigation needed to understand the physical causes of the collapse. The official request to investigate came from Senator Thomas Eagleton on July 20, 1981. The skill and celerity with which Pfrang and his colleagues dealt with the technical, legal, political and publicity challenges surrounding the investigation probably was the single most important factor in the successful defense of CBT and the Center for Fire Research against the subsequent Administration efforts to eliminate these programs. Pfrang was outstanding for his imagination, forcefulness, and comfort with conflict where he showed extraordinary ability to think on his feet.

David Didion received the Silver Medal of the Department of Commerce for his research in development of more efficient test methods for the seasonal efficiency of heat pumps and air-conditioners. Edward Prang received the Silver Medal for his leadership in advancing performance criteria for housing.

5.3 1982

At the beginning of the fiscal year in October, as part of a budget reducing exercise imposed by the Department of Commerce, the NBS Director proposed to cut CBT's directly appropriated funding by about 40 percent, but this cut was not accepted by the Secretary of Commerce. Indeed, in March, Secretary Baldrige gave Director Ambler an "A" for the Bureau's successful investigation of the Kansas City Hyatt Regency skywalks collapse. However, budget pressures did not end. In July, CBT was visited for a day by two mid-level executives from industry, who were without research experience but, under the auspices of the Grace Commission, were exploring opportunities to reduce the federal government. In September, the Grace Commission recommended elimination of CBT - its work should be funded by industry and performed in universities. The Department of Commerce's recommendations for the 1984 budget were to eliminate the Center for Fire Research and to cut from CBT's budget $100,000 that had been devoted to solar energy research.

Congress showed direct interest in CBT's work. In February, the House Science and Technology Committee invited testimony on fire and earthquake research for the Federal Emergency Management Agency, and in August the House invited testimony on structural failures investigations.

Charles Thiel, who had been a leader in planning and implementing the National Earthquake Hazards Reduction Program (NEHRP) in his work at the National Science Foundation, on detail to the White House, and in the establishment of the

Federal Emergency Management Agency left the latter agency to join the private sector. Richard Wright succeeded Thiel as chairman of the Interagency Committee on Seismic Safety in Construction and represented NBS in the planning and management of the NEHRP.

Work on the Kansas City Hyatt Regency skywalks collapse was completed. Edward Prang and his colleagues were much involved in disseminating the findings and working with industry to improve quality in construction and avoid future failures from inadequate design and review of design. The Occupational Safety and Health Administration in April asked CBT to investigate the collapse of a highway overpass under construction. The National Academies' Evaluation Panel for CBT advised development of guidelines for CBT's involvement in disaster and failure investigations to avoid excessive involvement in investigations.

David Didion and his colleagues began studies of the performance of binary refrigerant mixtures in the refrigeration cycle. This work was motivated by desire to improve the efficiency of the refrigeration cycle, but subsequently became the basis for finding alternatives to the refrigerants harming the ozone layer. The National Academies' Evaluation Panel for CBT suggested that the staff return to programs more closely associated with CBT's goals, but CBT persisted.

Clinton W. Phillips, who had begun work as a technician with the CBT predecessor organization in the 40s and had risen to lead work on modular, integrated utility systems for buildings, was elected President of the American Society of Heating, Refrigerating and Air-Conditioning Engineers. Richard Marshall and Edward Pfrang received the Gold Medal of the Department of Commerce for their leadership of the investigation of the physical causes of the collapse of the skywalks of the Kansas City Hyatt Regency Hotel - the worst building accident in U.S. history. Richard Wright received the Gold Medal for his leadership of the restructuring of CBT without diminution of the effectiveness of the remaining staff. Geoffrey Frohnsdorff received the Silver Medal of the Department of Commerce for his leadership in the development of national standards for blended cements to improve cement performance and allow recycling of fly ashes and blast furnace slags. H.S. Lew received the Silver Medal for his leadership in national standardization for construction safety.

5.4 1983

1983 was the first and critical year of the Administration's efforts to obtain Congressional approval for the elimination of the Center for Building Technology.

In November of 1982, CBT was selected by NBS for review by the Inspector General of the Department of Commerce "to determine whether officials of CBT are managing and using their resources economically and efficiently and whether the officials are complying with the laws and regulations concerning matters of economy and efficiency." In the Inspector General's report to the President of the Senate and the Speaker of the House [2] CBT received an extraordinary, entirely positive evaluation:

The Inspector General reviewed building research activities of the National Bureau of Standards' (NBS) Center for Building Technology (CBT) and found that CBT test and research projects were effectively meeting user needs.

CBT is a comprehensive building research laboratory whose staff produce technical bases for building performance criteria and measurement technology to assess building performance. CBT fills key building research roles that would not otherwise be done. Both government and industry have benefited from CBT because of its high quality work, technical competence and responsiveness. CBT also is highly respected for its objectivity: unlike most laboratories, CBT is not oriented toward support of a specific industry or product and thus cannot be accused of having any special ax to grind.

We found that both government and industry rely on CBT because:

- *It has provided the research necessary to develop new criteria and performance standards to reduce product costs and improve performance of building materials.*

- *It has a leadership role as well as the resources to serve the various segments of the fragmented building community.*
- *Its noncompetitive relationship with other Federal agencies and industry has combined with its technical competence to help CBT do a commendable job.*

We found it particularly interesting and indicative that not one of the private or university laboratories whose staffs we interviewed supported the elimination of CBT - even though this action doubtless would give them substantial additional research contracts.

We concluded that CBT is an unbiased source of building research information and measurement technology which has made important contributions to the Nation as a whole and in particular to the building industries. The building community has depended on CBT to provide essential building research information that would not otherwise be available. We made no recommendations to CBT.

On February 22, 1983, the Subcommittee on Science, Technology and Space of the Committee on Commerce, Science and Transportation of the United States Senate held hearings on authorization of appropriations for NBS for fiscal year 1984. NBS Director Ernest Ambler dutifully testified for the Administration "that the private sector and state and local governments should support fire and building technology research programs." This perspective was contradicted in testimony and statements from the chairman of the National Research Council's Evaluation Panels for NBS, the chairman of the Statutory Visiting Committee for NBS, the Mineral Insulation Manufacturers Association, the American Society of Civil Engineers, the U.S. Chamber of Commerce and the National Institute of Building Sciences. The report of the Committee [3] stated:

The Committee believes that research performed at CBT is vital to public health and safety, and is worthy of continued support. The Committee intends that NBS fund CBT at the FY 1983 level.

On March 22 and 23, 1983, the Subcommittee on Science, Research and Technology of the Committee on Science and Technology of the U.S. House of Representatives held hearings on authorization of appropriations for NBS for fiscal year 1984 (Ninety-Eighth Congress, first session). Chairman Walgren, Congressman Reid, and Subcommittee staff had visited NBS on February 14, just three days after a major snowstorm, to see ongoing work and laboratories in CBT, CFR and the automation program. John Lyons, director of the National Engineering Laboratory, was tasked to give the Administration's rationale for elimination of CBT, but he also described its accomplishments. Testimony for the restoration of funds for CBT and CFR was presented by: Congressman Michael Barnes, who quoted many industry endorsements of the programs, professor Steven Fenves of Carnegie Mellon University, the National Institute of Building Sciences, the Construction Action Council of the U.S. Chamber of Commerce, and the American Institute of Architects.

Letters in support of CBT and CFR were provided by: the Statutory Visiting Committee for NBS, the American Association for the Advancement of Science, the National Forest Products Association, the American Society of Civil Engineers, the Council of American Building Officials, the American Iron and Steel Institute, SMACNA, Brick Institute of America, the American Society of Heating Refrigerating and Air-Conditioning Engineers, the United McGill Corporation, and the Asphalt Roofing Manufacturers Association. The restoration of CBT also was requested by: the American Association of State Highway and Transportation Officials, Professor Steven Kendall of the University of Colorado, the Atlantic Cement Company, the Illuminating Engineering Society of North America, Richard Berkely, mayor of Kansas City, MO, Ernst Fuel and Supply Company, Kalamazoo Ready-Mix Concrete Company, the Transit Mix Concrete Company, the Material Service Corporation, the National Concrete Masonry Association, the National Gypsum Company and the Conrock Company.

The Report of the Committee [4] stated:

In the area of building research, NBS provides a vital role in providing the tech-

nical basis for codes and standards which are the heart of our building system in the United States. In addition, the Center for Building Research provides a basis for NBS to develop significant expertise in the area of building technology and thereby it is able to well serve the needs of the public when expert, third party investigations are requested following a building failure such as the Kansas City Hyatt Regency walk-way collapse. These investigations, besides providing local governments and local officials with a very much needed service, also provide NBS with guidance for research efforts. The bill provides a minimum of $4.5 million for this center.

The House floor providing an increase in funding for CBT did not prevail in conference with the Senate, but CBT was restored in the 1984 budget at the 1983 level of funding. In spite of the outstanding support from the building community, this amounted to a cut in the program by the rate of inflation (4.3 percent by the Consumer Price Index).

CBT's Long Range Plan was updated and retitled Building Research for the Computer Age. Applications of advanced computation to buildings' systems and to the building process were anticipated to change radically:

- What we build - buildings will be automated to respond to dynamic human needs and environmental conditions,
- How we build - processes of design and construction will change to exploit potentials of computer-aided design and automated manufacture and construction,
- Who builds - roles in the building process will change as advanced computation and automation make some skills obsolete and require other new skills.

Program objectives were grouped in seven tasks:

1. Computer integrated construction
2. Structural safety
3. earthquake hazards reduction
4. building physics
5. building equipment
6. quality of building materials
7. cement hydration

Computer integrated construction is a vision for seamless, automatic, flow of information among all participants throughout the whole life cycle of a constructed facility (planning, design, manufacture, construction, operation, maintenance, renewal and removal). Research in computer integrated construction had begun with modeling of standards as networks of decision tables, developing computer aids to assist in the formulation and expression of standards, and techniques for interfacing machine representations of standards to programs for computer aided design. In 1983, CBT's Computer Integrated Construction group began to collaborate with the Center for Manufacturing Engineering in support of the Architecture, Engineering and Construction industries group working on the Initial Graphics Exchange Standard of the American National Standards Institute.

Cooperative efforts in computer integrated construction were discussed with other federal agencies and the private sector under the auspices of the National Academies' Advisory Board on the Built Environment for which John Eberhard was executive director. Richard Wright presented a keynote address on computers in buildings, building and building research at the triennial congress of the International Council for Research and Innovation in Building and Construction (CIB) formerly the International Council for Building Research, Studies and Documentation in Stockholm. CIB created working commissions for international collaboration in integrated computer aided design and in control of building service systems in which CBT researchers played leading roles.

CBT's work continued to be conducted in four divisions: structures, building physics, building equipment and building materials. Edward Pfrang left leadership of the Structures Division to become executive director of the American Society of Civil Engineers; Charles Culver became chief of the Structures Division. Charles Culver's philosophy was "results speak for themselves" in his work as program manager for earthquake hazards reduction, deputy director of CBT and chief of the Structures Division.

Charles Culver, chief, Structures Division

Preston McNall left leadership of the Building Physics Division because of illness; Tamami Kusuda became its chief. Kusuda had achieved an international reputation as the leader in the computer modeling of the thermal performance of buildings. James Gross became the deputy director of CBT.

James Gross represented CBT at the American Society of Civil Engineer's Structures Failure Conference which placed strong emphasis on better defining responsibilities during the development, design and construction of projects. Richard Wright was elected president of CIB for the period 1983-86. He also led the American Society of Civil Engineers' November 1982 Productivity Roundtable and September 1983 Productivity Workshop.

5.5 1984

Again, CBT and CFR were proposed for elimination in the President's request for the fiscal year 1985 budget. The rationale was that these programs are more properly the role of the private sector and of state and local governments. Again, private sector organizations and the National Conference of States on Building Codes and Standards testified that these programs are needed and cannot be funded by private industry or state or local governments. Congress concluded [5] "the research performed at CBT is vital to public health and safety, and is worthy of continued support." Funding was restored at the 1984 level - another cut by the amount of inflation (3.7 percent).

CBT continued in budget problems. NBS decided not to propose any budget increases to the Department of Commerce for CBT for fiscal year 1986. Before the year end, the President's Office of Management and Budget informed NBS that CBT and CFR again would be proposed for elimination in the President's budget request for fiscal year 1986.

Additional Congressional hearings on structural failures resulted in legislation authorizing NBS to investigate important structural failures at its own initiative. For unrelated reasons this legislation was pocket vetoed by the President, but became law subsequently.

CBT's strategy from its strategic planning was to build its capability in computer-integrated construction at the same time as it strengthened its laboratory-based performance prediction and measurement programs. However, both directly appropriated funding and sponsored research were essentially static in current dollars and declining in real dollars. Budget problems made it difficult to recruit strong staff. Human and financial resources were focused on the most significant issues and best technical opportunities. Knowledge based expert systems were identified as the emerging successor to paper standards as the principal vehicle for delivery of CBT research to practice. Training in expert systems was organized for interested staff and prototype expert system projects were funded in the divisions.

The Interagency Committee on Seismic Safety in Construction (with NBS chair and secretariat) decided to proceed with development of a seismic standard for new federal buildings and to draft an executive order for its implementation in federal and federally assisted new building construction. The federal standard would be based on the Recommended Provisions for Development of Seismic Regulations for New Buildings being developed by the Building Seismic Safety Council with financial support from the National Earthquake Hazards Reduction Program (NEHRP), and could be used if the voluntary national standards and model building codes did not adopt the NEHRP Recommended Provisions in form and substance suitable for federal use.

CBT added important new laboratory facilities:

- Tri-Directional Structural Testing Facility - a unique computer controlled apparatus capable of applying loads or displacements in six degrees of freedom (three transla-

tions and three rotations) to large scale structural components to simulate conditions in earthquakes or other extreme environments.
- Universal Testing Machine - added a reaction wall to the 53 MN testing machine to allow combinations of vertical and lateral loading to large specimens.
- Calibrated Hot Box - for precise measurement of air, heat and moisture transfer in full scale building wall sections, with doors and windows, over a wide range of climate conditions.

Emil Simiu was named Federal Engineer of the Year 1984 by the National Society of Professional Engineers for his leadership in wind research, contributions to the improvement of standards for wind loadings, and co-authorship of the nation's leading reference book on wind engineering. He also received the Department of Commerce Silver Medal in recognition of these accomplishments.

5.6 1985

Again, CBT and CFR were proposed for elimination in the President's budget request for fiscal year 1986. Again, the rationale was that these programs are more properly the role of the private sector and of state and local governments. It seemed that the Administration wanted to show sustained commitment to reducing the size of the federal government and required NBS to offer its sacrifice. And, NBS had learned that it was safe to offer CBT and CFR for cuts, and that the exercise did not require imperiling other programs.

It was tedious to again supply information for testimony to private sector collaborators when Congress seemed resolute in its support for building and fire research, but existence is a serious business and had to be top in priority. Testimony from collaborators was strong. ASTM stated to the House of Representatives on February 28, 1985:

> *The work of the Center for Building Technology and the Center for Fire Research are essential to the development of consensus standards for many, many ASTM committees, and this work becomes an integral part of probably one of the most important regulatory processes in America - Building Codes and Life Safety Codes.*

At the same hearing, the National Institute of Building Sciences testified:

- *The Centers for Building Technology and Fire Research are essential parts of an overall framework intended to improve the quality of the built environment. --- the nation's construction industry has come to rely on these centers for thorough and objective data, and for services available nowhere else. --- the programs at CBT and CFR should be continued and are best supported and fostered by non-proprietary interests. --- Our belief is that these centers help stimulate new technological developments and speed their use in design and construction practice, as a result of open public disclosure, where new information and ideas may be further advanced by innovative individuals and corporate interests.*

The American Society of Heating, Refrigerating and Air-Conditioning Engineers wrote to the House of Representatives on March 5, 1985:

> *The two centers under discussion have produced research which finds its way promptly into the private sector for the benefit of the general public, business, industry and all levels of government. --- More than one-third of the ASHRAE standards are based in whole or in part on information developed at the Bureau, further evidence of government agency-private sector cooperation.*

The American Society of Civil Engineers wrote to the House of Representatives on March 6, 1985:

> *CBT is the only research program that integrates complex technical issues affecting the vast building industry. Despite the fact that it amounts to about 10 percent of the GNP, and that almost two-thirds of the nation's wealth is invested in constructed facilities, the building industry is very fragmented. CBT provides a uniform base of information, and serves as a unifying force for the entire industry. Because of the industry's size and diversity, no part of the private sector can duplicate these efforts or adequately distribute the findings on its own. This interdisciplinary laboratory also integrates complex technical issues in a way that more narrowly-focused proprietary research and development cannot.*

The National Conference of States on Building Codes and Standards testified at the Senate hearing on March 8, 1985:

1. *The National Bureau of Standards' Center for Building Technology and Center for Fire Research continue to provide the nation's states and local governments with invaluable building and technological research which the state and local governments depend upon to help them adopt and enforce modern building and fire codes which provide for their public's health and life safety in new and existing buildings.*
2. *That the states individually or working together cannot and will not be able to build, staff, and fund or contract for such research should the Centers for Building Technology and Fire Research cease to operate.*
3. *That even if the states were able to build, staff, and fund or contract for such research, that each state would duplicate the research programs of the other states in the area of building and fire safety, resulting in a large and inexcusable was of taxpayers' funds.*

Congress restored funding for CBT and CFR for fiscal year 1986 and provided specific authorization for future investigations of structural failures:

> *The National Bureau of Standards, on its own initiative, but only after consultation with local authorities, may initiate and conduct investigations to determine the causes of structural failures in structures which are used or occupied by the general public.*

The President's Office of Science and Technology Policy, acting upon a recommendation from the National Academies' National Research Council, requested CBT to initiate a design study for a National Earthquake Engineering Experimental Facility with exploration of research needs for the facility. The goal was to develop a world class, national user facility to provide the data and understanding necessary for rapid improvements in the design and construction of earthquake resistant structures. The study was funded by the Federal Emergency Management Agency and the National Science Foundation.

CBT worked with the Center for Manufacturing Engineering to explore with owners, designers, contractors and manufacturers the potential and research needs for robotics in construction [6]. Automated construction site metrology was seen as a higher priority than robotic equipment. The value of the metrology would be high for locating equipment and materials and documenting what actually was built, even if there were no automatic equipment to control.

The CBT plan for 1986-1990 addressed opportunities and challenges for international competitiveness that information technologies bring to the building community. Areas of work included:

1. Advanced measurements for building diagnostics and quality assurance.
2. Performance modeling and prediction technologies.
3. Automation of building operating systems
4. Robotics in construction.
5. Information interfaces for integrated computer-aided design, construction and operation.
6. Technologies for standards and expert systems.

The National Academies' Panel for Building Technology [7] agreed that the strategic direction was sound but was skeptical about the Center's ability to address artificial intelligence and computer-aided construction processes with available resources and did not want resources diverted from ongoing programs. The Center persisted in research on measurement and modeling bases for information technologies in construction, but had to limit its work in expert systems to exploring applications of technologies developed elsewhere.

Under the direction of Secretary of Commerce Herbert Hoover in the 1920s, NBS had undertaken the secretariats of important national voluntary standards to assist in their development and maintenance. One of these became American National Standards Institute Standard A.58.1 *Minimum Design Loads for Buildings and Other Structures*. However, NBS management now desired to focus its work on measurement technology, rather than standards administration. After 60 years at NBS, the secretariat of A.58.1 was transferred to the American Society of Civil Engineers (ASCE) in 1984. Bruce Ellingwood, who had served as the standard's secretary, and had received the ASCE's highest award, the Norman Medal, in 1983 for two papers that he co-authored on probability-based limit states design for the standard, left CBT in 1986 to become professor of civil engineering at The Johns Hopkins University.

Another effect of advancing information technologies was the elimination of the Center's word processing center in order to optimize deployment of clerical staff. It had been established to achieve the same objective in 1977. Increasing availability of personal computers made it possible for manuscript preparation to be handled principally by the researchers and clerical staff in the groups. The Structures Division eliminated its Geotechnical Group. With staff and funding attrition, it was infeasible to maintain this competence.

On a higher note, David Didion's research on mixed refrigerants showed achievement of a 15 percent increase in heat pump capacity at low temperatures which promised substantial energy savings by reducing needs for electrical resistance backup heating.

5.7 1986

Again the Administration proposed elimination of CBT and CFR in its budget request for fiscal year 1987, and again the building and fire communities strongly supported the continuation of the centers. Congress received testimony or letters supporting CBT and CFR from ASTM, American Institute of Steel Construction, American Society of Civil Engineers, National Conference of States on Building Codes and Standards, National Institute of Building Sciences, Portland Cement Association, National Society of Professional Engineers, and USG Corporation. Additional support for CBT was received by Congress from American Society of Plumbing Engineers Research Foundation, American Concrete Institute, Ayres Consulting, Carnegie Mellon University, Dow Chemical, ETL Testing Laboratories, Honeywell Corporation, Institute of Noise Control Engineering, Lighting Research and Education Fund Committee, Mineral Insulation Manufacturers Association, National Ready Mixed Concrete Association, National Roofing Contractors Association, New Jersey Institute of Technology, Ross Meriwether and Associates, and Ryland Group. Also, the Congressional Research Service of the Library of Congress prepared a report for the House Committee on Science and Technology [8] which concluded "Many of CBT's current functions appears to be consistent with the Administration's stated views on the proper role of the Federal government with respect to both the private sector and State and local government."

The outcome of the budget process, however, was different - a compromise. To end this cycle of proposed eliminations and restorations, the Congress and the President's Office of Management and Budget agreed that CBT's and CFR's funds for fiscal year 1987 each would be reduced by $500,000, and there would be no further cuts proposed for the remaining budgets (1988 and 1989) to be proposed by the Reagan Administration. The cuts occurred. However, the Administration subsequently reneged on the agreement and proceeded to propose additional reductions for fiscal years 1988 and 1989.

The consequences of the cuts included termination of research in acoustics and plumbing and substantial reductions of research in lighting.

The reductions in directly appropriated funding for 1987 were exacerbated by projected reductions in funding from the Department of Energy of 1 million to 1.5 million as energy conservation funding would be reduced about 40 percent and solar energy funding terminated. Therefore, a reduction in force of sixteen positions was decided upon at the end of fiscal year 1986. However, the National Appliance Energy Conservation Act of 1986 called for NBS to develop test procedures for determining the annual operating costs and energy consumption of eleven specified appliances. The Act assured continuity of funding from the Department of Energy for this work.

The Continuing Appropriations legislation for fiscal year 1987 called for NBS to conduct an independent investigation of the structural integrity of the new U.S. embassy office building in Moscow. The report, including an assessment of the existing structure and recommendations and cost estimates for correcting any structural flaws and construction defects, was required to be transmitted to Congress by April 15, 1987. Funding was provided by the Department of State.

At the request of Congressman Sherwood Boehlert, NBS, ENR (the principal weekly journal of the industries of construction), and SUNY-Utica College of Technology sponsored a Roundtable on Construction Technology for the 90s. It was the cover story in the August 4, 1986, ENR. Twenty-five participants, representing owners, designers, contractors, regulators, labor, manufacturers, educators and researchers, identified critical technical issues for the industries of construction:

- Information interface technologies supporting the automatic exchange of information between all participants in a construction project and conducive to open systems of computing hardware and software for the participants.
- Automated communications and control systems for constructed facilities (such as "smart houses" and "intelligent buildings") that are reliable, break down gracefully, and are open for partial upgrading and to innovations by small manufacturers.
- Low-risk test beds for innovations such as trials of novel materials and systems in the construction programs of federal agencies.
- Informing public policy makers, such as regulators, of the technical bases for sound public policy decisions.
- Learning from and applying to U.S. practices the accomplishments of foreign research and development.

The CBT program responded to all these issues.

CBT conducted the first full-scale laboratory test of a bridge column subjected to simulated seismic loading. The specimen, fabricated in accord with California State specifications, was 13.7 m tall and weighed more than 200 t. It resisted more than ten cycles of inelastic deformation exceeding six times the yield deformation, and showed how seismic resistant construction could be made more economical. Project leader William Stone and division chief Charles Culver made extraordinary efforts to conduct the test on a schedule convenient to a Congressional audience and the test received front page coverage in the Post.

The Interagency Committee on Seismic Safety in Construction (ICSSC), chaired by Richard Wright, developed the proposed executive order on seismic safety of federal and federally assisted construction, which was then approved by the Interagency Coordinating Committee of the National Earthquake Hazard Reduction Program and transmitted to the President's Office of Management and Budget. There it went through many cycles of review and was reduced in scope to new federal and federally assisted or regulated buildings, and was ready for issuance when the Loma Prieta earthquake in 1989 demonstrated its need to policy makers.

James Clifton and Lawrence Kaetzal produced CBT's first major expert system DURCON (durable concrete) in cooperation with the American Concrete Institute Committee on Durability of Concrete.

CBT, in cooperation with the Building Research Board of the National Research Council and the International Union of Bricklayers and United Craftsmen, hosted the CIB 1986 Triennial Congress. Over 500 researchers and practitioners shared research findings and addressed issues of advancing building technology: for the computer age, for shelter for the homeless in developing countries, and for translating research into practice. Richard Wright was president of CIB, Noel Raufaste led the organizing committee, and James Clifton chaired the program committee. Richard Wright also was elected president of the Liaison Committee of International Civil Engineering Organizations for 1985-87. Any joy in these recognitions of CBT's international leadership was squelched by the simultaneous reductions in loyal and productive staff required by CBT's budget cuts.

E.V. Leyendecker received the Silver Medal of the Department of Commerce for his technical support of the consensus development of Recommended Provisions for Seismic

Regulations for New Buildings by the Building Seismic Safety Commission.

5.8 1987

In its continuing attacks on appropriated funding for CBT and CFR, the Administration proposed for the fiscal year 1988 budget to merge the centers and fund the combined center at a level of $5 million. This would have been a fifty percent cut in directly appropriated funding. Community support for the centers remained strong and their funding was authorized and appropriated by Congress at the "compromise" level with allowance to receive adjustments to base (their pro rata share of appropriations intended to cover inflation). Moreover, the Department of Commerce refused to consider a proposal to increase CBT's funding for construction automation for fiscal year 1989 as inconsistent with Administration policy.

As a result of reductions in its funding for solar energy research, the Department of Energy (DOE) eliminated support of solar energy in buildings research in CBT. CBT had a strong record of success in solar energy research including test methods for solar thermal equipment, minimum property standards allowing federally insured mortgages on solar-equipped homes, and organization of and contributions to ASTM and ASHRAE standards programs for solar energy components and systems. However, the national laboratory managing the building solar program for the DOE gave its own work priority over CBT's.

When DOE was established in the 70s, NBS decided against undertaking program management for DOE because it would be a substantial diversion of effort from research. Was NBS wrong? Probably not. While CBT's research funding from DOE suffered from preferential funding of their own laboratories by program managers at national laboratories, program management would have been a severe distraction from the NBS mission and an NBS role in program management would have been difficult to maintain in competition with DOE national laboratories.

Because of the reductions in research for the Department of Energy, the Building Physics Division and the Building Equipment Division were combined to form the Building Environment Division under the leadership of James Hill. Hill superbly managed the necessary reductions in force to retain the most productive and promising research staff - for which he received the Presidential (of the U.S.) Meritorious Executive Rank Award in 1988. Tamami Kusuda retired as chief of the Building Physics Division to complete his career as the world's pioneer in computer methods for analysis of building thermal performance.

CBT's work on refrigerant mixtures proceeded very well. Laboratory studies demonstrated a 32 percent improved efficiency for a heat pump operating at steady state conditions in the cooling mode compared to a heat pump under the same conditions using R-22 as the working fluid. David Didion received the Gold Medal of the Department of Commerce and the Applied Research Award of NBS for these accomplishments. Moreover, work began on finding efficient substitutes for the refrigerants harmful to the ozone layer. In Indoor Air Quality, CBT developed and verified a model to predict indoor contaminant levels as functions of emission, dilution and intra-building air movement (the first model not to consider a building as one, large, uniform space).

Under the leadership of Nicholas Carino, CBT completed its study of the structural integrity of the new U.S. embassy office building in Moscow, by the Congressionally imposed deadline of April 15, 1987, and for about half of the funding allowed by Congress. The investigation identified important structural defects and defined remedial measures to correct them. While important, these structural defects were modest in scale and fully correctable. There were no perceptible disagreements with these recommendations; in the 90s the building was repaired (with the upper stories, where information security concerns were greatest, removed and replaced) and put into service. Carino received the Silver Medal of the Department of

Commerce for his leadership of this investigation.

For the Occupational Safety and Health Administration (OSHA) and under the leadership of Charles Culver, CBT investigated the physical causes of the collapse of the L'Ambience Plaza apartment building in Bridgeport, Connecticut on April 23, 1987, which killed 28 construction workers. In contrast to earlier CBT structural failure investigations, there was substantial professional controversy about the CBT findings, but they stood up well over several years of discussions in professional conferences and papers. OSHA was pleased with the results and subsequently hired Culver to lead its new Office of Construction Safety.

This was the last of CBT's investigations of construction failures for OSHA. Under Culver's leadership, OSHA conducted its own investigations. These investigations were high risk for NBS. Reports were due for release six months after the accident to be a basis for OSHA's legal actions. Could a sound determination of the physical cause always be so quickly accomplished? CBT succeeded for the Skyline Plaza Tower and Parking Garage in 1973, the Willow Island Cooling Tower in 1978, the Harbour Cay Condominium in 1981, the Riley Road Interchange Ramp in 1982 and the L'Ambience Plaza Apartment in 1987, and probably would have continued if requested and given proper authority and funding for thorough investigations. The investigations were important public service, a valuable professional experience for staff and a distraction from CBT's research mission.

Mary McKnight, Jonathan Martin, Edward Embree and Dale Bentz won an IR-100 Award for their surface profilometer which uses infrared emissions to measure surface topography. Robert Mathey and James Clifton won the Lindau Award of the American Concrete Institute for their research on epoxy coated reinforcing bars to improve the service lives of concrete slabs exposed to deicing salts. This work was the basis for the development of the epoxy coated reinforcing industry.

5.9 1988

In its request to Congress for the fiscal year 1989 budget for CBT and CFR, the Administration proposed again to merge the centers and fund the combined center at a level of $5 million. Again, the centers received strong support from the building and fire communities, and their funding was restored. The budget environment for CBT remained such that no request for increased funding for fiscal year 1990 was submitted by NBS to the Department of Commerce.

However, a budget initiative increase of $250,000 for fiscal year 1989 was appropriated for research on replacements for the refrigerants that threaten the ozone layer. This increase was accomplished by budgeting the program in the for Chemical Engineering, which received an equal increase, even though the initiative was led by David Didion and based on his pioneer work in CBT. Chemical Engineering studied the thermo-physical properties of alternative refrigerants and Building Technology studied their performance in the refrigeration cycle.

This was the first initiative increase in appropriated funds (beyond adjustments to base for inflation) received by CBT since the fiscal year 1974 initiative of $400,000 for energy conservation. However, a doubling of both directly appropriated and other agency funding would have been required to return CBT to its level of effort in fiscal year 1980. CBT since 1974 annually had developed initiative proposals to respond to needs of the building community. Among the topics were technologies (measurements and test methods) for: earthquake hazard reduction, building rehabilitation, construction productivity, quality assurance and condition assessment, and computer integrated construction. These did not attract support of NBS management, in spite of industry demands and the importance of the industries of construction in the Nation's economy, CBT's national and international technical leadership, Administration initiatives and potential for Congressional support, seemingly because NBS management preferred to try for growth in other areas and disciplines.

The National Science Foundation established in February 1988, the Center for Advanced Cement-Based

Materials at Northwestern University. NBS, University of Illinois at Urbana-Champaign, University of Michigan and Purdue University were the other member institutions. NBS's participation in the planning and conduct of the Center was led by Geoffrey Frohnsdorff and James Clifton. The Center's thrust to make concrete a well characterized material of predictable performance was based substantially on the accomplishments of NBS's Cement Hydration Competence Project. The Center's long- term, fundamentally-oriented research allowed NBS and collaborators to make great contributions over the following 11 years.

NBS became the National Institute of Standards and Technology (NIST) on August 23, 1988, when the Omnibus Trade and Competitiveness Act of 1988 became effective. The Act provided for continuity of NBS functions, such as building and fire research, and added the Advanced Technology Program (ATP) to cost share high risk research with industry, and the Manufacturing Extension Partnership (MEP) to assist small and medium sized manufacturing companies. CBT staff were proud of being part of NBS and many were uncomfortable with the change in name, but both the ATP and MEP were seen as opportunities to collaborate effectively with the industries of construction. In later years, many companies developed ATP projects with which CBT collaborated. However, the MEP did not extend its scope to consider construction contractors and builders as manufacturers even though the National Association of Home Builders, and other construction organizations, expressed interests in participating in MEP.

Through its participation in and leadership of CIB (Richard Wright was its past president and Programme Committee chairman) CBT became aware of the importance of the Single European Act calling for the free flow of goods and services within the European Community (EC) by 1992. At CIB's May 1988 Research Managers' Meeting, European members organized the European Network of Building Research Institutes (ENBRI) to participate in programs for standards, regulation, certification and testing which will make products and services acceptable in all the EC countries. These activities were anticipated to have substantial effects on U.S. industries of construction since the European standards could be barriers to the export of U.S. products and services, and since European firms working successfully in the larger European market would be better prepared to compete in the U.S. market.

In its update for 1989-1993 of its Long Range Plan, CBT organized its program by three focuses:

1. Quality Assurance and Condition Assessment technologies to improve U.S. competitiveness.
2. Computer-Integrated Construction technologies for the long range technical leadership and competitiveness of the U.S. industries of construction.
3. Earthquake Hazard Reduction. The first comprised almost 90 percent of the current level of effort. The latter two were developed separately because of high demand for program growth in these areas.

David Didion and Mark McLinden published *Quest for Alternatives: A Molecular Approach Demonstrates Tradeoffs and Alternatives are Inevitable in Seeking Refrigerants* in the December 1987 ASHRAE Journal, which described the systematic, CBT-developed approach to obtaining energy-efficient alternatives to environmentally-harmful refrigerants. The paper received ASHRAE's best paper award and the 1988 NIST Condon Award for expository excellence.

The Initial Graphics Exchange Specification (IGES) Version 4.0 standard was published with a new capability for exchanging tabular and relational data in addition to graphical data. The capability was developed and championed by the IGES Architectural, Engineering, and Construction Committee chaired by Kent Reed of CBT.

Emil Simiu was awarded by the NBS Director a competence project on chaotic structural dynamics to be conducted jointly by CBT and the Center for Computing and Applied Mathematics. Avoidance of chaotic response is important for deep-water compliant structures, flexible space structures and robot arms, and other non-linear systems. Simiu also was appointed an NBS fellow based on his national and international leadership in wind engineering and structural dynamics.

Richard Wright was named Federal Engineer of the Year 1988 by the National Society of Professional Engineers (NSPE). NSPE cited CBT accomplishments in structural failure investigations, improvements of the refrigeration cycle and leadership in international building research organizations. Wright also received the President's Meritorious Executive Award for leadership of CBT. James Hill also received the President's Meritorious Executive Award for achieving outstanding accomplishments in the Building Environment Division at the same time that it was being substantially cut in staff. It seems remarkable that the President, who sought to eliminate CBT, also would recognize its managers for outstanding performance.

5.10 1989

The Administration's request to Congress for the fiscal year 1990 budget, the last prepared by the Reagan Administration, proposed again to merge CBT and CFR and fund the combined center at a level of $5 million. The proposal also called for termination of the $250,000 funding for alternative refrigerants. Congress again restored the funding for the fiscal year 1990 budget. Also, CBT and CFR directors discussed the programs with the new Bush Administration officials in the Department of Commerce and the Office of Management and Budget with the result that the cuts no longer were proposed for the fiscal year 1991 budget.

The 1989 Panel for Building Technology of the Board on Assessment of NIST Programs, in December 1988, suggested that CBT prepare a report on the international competitiveness of the U.S. construction industry. The report [9] was published in May 1989, and used to focus the CBT program and guide collaborations with other organizations. It was presented to: the Sixth International Symposium on Automation and Robotics in Construction (sponsored by the Construction Industry Institute), the Building Research Board of the National Academies, and the Hearing on R&D in Construction of the House Subcommittee on Science, Research and Technology. It recommended that the U.S. industries of construction work for open systems of technology for construction products and services to facilitate innovations. CBT's role would be to provide measurement and test methods for assurance of quality and acceptance of innovations.

The Building Seismic Safety Council (BSSC), since it was organized in 1979, had worked to review the Tentative Provisions for the Development of Seismic Regulations for Buildings published by the Applied Technology Council, NSF and NBS in 1978, revise provisions appropriately, and conduct trial designs to test their usability, cost impact and technical validity. As a result of these studies, BSSC published the *National Earthquake Hazards Reduction Program Recommended Provisions for the Development of Seismic Regulations for New Buildings* (Recommended Provisions) in 1985, and with further studies published an updated version in 1988. When he became a member of the BSSC Board in 1989, Richard Wright noted that there were no ongoing efforts to incorporate the Recommended Provisions in the national standards and model codes even though these organizations were represented on the Board and were involved in the development of the Recommended Provisions. The BSSC and the Federal Emergency Management Agency (FEMA), which had sponsored the BSSC work, agreed that such efforts were appropriate. NBS, with FEMA's approval, reprogrammed funding it had received from FEMA for other technical studies to prepare proposed changes to the American Society of Civil Engineers' standard for design loads on buildings and to the Basic Building Code. These proposals were available when severe losses in the October 17, 1989, Loma Prieta California earthquake produced enhanced national concern for seismic safety and led to timely revisions in the ASCE standard and in the Basic Building Code used in the eastern U.S. and the Standard Building Code used in the southeastern U.S. The Uniform Building Code used in the western U.S., although it used a working stress approach different from that of the Recommended Provisions, also benefited from the BSSC studies in its revisions.

Reorganization of NIST was anticipated from the time of its creation in 1988, but the NIST Visiting Committee recommended that reorganization await the appointment of a new NIST director (Ernest Ambler had become acting Under Secretary for Technology in December 1988 and retired from government service in April 1989.) CBT and CFR management anticipated that their merger would occur and held joint meetings in fiscal year 1989 to gain mutual familiarity with their programs.

In the decade since its founding, the CBT Building Controls program had developed dynamic control system simulation techniques and measurement and test methods for sensors and for control algorithms to support open, intelligent, integrated and optimized building mechanical systems that give customers the reliability and economy resulting from independence from a single manufacturer. In 1989 to advance this work, Steven Bushby became secretary for ASHRAE Standard Project Committee 135 on Energy Monitoring Control System Message Protocol and chairman of its Application Sources Working Group which led in time to national and international open systems standards for building automation.

Under the leadership of CBT deputy director James Gross, CBT began work with U.S. standards organizations and industry to open global markets to U.S. construction products and services by: (1) developing an active U.S. advocacy role in international standards activities, (2) establishing a coherent system for acceptance of innovative building products, and (3) improvement of the acceptance and quality assurance of products for which there are applicable international standards. To advance these objectives, Gross led a task force of the ANSI Construction Standards Board to plan its future functions and activities, led development of a five year plan for ASCE's Codes and Standards program, participated in a delegation of the Department of Commerce to discuss testing, certification and conformity assessment with the EC Commission, and served on the CIB Board and Programme Committee.

RILEM (the International Union of Testing and Research Laboratories for Materials and Structures) adopted as a technical recommendation for international standardization the Standard Practice for Developing Accelerated Tests to Aid Prediction of the Service Life of Building Components and Materials. The document was based on CBT research and Larry Masters of CBT led the ASTM and RILEM committees that developed the ASTM standard and the RILEM technical recommendation.

Nicholas Carino and Mary Sansalone developed the impact echo method for flaw detection in reinforced concrete structures which was independently assessed as having demonstrated applicability to flaw detection in thick and layered structures and the best potential for field use.

Hai Sang Lew, chief, Structures Division and leader of numerous post earthquake investigations.

George Walton completed AIRNET, a computer simulation model for airflows between rooms and through the envelope of a building. It was cited at an international air infiltration workshop as "the world's best and fastest ventilation model with a well-defined open structure suitable for widespread use."

H.S. Lew participated in the U.S. team studying structural performance of buildings in the December 1988 Armenian earthquake. The earthquake was particularly interesting for U.S. practice because of the exposure of modern pre-cast concrete buildings to strong shaking. Findings were reported to Congress and regional conferences on seismic safety and published by the Earthquake Engineering Research Institute. Dr. Lew, who had twenty-years experience at NIST as structural research engineer and group leader, became Chief of the Structures Division in December 1988 when Charles Culver transferred to OSHA to lead its Office of Construction.

Emil Simiu received the Gold Medal of the Department of Commerce for his studies of wind and wave effects on off shore structures - knowledge essential to oil recovery from deep water sites.

5.11 1990

The Loma Prieta, California earthquake of October 17, 1989, (sometimes called the World Series earthquake because it interrupted the start of a game at San Francisco and showed fans a real time view of the fires in San Francisco), had great effects on the National Earthquake Hazards Reduction Program (NEHRP) and NIST's work in NEHRP. The ICSSC (chaired by Richard Wright and with a NIST secretariat) immediately dispatched a multi-agency team led by H.S. Lew to investigate damages to structures and fires. The report made substantive recommendations to improve design and construction practices for buildings and lifeline structures and to mitigate damages to existing structures in future earthquakes.

On January 5, 1990, President Bush issued Executive Order 12699, Seismic Safety of Federal and Federally Assisted or Regulated New Building Construction, that NIST drafted and redrafted through reviews and approval by the ICSSC from 1984-86, and by the Federal Emergency Management Agency (FEMA), the White House and the federal agencies from 1986-90. The Order required that all new buildings constructed or lease-constructed for federal use must immediately be designed and constructed in accord with appropriate seismic standards. By January 5, 1993, similar requirements applied to all federally supported or regulated new building construction, e.g., homes financed with FHA or VA mortgages. Building code organizations welcomed the Order. The work to develop the NEHRP Recommended Provisions for the Development of Seismic Regulations for New Buildings, test them in trial designs, and translate them to standards and code language made the Order feasible, and its existence provided an incentive to State and local governments to adopt and enforce up to date building codes. The sustained financial and political support of FEMA deserves primary credit for the development of the Recommended Provisions and the Order. NIST provided sustained technical support and research, the National Science Foundation provided the principal structural research support over many years for the knowledge base, and the U.S. Geological Survey (USGS)provided the knowledge base for definition of the earthquake hazard. The Order marked a real success story for NEHRP.

In October 1989, Congress made a supplemental appropriation to support NEHRP studies of the earthquake. NIST received $2 million available over two years which it used to hire excellent additional staff, including Albert Lin, Harry Shenton and Diana Todd, and strengthen its research program. However, it was not possible to convert this to an increase in base funding and the financing of the program became difficult in fiscal year 1993.

The enhanced earthquake interests led to some tensions in NEHRP. There was an effort to replace FEMA with USGS as lead agency, in which NIST did not get involved, and which failed in Congress because of FEMA's strong support by State and local governments.

With John Lyons' strong interest in NEHRP, NIST endeavored to gain the lead role in support of the development of seismic safety standards and practices, which had been intended for NBS in the NEHRP authorizing legislation, but had been assumed by FEMA when NBS declined to request funding for the role. FEMA wished to keep its role in support of development of building standards and practices because its successes were much appreciated in the private and public sectors and within FEMA. Moreover, the seismic standards and practices community did not support transfer of this role to NIST because it had good working relations with FEMA, was grateful to FEMA for its sustained support over ten years, and had no reason to believe that NIST would provide better support or management. The outcome was that FEMA maintained its role in building standards and practices with technical support from NIST and others, and that NIST assumed responsibility for development, with the community, of seismic safety standards and practices for lifelines (public works and utilities). This and the special funding for investigations of the Loma Prieta earthquake gave CBT hope for a strengthened role in NEHRP. However, over the next several years, NIST was unable to obtain directly appropriated funding for development of seismic safety standards and practices for lifelines and asked that FEMA assume this role, too.

In cooperation with ENR magazine and the National Institute of Building Sciences on February 27, 1990, CBT co-sponsored the "Roundtable on International Harmonization of Construction Standards and Practices - Assets or Liabilities for Competitiveness" to define private and public sector activities needed for competitiveness of the industries of construction. It was the basis for a feature article "Standards for a Global Market" in the April 19, 1990 *ENR*. CBT also organized and chaired at the Structures Congress of the ASCE a plenary session and a technical session "Prospects for International Engineering Practice." Topics included: Structural Engineering in the European Community, International Harmonization of Standards, Evolution of the U.S. building regulatory system, and International Recognition of Professional Engineering Credentials. CBT also participated in the Japanese Technology Evaluation Center's study of Construction Technologies in Japan which assessed the relative effectiveness of Japanese and U.S. construction research and technology transfer [10].

Edward Garboczi and Dale Bentz published Analytical and Numerical Models of Transport in Porous Cementitious Materials which represent rate controlling processes including diffusion, convection, reaction and sorption involved in corrosion of reinforcement, sulfate attack, acid attack and leaching.

William Thomas and Douglas Burch completed experiments to determine for important building materials the moisture transfer properties that are critical to build up of moisture in and consequent degradation of building envelopes. This became the basis for the MOIST computer program - a practical means for assessing the vulnerability of building envelope designs to moisture.

James Hill was elected to the ASHRAE Board of Directors. Lorraine Freeman retired after serving as the CBT director's secretary since 1977. Gail Crum succeeded to the position and took charge rapidly and effectively based on her experience as James Wright's secretary in the Building Research Division, CBT, the Institute for Applied Technology, and the National Engineering Laboratory.

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6. BUILDING AND FIRE RESEARCH LABORATORY IN THE 90s

6.1 Overview

Fiscal year 1991 began auspiciously with fire research expert (and building research supporter) John Lyons the new NIST director, the Administration efforts to eliminate building and fire research ended, and a new Building and Fire Research Laboratory (BFRL) organized at NIST by merger of the Centers for Fire Research and Building Technology.

Jack Snell, deputy director of BFRL and former director of CFR, described the new organization as "half of a laboratory" in comparison with the size and funding of the other new NIST laboratories. BFRL management was resolved to correct this situation by working with leaders of the fire and building communities to produce and implement such excellent results, and define such national needs and plans to respond to them, that BFRL would attract the resources required to provide the needed performance prediction methods, measurement technologies, and technical advances. BFRL management also was resolved to correct its own "bunker mentality" and that of the staff created by seven years of Administration proposals for elimination or halving of the programs, and to attract the excellent new staff needed for technical leadership in the 90s and in the 21st century.

This chapter describes significant accomplishments and substantial disappointments. New directly appropriated funding was received: in 1992 for fire research and for earthquake engineering, in 1993 for green buildings, and in 1994 for high performance materials research. The White House gave priority to construction and building research in 1994 and CBT provided leadership for the multi-agency coordinated program. These and the efforts and ingenuity of staff led to many significant, high-impact research results. However, the Congressional elections of 1994 created a divided government that was unable to focus its attention on needs for and benefits of building and fire research. In 1991 there were 195 total staff, this rose 20 percent to reach 216 in 1995, but declined again to 186 in 2000. To increase effectiveness with such constrained resources, BFRL focused most of its resources on six major products beginning in fiscal year 1998, but continued to give attention to selected other topics likely to become the major products of the 21st century.

A series of annual and biannual reports provide a good summary of activities and references for this period [1-6].

6.2 1991

The Building and Fire Research Laboratory (BFRL) began operationally on October 1, 1990, and was established formally on January 31, 1991. Its mission was “increasing the usefulness, safety and economy of constructed facilities and reducing the human and economic costs of unwanted fires.” It performed and supported “field, laboratory and analytical research on the performance of construction materials, components, systems and practices, and the fundamental processes underlying the ignition, propagation and suppression of fires.” It produced “ technologies to predict, measure and test the performance of construction and fire prevention and control products and practices.” The organization was:

Headquarters: Richard Wright, director; Jack Snell, deputy director; James Gross, assistant director; and Kathryn Stewart, executive officer.
Structures Division: H.S. Lew, chief
Building Materials Division: Geoffrey Frohnsdorff, chief
Building Environment Division: James Hill, chief
Fire Science and Engineering Division: Andrew Fowell, chief
Fire Measurement and Research Division: Richard Gann, chief

Andrew Fowell had been deputy director of CFR and was reassigned as division chief to replace James Quintiere who had moved to the University of Maryland in 1990. The persons named above comprised the Management Council of BFRL.

The BFRL program was comprised of three major thrusts, each involving multiple divisions, with subelements as noted below:

Fire Research

1. Fire risk and hazard prediction
2. Fire safety of products and materials
3. Advanced technologies for fire and fire risk sensing and control

Earthquake Hazard Reduction

Construction Industry Competitiveness

1. Construction materials
   a. Service life prediction
   b. Advanced organic materials
   c. High performance concrete
   d. Quality assurance of construction materials testing laboratories
2. Structural Evaluation
   a. Condition assessment
   b. Structural response control
   c. Failure investigations
3. Building performance
   a. Alternative refrigerants
   b. Building controls
   c. Building envelope
   d. Computer-integrated construction
   e. Indoor air quality
   f. Lighting
   g. Test procedures for major energy appliances

The Building Program, comprised of Earthquake Hazard Reduction and Construction Industry Competitiveness, and the Fire Program essentially were continuations of the work of CBT and CFR.

The Principles and Values of BFRL, as discussed with the staff on August 3, 1990, were:

1. **Building and Fire Research programs continue.**
2. **Excellent public service.**
3. **Technical excellence in R&D and Technology Transfer**
4. **Advance fire and building science.**
5. **Responsive to mandates and public policies**
6. **Responsive and close to user communities**
7. **Build a new organization and develop esprit de corps**
8. **Open, candid, interactive, enthusiastic and productive people; teamwork and delight in our work.**
9. **Good environment for career development of staff**
10. **Simple, responsive, efficient organizational structure.**

There were cultural differences. Fire staff commonly lunched together combining divisions and groups; building staff did not. Weekly Fire seminars shared current research with the whole Fire staff; building staff would not voluntarily participate in seminars beyond group interests. An open house was held to give staff opportunities to see all the work of the laboratory and meet each other. Management and staff worked hard to make the laboratory seen as a merger, not an acquisition. Jack Snell took on double duties to make the laboratory succeed: he served as deputy director for the whole laboratory and continued as manager of the Fire Program. The Management Council assigned its members responsibility for developing "big chunks" of funding (multi-year programs of $1 million or more total funding, directly appropriated or funded by other agencies or the private sector) in contrast to the roughly $100 thousand per year projects that were best negotiated by group leaders or senior researchers and tended to diffuse BFRL's focus.

BFRL reached out to its community to gain ideas for, understanding of, and collaborators in its work.

- A three day workshop, involving 27 state fire marshals or chief deputies, was conducted with the National Association of State Fire Marshals to identify 15 project areas where BFRL research was needed to address critical issues affecting the Nation's fire service.
- A workshop of the International Council for Research and Innovation in Building and Construction (CIB) was hosted on fire model verification, selection and acceptance for fire safety engineering practice.
- The newly created Civil Engineering Research Foundation organized and held, with BFRL support and participation, the Civil Engineering Research Needs Forum, January 28-30, 1991. It attracted community leaders, including the chief engineers of the Army, Navy, and Air Force on the eve of the Kuwait war, and produced recommendations for national programs in high performance concrete and steel, national and international acceptance of innovative products and services, and integrated, computer-aided engineering design and construction.
- The report on Construction Technologies in Japan by the Japanese Technology Evaluation Center showed that the much greater Japanese investments in R&D for construction had given them leadership in high performance construction materials and in construction robotics.

Barbara Levin, Vytenis Babrauskas, and colleagues completed a comprehensive methodology, with minimal dependence on animal testing, for obtaining and using smoke toxicity data for fire hazard analysis. It built on two decades of research and national and international collaborations with the National Institute of Building Sciences, the Southwest Research Institute and others, and became the basis for standards of NFPA, ASTM and ISO.

William Danner and Mark Palmer developed the application protocol technique for the STEP (Standard for Exchange of Product Model Data) international standard effort. The application protocol provides a complete and unambiguous characterization of the data to be exchanged. The richness of construction data required this technique and it is used internationally for data for all types of products.

Takashi Kashiwagi received the Applied Research Award of NIST for his pioneering studies of the thermal degradation of PMMA, and the Silver Medal of the Department of Commerce for the rational characterization of the phenomenon of flame spread on materials.

6.3 1992

Congress appropriated an increase of $409,000 for earthquake engineering in 1992, the NIST director transferred an additional $200,000 for fire research, and earlier funding of $250,000 for alternative refrigerants and $250,000 for furniture flammability were made part of the BFRL base funding. Moreover, the President requested funding increases for 1993 of $1 million for earthquake engineering and $300,000 for computer integrated construction, but proposed cutting BFRL by $350,000 for administrative savings from the reorganization.

BFRL's strategic plan of November 1, 1991, maintained the program thrusts described for 1991, but augmented the BFRL mission:

- Increase the usefulness, safety and economy of constructed facilities.
- Improve the productivity and international competitiveness of the construction industry.
- Reduce the human and economic costs of unwanted fires.

Fire research divisions and groups were reorganized to distinguish their roles:

- Fire Safety Engineering Division, Andrew Fowell, chief, had groups:
    - Fire Protection Applications, Richard Bukowski, leader
    - Fire Modeling, Walter Jones, leader
    - Large Fire Research, David Evans, leader
- Fire Science Division, Richard Gann, leader, had groups:
    - Smoke Dynamics Research, George Mulholland, leader
    - Materials Fire Research, Takashi Kashiwagi, leader
    - Fire Sensing and Extinguishment, William Grosshandler, leader

Unfortunately, the very promising collaborations with the National Association of State Fire Marshals came to a halt. Subsequently, a journalist [7] attributed this to the Association's close links to the tobacco industry that opposed BFRL's research on cigarette ignition propensity.

Richard Gann led the development of a multi-million dollar, multi-year program with Air Force funding to develop replacements for the halogenated fire suppressants that will provide safety in aircraft and buildings while avoiding damage to the environment. The program built upon the experiences of BFRL and the Center for Chemical Sciences and Technology in developing energy efficient replacements for refrigerants that threatened the ozone layer.

In a series of laboratory and mesoscale experiments, David Evans and his colleagues demonstrated for the Minerals Management Service and the Environmental Protection Agency that burning is a rapid and cost effective method of removing oil spills from the surface of water. Howard Baum and his colleagues developed a large eddy simulation computer model to understand the dynamics of smoke plume motion and smoke particle deposition.

Geoffrey Frohnsdorff led the private sector planning group for the Civil Engineering Research Foundation and provided the secretariat for the multi-agency Infrastructure-Construction Task Group of the President's Office of Science and Technology Policy that prepared the 10 year, $2 billion to $4 billion, High Performance Construction Materials and Systems program for private and public sector initiatives.

James Gross, working with U.S. standards organizations, and representing the American National Standards Institute in the management of construction standards for the International Organization for Standardization (ISO), arranged for U.S. leadership of ISO standards committees for Building Performance, Concrete, Timber, Masonry, Structural Design Loads, and Building Environmental Design. Leadership opportunities were available because European interests were focused on European standards. U.S. involvement was important to assure that good, up to date, ISO standards existed when European standards were completed, without U.S involvement, and proposed for adoption by ISO.

BFRL was hurt and saddened by the untimely death of Albert Lin. In his two years with BFRL, he initiated an important and successful program for performance criteria and test methods for seismically base-isolated structures, and achieved professional recognition as coordinator of CIB Working

Commission 73, Natural Disasters Reduction, and as editor of the newsletter of the Earthquake Engineering Research Institute.

John Klote won the 1992 Best Paper Award from ASHRAE for Design of Elevator Smoke Control Systems for Fire Evacuation with his coauthor George Tamura of the National Research Council of Canada, and also received the honor of ASHRAE Fellow. Vytenis Babrauskas received the NIST Rosa Award for developing and standardizing new techniques for measuring the fire properties of materials. Edward Garboczi received the L'Hermite Medal from the International Union of Research and Testing Laboratories for Materials and Structures (RILEM) for his contributions to the understanding of concrete and other random structures through the simulation of porous microstructures and of transport phenomena. Kermit Smyth received the Silver Medal of the Department of Commerce for pioneering measurements of the chemical structure of flames. James Hill was elected Vice President of ASHRAE.

6.4 1993

Section 104(g) of the American Technology Preeminence Act of 1992 (PL 102-245, February 14, 1992 stated:

> *The fire research and building technology programs of the Institute may be combined for administrative purposes, only, and separate accounts for fire research and building technology shall be maintained.*
>
> *No later than December 31, 1992, the Secretary, acting through the director of the Institute, shall report to Congress on the results of the combination, on efforts to preserve the integrity of the fire research and building technology programs, on procedures for receiving advice on fire and earthquake research priorities from constituencies concerned with public safety, and on the relation between the combined program at the Institute and the United States Fire Administration.*

The report to Congress dated December 9, 1992 responded to each of the points cited in the Law. The Report summary stated:

> *The combination of the building technology and the fire research programs has brought both of these programs closer to the Director of NIST, thereby increasing their internal visibility. The increased scale of the Laboratory relative to either of the original centers has created the opportunity for BFRL to conduct outreach activities that neither of the Centers could afford previously. The combination has opened the possibility for a number of important synergistic programs of benefit to both of the communities served, and effected a modest administrative savings that has been used to increase technical activities. It is the desire and intent of all concerned within NIST to continue the development of the Building and Fire Research Laboratory.*

The advent of the Clinton Administration in January 1993 brought promise of doubling NIST's budget and an unprecedented political change in NIST's leadership. John Lyons was made Acting Undersecretary of Commerce for Technology, with the understanding that he would not be reappointed as NIST director. This was the first time that an NBS or NIST director had been replaced by an incoming administration, but was expected to become a precedent for the future. When the new Undersecretary, Mary Good, was confirmed, Lyons became a senior scientist at NIST until he was appointed director of the new Army Research Laboratory in late 1993. BFRL appreciated and would miss his understanding, leadership and support. To make a place for a political appointee at the National Oceanic and Atmospheric Administration, Ray Kammer was reassigned to NIST as deputy director and acting director. Samuel Kramer was reassigned as assistant director. Arati Prabhakar from the Defense Advanced Research Projects Agency became NIST director on May 28, 1993; she was NIST's youngest and first female director. Prabhakar, who had worked in microelectronics, was open minded and decisive on BFRL issues. As she became familiar with BFRL's program, she expressed a clear preference for programs supporting economic growth over those responding to legislative mandates such as fire safety and earthquake hazard reduction.

The President's requests for increases in appropriations for BFRL for 1993 were not funded by Congress, but Congress did provide an increase of $800,000 for green building technology (half of which was earmarked for

Iowa State University) and NIST reprogrammed $400,000 to the earthquake program and $200,000 to alternative refrigerants.

William Allen continued to advise BFRL with renewed enthusiasm for the potential of the new laboratory. Among his major points were:

1. BFRL must be close to and valued by customers, not just intermediary standards organizations or the Washington representatives (lobbyists) of companies, but leading architects, engineers, contractors, regulators and the executives of manufacturers.
2. To merit the attention of customers, BFRL must produce valuable products that respond to their problems or give them new opportunities. Our job is not done until our products are in beneficial use. We must participate in the implementation or our efforts may be wasted. Also, is not measurements and standards too limiting for the scope of BFRL products?
3. To define these products, assure their production and achieve their acceptance, BFRL must have senior staff that understand the customers needs and capabilities - people like William Allen - to assure us we are doing the right job as well as doing the job right. Generally, these will not be researchers, but they should be understanding of research and work well with researchers. (They can be researchers, David Didion, for instance, was close to leaders of equipment manufacturers to understand and respond to their needs.) Senior architects are particularly vital to BFRL's mission and customers.
4. BFRL's strategic vision must express its vital and credible role in a manner inspiring to both customers and staff. The understanding and enthusiasm of customers, and BFRL managers and researchers can get us great assignments and great results.

BFRL tested these ideas with leaders of the industry by convening an ad hoc working group on May 5-6, 1993. The participants were: Kenneth Reinschmidt, Vice President, Stone and Webster Engineering Constructors; Dean Stephan, President, Pankow Construction; Jerome Sincoff, President, HOK Architects; Steven Mitchell, Chairman, Lester B. Knight Engineering; Michael Martin, Manager, Consumer and Construction, GE Plastics; Steven Bomba, Vice President, Johnson Controls; James Nottke, Director, Technology Acquisition, Dupont; J. Roger Glunt, Glunt Building Company and President, National Association of Home Builders; Miles Haber, Monument Construction; Gerald Jones, Director of Codes Administration, Kansas City, MO; and Thomas Castino, President, Underwriters Laboratories. Their advice was:

1. Change the name to Building Systems Laboratory
2. Focus on the life cycle construction process and integration of its steps.
3. Emphasize existing buildings.
4. Become the national focal point for a database of critical information (for the life cycle construction process).
5. Relate directly to customers, intermediaries are inadequate.
6. Continue valued work on measurement and test methods and data.
7. Get a champion in Congress.

BFRL has acted on these recommendations with three exceptions. The name change was seen as undesirably inhospitable to the fire community, data is increasingly decentralized with Internet and BFRL has not seen a way to take overall responsibility and gain credit for accessibility and quality, and BFRL has yet to find a champion in Congress.

A major concern to BFRL and to the Panel for Building and Fire Research was the degradation of a number of BFRL's important research laboratories. Major problems existed in: the environmental controls and instrumentation for the large fire test facility; the operability of the large environmental chambers for research on heating, ventilating and air-conditioning systems; and the controls and hydraulics of the 53 MN universal structural testing machine. NIST laboratories in general were aging and in need of renovation, but BFRL facilities were not included in NIST renovation plans for the 20th century.

Richard Marshall studied the very limited wind measurements and very extensive wind damages in Hurricane Andrew of August 24, 1992, and produced recommendations for improving the wind load provisions of the Manufactured Home Construction and Safety Standard (MHCSS) to reduce wind damages to manufactured (mobile) homes. These resulted in MHCSS adopting ASCE Standard 7-88, Minimum Design Loads for Buildings and Other Structures, and in improvements to the ASCE standard.

Geraldine Cheok, William Stone, and H.S. Lew, in cooperation with Pankow Construction, completed experimental studies of hybrid, pre-cast, reinforced concrete beam to column connections for regions of high seismicity. Design recommendations were formulated and presented to the American Concrete Institute and to the Structural Engineers Association of California. By the end of the decade these became the basis for construction of the tallest reinforced concrete buildings ever built in California.

Lawrence Kaetzel and James Clifton developed HWYCON, an expert system on the durability of concrete for highways, to implement the results of NIST research and the Federal Highway Administration's Strategic Highway Research Program. Over 2,000 copies were distributed to and used by state and local highway departments.

George Walton completed CONTAM93, a multizone airflow and contaminant dispersal model with a graphical user interface to assist designers and researchers understand the effects of materials choices and heating, ventilating and air-conditioning systems design and performance on indoor air quality and radon transport.

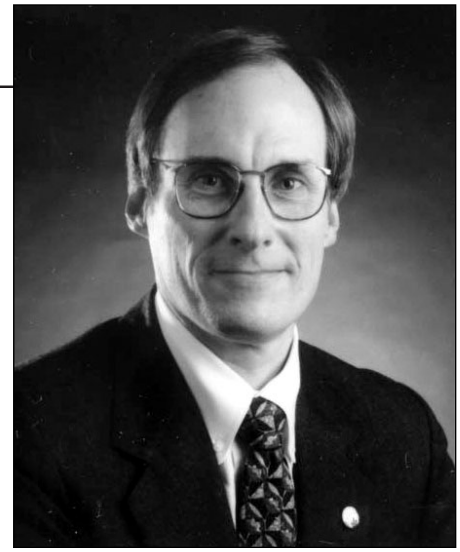
Nora Jason and colleagues implemented on Internet FIREDOC, the automated database of BFRL's Fire Research Information Services (FRIS), to greatly enhance access for fire protection engineers and researchers worldwide.

Mark Nyden and James Brown described how computer-aided molecular design can be used to achieve a new generation of fire resistant polymers. Cross linking can improve functional mechanical properties and promote formulation of heat resistant chars which reduce heat release rates during unwanted combustion.

6.5 1994

This was a euphoric year for NIST and BFRL. The perspective was given in Director Prabhakar's letter of January 19, 1994, to the National Research Council's Panel on Building and Fire Research:

> *As you know, President Clinton has proposed to increase the budget for the NIST laboratories from $193 million in 1993 to more than $430 million in 1997. This is a significant challenge for NIST. It gives us a chance to take control of our own future as we move away from dependence on other agency funding. Our general strategy is to offset some other agency funding with STRS funds and to increase staff by roughly 10 percent. We are also considering strategies for greater extramural collaboration with selected organizations.*



David Evans, chief, Fire Safety Engineering Division.

NIST also was receiving large increases in funding for the Advanced Technology Program (ATP) which cost-shared high risk industry research, and the Manufacturing Extension Partnership (MEP) which cost-shared technology transfer centers nationwide serving small and medium sized industry. ATP also supported BFRL research in collaboration with ATP grantees. BFRL worked with construction industry groups (most contractors are small or medium sized manufacturing industry), particularly the National Association of Home Builders, to explore establishment of one or more technology transfer centers for contractors. However, after supporting studies of the potential for construction-oriented centers, MEP decided to focus its resources on discrete parts manufacturers.

The BFRL director's report to the Panel on April 19, 1994, stated:

> *The Building and Fire Research Laboratory has been identified by NIST management and the Administration as a major player in NIST's support of U.S. industry. Our base funding is proposed to increase from $12.1 million in FY 1993 to $21.7 million in FY 1995; our total program was $25 million in FY 1993. Major increases came in computer integrated construction, high performance construction materials and systems, alternatives to halon fire suppressants and CFC refrigerants, green building technologies and earthquake engineering. Senate- and House-passed reauthorization legislation for NIST calls for establishment of a National Wind Engineering Research program with NIST as lead agency; this should lead to new funding for wind engineering research including aspects of wind-driven fires. (Editor's Note - the Director's report was based on figures inconsistent with the final figures).*

There were increases of directly appropriated funds for 1994 of $200,000 for earthquake engineering, $100,000 for alternative refrigerants, $450,000 for high performance construction materials, $950,000 for computer integrated construction, and $4.5 million one-time funding for investigations related to the Northridge earthquake of January 17, 1994, Northridge, California earthquake.

However, the BFRL Management Council advised BFRL managers and staff to maintain good working relations with present and potential sponsors of work consistent with the BFRL Strategic Plan for two good reasons. First, collaborations with other agencies were among the best mechanisms for implementation of research, and, second, expectations for greatly increased directly appropriated funding might not be realized.

NIST defined its mission very simply to incorporate the work of the laboratories, the Advanced Technology Program, the Manufacturing Extension Program and the Baldrige National Quality Award:

> *To promote U.S. economic growth by working with industry to develop and apply technology, measurements and standards.*

In its 1994 Strategic Plan, BFRL expressed itself as:

> The national laboratory dedicated to the life cycle quality of constructed facilities.

BFRL's mission was expressed to support that of NIST:

> *To enhance the competitiveness of U.S. industry and public safety through performance prediction and measurement technologies and technical advances that improve the life cycle quality of constructed facilities.*

The BFRL program was expressed by three themes incorporating eleven program thrusts:

1. Advanced Technology for Constructed Facilities
   - High performance construction materials and systems.
   - Construction automation and robotics.
   - Reducing the hazards of natural disasters.
   - Affordable housing.
2. Advanced Fire Safety Technologies
   - Performance fire standards
   - Fire-safe products and materials
   - Advanced technologies for fire sensing and suppression
   - Large/industrial fires.
3. Green Building Technologies
   - Green buildings
   - Alternate refrigerants
   - Halon alternatives.

President Clinton established the National Science and Technology Council (NSTC) in 1993 to focus and coordinate R&D investments across the federal agencies. With strong support from John Gibbons, the President's Science Advisor, and Mary Good, Undersecretary of Commerce for Technology, the Civil Engineering Research Foundation and other industry groups, NSTC established a Subcommittee on Construction and Building (C&B) in April 1994. Richard Wright and Arthur Rosenfeld, scientific advisor the Assistant Secretary of Energy for Conservation and Renewable Energy, were chosen as co-chairmen of C&B. Andrew Fowell accepted the position of Associate Director of Construction and Building in BFRL to serve as secretariat of C&B.

In meetings of the fourteen participating agencies of C&B, and in meetings with industry, the vision, mission, and National Construction Goals of C&B were established. The vision was:

- High quality constructed facilities support the competitiveness of U.S. industry and everyone's quality of life.
- U.S. industry leads in quality and economy in the global market for construction products and services.
- The construction industry and constructed facilities are energy efficient, environmentally benign, safe and healthful, properly responsive to human needs, and sustainable in use of resources.
- Natural and manmade hazards do not create disasters.

The mission of C&B was to enhance the competitiveness of U.S. industry, public and worker safety and environmental quality through research and development, in cooperation with U.S. industry, labor and academia to improve the life-cycle performance and economy of constructed facilities.

The National Construction Goals were:

1. 50 percent reduction in project delivery time
2. 50 percent reduction in operation, maintenance and energy costs
3. 30 percent increase in productivity and comfort
4. 50 percent fewer occupant related illnesses and injuries
5. 50 percent less waste and pollution
6. 50 percent more durability and flexibility
7. 50 percent reduction in construction work illnesses and injuries.

The baseline for each goal was industry performance in 1994, and the objective was to make available by 2003 practices capable of meeting the goals. Many initially felt the goals were incredible, but only the 7th came to seem to need revision. It was insufficiently challenging. Even in 1994, the best construction projects and firms, such as the members of the Construction Industry Institute, had injury rates of 1/7 the industry average.

David Evans became chief of the Fire Safety Engineering Division. In addition to his vigorous leadership of BFRL's studies for burning oil spills and for advances in simulation and modeling of fire phenomena, Evans became president of the Society of Fire Protection Engineers.

The enthusiastic response of the industry and agencies to the C&B program led to the President giving top-six priority to C&B funding for his fiscal year 1996 Budget Request to Congress. Never before, to the knowledge of the members of C&B, had an administration given top priority to research for construction.

A landmark report was completed on methodologies to evaluate fire suppressants for in-flight fire in aircraft. The evaluation includes suppressant effectiveness under harsh conditions, compatibility with materials and people, and environmental cleanliness. The methods were used to identify an optimum substitute for halon 1301 for certifying the fire suppression system effectiveness for engine nacelles.

A series of large-scale crude oil burns were completed near Prudhoe Bay, Alaska, in cooperation with Alaska Clean Seas. Smoke particulate measurements, both close to the fire and several kilometers downwind, were made to assess the impact of the burns and evaluate BFRL's Large Eddy Simulation (LES) model of the fire plume flow. Alaska adopted the model as part of its approval process for intentional burning of oil spills. Calculations using worst case atmospheric conditions indicate that ambient air quality standards are not exceeded beyond 5 km from a burn. This distance has been adopted in burning guidelines throughout the U.S.

A new computer model, called LEAK, was developed to predict the shift in composition of zeotropic refrigerant mixtures during slow or fast leaks to assure that new refrigerant mixtures do not leak flammable vapors.

BFRL led the reconnaissance team of the Interagency Committee on Seismic Safety in Construction investigating the January 17, 1994 Northridge California earthquake, and issued the report Performance of Structures, Lifelines and Fire Protection Systems in the 1994 Northridge Earthquake. A number of projects were initiated with

$4.5 million supplemental funding to gain knowledge for improvement of construction and fire safety practices. These projects were performed in cooperation with industry and universities and included research in repair and strengthening of welded steel moment connections, performance of lifeline systems, mitigation of large-scale fires and the performance of fire suppression on large-scale fires in neighborhoods.

James Hill received the Gold Medal of the Department of Commerce for outstanding management of the Building Environment Division. Richard Gann received the Silver Medal of the Department of Commerce for leading fundamental and important studies of the ignition propensity of cigarettes under careful and hostile scrutiny by the tobacco industry.

6.6 1995

BFRL and NIST peaked early in 1995. Budget increases for fiscal year 1995 included: green building technology $0.45 million, halon replacements $0.45 million, and high performance construction materials and systems $ 2 million. NIST funded a new competence project on high heat flux measurements led by William Grosshandler of BFRL and conducted jointly with the Physics Laboratory and the Chemical Science and Technology Laboratory.

James Hill, in a dual role as program manager for the Advanced Technology Program and as chief of BFRL's Building Environment Division, helped organize a focused, five year, $50 million program on Advanced Vapor Compression Refrigeration Systems for the refrigeration industry. Its goals were to increase system efficiency, reduce noise levels and reduce component sizes, each by 25 percent, and to prevent refrigerant leaks.

The Congressional elections of November 1994, led to Republican majorities in the House and Senate that were not simply in opposition to the Democratic administration, but sought major changes in government. Bills were introduced to eliminate the Department of Commerce (H.R. 1756, The Department of Commerce Dismantling Act) and the Advanced Technology Program was particularly attacked as welfare for industry. In this atmosphere, the $6 million construction and building initiative proposed by the President for BFRL was dropped by Congress without any direct attention.

The Office of Applied Economics returned to BFRL after a fourteen year organizational stay in the Computing and Applied Mathematics Laboratory (CAML). Harold Marshall led the Office from its founding as the Building Economics Section in CBT in 1973, through its stay in CAML, and again in BFRL. Although the Office had worked with the other NIST laboratories, the Advanced Technology Program and the Manufacturing Extension Partnership, it maintained close professional and program relations with BFRL and readily was reincorporated in BFRL. An example accomplishment in fiscal year 1995, was the release by Stephen Weber and Barbara Lippiatt of ALARM 1.0, Decision Support Software for Cost-Effective Compliance with Fire Safety Codes. The optimization method was field tested in nearly 100 hospitals with cost savings averaging between 30 percent and 35 percent of the cost of traditional code compliance strategies.

BFRL revised its program strategy to support the program of the Subcommittee on Construction and Building (C&B) of the National Science and Technology Council and its National Construction Goals. Although Congress had not supported the President's request of new funding for fiscal year 1996, C&B retained high priority in the Administration. The BFRL program had three thrusts and eight major products:

High Performance Construction Materials and Systems
- Performance standard for dwellings
- Integrated knowledge system for high performance concrete

Automation of Facilities and Processes
- Building automation control
- Automated condition assessment
- PlantSTEP

Loss Reduction
- Fire simulator
- Wind engineering standards
- Lifeline seismic standards

Could BFRL take advantage of the Administration's priority for the C&B program and the strong industry interest it created? BFRL had the strong researchers, experts in transfer of results to practice, and record of significant accomplishments needed for credibility, but management felt it needed to be focused on appropriate contributions to accomplishment of the National Construction Goals if these were to be the basis for growth of BFRL. This was an extraordinary opportunity to become more than "half of a laboratory."

BFRL management knew an extraordinary effort would be required to align the staff, in spirit and in practice. Survival of individuals and groups through the reductions of the 80s had depended largely on their abilities to provide sound, measurement-oriented work palatable to NBS/NIST management, to attract funding from other agencies through personal contacts, and collaborate with industry and standards organizations for implementation of results. How many program themes had been used over the years to exploit transient initiatives of administrations and concerns of industry (housing, rehabilitation, energy conservation, solar energy, workplace and consumer safety, disaster mitigation, productivity, competitiveness, etc.) and yielded little in terms of lasting new resources and program growth in quality and quantity? Staff had reason to be cynical.

Doug Brookman was engaged as facilitator for what was named originally an "Alignment" initiative. He met with members of the Management Council, and representative group leaders, researchers and support staff to explore feelings about an alignment initiative:

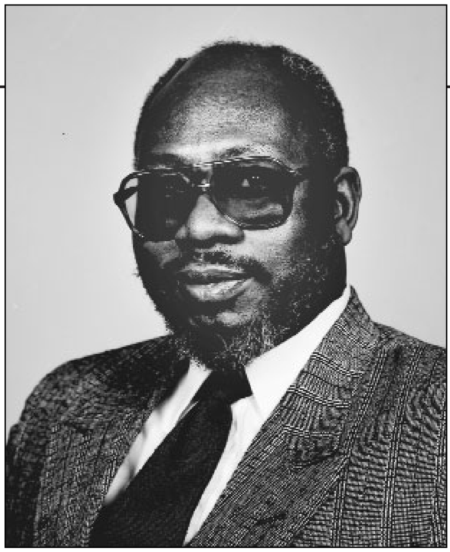
1. Why is this a problem and why should BFRL address it now?
2. What are the barriers/impediments to a more complete organizational alignment?
3. How can we make this initiative successful?
4. Where are the best opportunities?

He found significant doubt and cynicism about the prospects for the initiative. It would require real commitment by Richard Wright and Jack Snell and engagement of a majority of BFRL's employees.

The name of the initiative was changed to "BFRL Success" to make the purpose clear. The Management Council and staff were informed:

1. We need to develop a strategy to assure the success and survival of BFRL. The present political environment is perilous, but provides opportunities we need to seize to assure our future.
2. We identified six keys to success:
   - Administration (White House, Commerce, NIST) support
   - Congressional support
   - Industry support
   - OA funding
   - Significant accomplishments
   - Active participation and commitment of the entire laboratory.

Diversity in the workforce had become an important objective for the Administration and NIST. Charles Yancey, an African American and



Charles Yancey, structural research engineer and chairman of NIST's Diversity Board.

Structural Research Engineer in BFRL since 1970, in 1994 became chairman of NIST's Diversity Board which advised NIST's management on its diversity programs. BFRL created its Diversity Plan in March 1995 with thrusts for:

1. Development of candidates for employment
2. Recruitment of staff
3. Development and retention of staff.

James Hill led an ad hoc committee to review the plan and recommend actions BFRL should take to further its Diversity goals. As a result, BFRL formed a Diversity Committee, subsequently chaired by Kathy Butler and then by Nelson Bryner, which became the prototype for diversity committees of NIST laboratories and led to NIST awards for their leadership.

On December 1, 1994, the President signed Executive Order 12941, Seismic Safety of Existing Federally Owned or Leased Buildings. The Executive Order implemented the Standards of Seismic Safety for

Existing Federally Owned or Leased Buildings. The Executive Order and the Standards were drafted by the Interagency Committee on Seismic Safety in Construction (ICSSC) which represented 30 federal agencies. BFRL provided the chairman (Richard Wright), chairman of the Subcommittee on Building Standards (H.S. Lew) and secretariat (Diana Todd) for ICSSC. ICSSC had prepared the proposed executive order prior to the Northridge Earthquake of January 17, 1994, to be ready for consideration when earthquake hazards again received high level attention.

The January 17, 1995, earthquake which struck Kobe, Japan killed more than 6,000 people, injured more than 30,000 and caused economic losses of $200 billion. H.S. Lew and Riley Chung of BFRL led a team, with members from other federal agencies, academia and industry, to study seismology, geology, and geotechnical effects, as well as the performance of buildings, lifelines and fire safety systems. Key findings of the investigation included needs for research and improvements in practices to achieve earthquake hazard reduction in the U.S. The study was conducted under the auspices of the U.S./Japan Panel on Wind and Seismic Effects, for which BFRL provided the U.S.-side chairman (Richard Wright) and secretariat (Noel Raufaste).

Geoffrey Frohnsdorff received the William T. Cavanaugh Memorial Award of ASTM for technical leadership in the initiation and development of international standards for construction materials and systems. Mary McKnight received the ASTM Award of Merit and honorary title of Fellow for administrative and technical leadership of Committee E06 in the development of standards for the abatement of hazards from lead paint in buildings.

Piotr Domanski developed CYCLE_D, a model for simulating vapor compression refrigeration cycles in preliminary refrigerant screening, system design, education and training. It could simulate systems using up to 38 different refrigerants and refrigeration mixtures with up to five components. It was published as Data Base 49 of the NIST Office of Standard Reference Data and distributed initially to over 60 customers. Also, the NIST Slichter Award was won by David Didion, Piotr Domanski and Mark Kedzierski for their work in finding alternatives to the refrigerants banned from production to protect the atmosphere.

BACnet, a data communication protocol for building automation and control network, was approved as ASHRAE Standard 135-1995. Steven Bushby was a major contributor to the standardization and then organized a consortium of 17 partners to assist members in developing products conforming to the standard and to develop conformance testing tools and procedures for an industry-run certification program.

William Pitts led a team providing the first understanding of the mechanisms leading to high concentrations of CO and extensive smoke-induced deaths from flashed-over enclosure fires. The results were incorporated into an algorithm which defined the amounts of CO generated for a given fire scenario, and showed that small scale toxicity tests are not adequate for characterizing the toxicity of smoke from real fires.

Richard Gann led the team that provided the technical basis for the selection of HFC-125 as the substitute for halon 1301 for suppressing in-flight air craft fires. Research included the dynamics of fire suppressant release, two-phase pipe flow, and the character of the spray. The results were adopted by the Boeing Company for the 777 airplane and by the U.S. Navy. William Grosshandler received the Silver Medal of the Department of Commerce for his technical leadership of this work.

David Evans received the Silver Medal of the Department of Commerce for leadership of analytical, laboratory and field studies of burning oil spills as a means to minimize environmental damage.

6.7 1996

The flow of new directly appropriated funding ended with fiscal year 1995. None was received for 1996 and, in spite of continued Administration priority for construction, no initiatives received support for 1997. However, Mary McKnight of BFRL led a team including researchers from the Physics, Manufacturing Engineering and Information Technology Laboratories which was awarded a five-year NIST competence project on color appearance. The objective was to develop models and measurement methods for predicting the appearance of coated objects.

Degradation of BFRL facilities remained a major issue. Failure of the smoke cleaning system for the large fire test facility caused its shut down. The efficiency of fire research was much inhibited by the extra expense and staff time required to conduct tests in others' facilities - some as far away as Japan. Funding from the Department of Energy was obtained to renew a portion of the environmental laboratories. BFRL cosponsored with the National Science Foundation a study of national needs for large scale structural experimental facilities for earthquake engineering and other purposes. One issue was whether BFRL's large scale structural testing facility should be renovated to become a national user facility. Still, NIST's plan for renewal of facilities provided nothing for BFRL in the 20th century.

The budget stalemate between Congress and the Administration caused a three week shutdown of NIST and other agencies beginning in mid-December 1995. A severe snowstorm kept NIST shut down for several more days after funding was restored. NIST cancelled its assessment panel meetings for 1996 to give staff more opportunity to catch up on research. Many BFRL staff had continued to work at home during the shutdown; by year's end there was no detectable loss of accomplishments from the shutdown.

The Administration continued to give priority to construction and building research. Meetings were held with industry sectors (housing convened with the National Association of Homebuilders, commercial and institutional convened with the National Institute of Building Sciences, public works convened with the American Public Works Association, and industrial convened with the Construction Industry Institute) to identify each sector's priorities among the National Construction Goals and to explore opportunities for joint programs.

NIST's Manufacturing Extension Partnership (MEP) funded, with technical support from Shyam Sunder of BFRL, a study by the National Association of Home Builders Research Center of the potential for one or more technology transfer centers for home builders [8]. Industry interest was high but MEP, in the end, did not find justification for extending its mission from small and medium size manufacturers, in general, to home builders and to their suppliers, which are dominantly large manufacturers.

The National Conference of States on Building Codes and Standards brought together about forty private sector organizations, with support from the NSTC Subcommittee on Construction and Building, to explore streamlining the building regulatory system. Streamlining would involve coordination and cooperation among the many local, state and federal regulatory authorities responsible for approving aspects of each construction project. It was anticipated that the time and cost involved in getting regulatory approvals could be halved without any relaxation of safety or environmental protections.

The BFRL program continued to focus on major products. The more general Computer Integrated Knowledge System replaced the Integrated Knowledge System for High Performance Concrete, and William Stone's Real Time Construction Site Metrology was added.

In light of NIST's focus of its resources on economic growth and international competitiveness, BFRL negotiated with FEMA to transfer to FEMA the responsibility for support of development of seismic safety standards for lifelines. It seemed impossible to obtain the necessary funding through the NIST budget and FEMA could build upon its successful program for development of seismic standards and practices for buildings. FEMA and NIST cosponsored the Lifeline Policy Makers Workshop in January 1997. FEMA then supported the organization by the American Society of Civil Engineers of the American Lifelines Alliance to facilitate the development of guidelines and national consensus documents for improving the performance of utility and transportation lifelines subjected to natural hazards.

The results of BFRL research cited at the NIST Director's program review included:

1. Dale Bentz's and Edward Garboczi's work on modeling the chloride diffusivity of concrete to allow service life prediction for structures exposed to chlorides.

2. Steven Bushby's advancement of standard communication protocols for building automation and control systems from the 1995 ASHRAE standard to status as an ANSI standard and a European pre-standard and to consideration as an ISO standard. A consortium of 18 companies began developing protocols for conformance testing, and research began on extension to electrical load management, fire detection and suppression, and access and security systems. Bushby received the Slichter Award of NIST for this work.

3. Walter Jones' and colleagues development of CFAST and FASTlite as practical methods for modeling the fire performance of building designs. These methods provided the technical basis for performance based design of fire safety systems and were used world wide in fire safety engineering practice and education.

4. Kent Reed's and Mark Palmer's leadership of the production of the Application Protocol 227, Plant Spatial Configuration for automatic exchange of information in process plant design. The PlantSTEP consortium was formed with owners, engineering construction firms and CAD systems vendors to advance automatic exchange of information in process plant design, construction, operations and maintenance.

James Hill became President of the American Society of Heating, Ventilating and Air-Conditioning Engineers (ASHRAE) for 1996-1997 in recognition of his personal leadership in ASHRAE programs. He and many other BFRL staff have participated for years in cooperative ASHRAE-NIST efforts to improve knowledge, standards and practices and the national and international competitiveness of U.S. products and services.

The White House presented a "Hammer Award" for the BACnet demonstration project at the Phillip Burton Federal Office Building in San Francisco. BFRL worked with the General Services Administration, the Department of Energy, the Federal Energy Management Program, and the Lawrence Berkeley Laboratory in this demonstration of the performance improvements and cost savings to be realized from implementation of the BACnet communication protocol for building automation.

Noel Raufaste led the work to produce BFRL's Video, Your Partner in Building that received a 2nd place Telly Award for production excellence and the prestigious Crystal Award of Excellence from a Communications Awards competition. This award is presented to entrants whose ability to communicate elevates them above the best in the field.

William Pitts received the Silver Medal of the Department of Commerce for his research that identified the important mechanisms for production of life-threatening carbon monoxide in fires.

6.8 1997

This first year of the second Clinton Administration saw major changes in the leadership of NIST, the Department of Commerce and the White House Office of Science and Technology Policy. William Daley became Secretary of Commerce and called Ray Kammer from his position as Deputy Director of NIST to become Acting Assistant Secretary for Administration. Robert Hebner, a career NIST researcher and manager, was called upon to become Acting Deputy Director of NIST from his permanent position as Deputy Director of the Electronics and Electrical Engineering Laboratory. Arati Prabhakar resigned as Director of

NIST for a position in industry, and Hebner served as Acting Director until Ray Kammer was nominated and confirmed as NIST Director. Neil Lane moved from Director of the National Science Foundation to become the President's Science Advisor and Director of the Office of Science and Technology Policy (OSTP) replacing John Gibbons. Mary Good resigned as Undersecretary for Technology of the Department of Commerce; her deputy Gary Bachula then served as Acting Undersecretary.

The Construction and Building Subcommittee of the National Science and Technology Council continued to receive Administration priority. The Partnership for Advancement of Technology in Housing (PATH) was developed with active support in the White House contributing to the enlistment of leaders of the housing industry and its suppliers. PATH was designed to bring together government and industry to develop, demonstrate and deploy housing technologies, designs, and practices that could significantly improve the quality of housing without raising the cost of construction. The Department of Housing and Urban Development (HUD) and the Department of Energy became co-leaders for PATH. NIST was recognized as a key technical participant and supported by OSTP for a fiscal year 1999 budget increase for PATH. However, NIST gave higher priority to a Climate Change initiative, which was not funded by Congress, while HUD succeeded in gaining new funding for PATH. BFRL did receive substantial funding from HUD for technical support of PATH.

James Gross retired as Assistant Director of BFRL. Since 1971 he had been a leader for NBS/NIST in developing funding for and conducting housing technology and in building standards and codes programs. He was recognized for these accomplishments by the Department of Commerce Silver Medal, the Conference of States Award of the National Conference of States on Building Codes and Standards, the Award of Merit and of Honorary Fellow from ASTM, and the President's Award of the American Society of Civil Engineers. As Deputy Director of CBT in the 1980s he was a great source of strength in mobilizing support of industry for the survival of building and fire research at NBS, and in managing for continuing productivity while dealing with decreasing funding and reductions in staff. He was many times helpful to a division chief when tight funding required development and implementation of a "solvency plan" including lending staff to other organizations or assisting in their work, reducing expenditures to those essential, developing new sources of funding and reductions in force.

Joel Zingeser joined BFRL as manager of standards and codes services. Building on his background with the housing industry and applying his strong teambuilding skills, he played a major role in the development of PATH. Indeed, he coined the name and acronym in an early meeting of the agencies involved, represented NIST in the White House team that worked with industry to develop the program, and worked with HUD and BFRL managers to develop the technical support BFRL would provide to HUD for PATH.

BFRL joined the Construction Industry Institute (CII) in fiscal year 1995 because its goals were consistent with the National Construction Goals and because collaborations with CII offered unparalleled opportunities to work directly with leading executives from major owners of constructed facilities (such as Dupont and General Motors) and major engineering construction firms (such as Bechtel and Fluor-Daniel). CII declined to participate in any program to realize the National Construction Goals because it did not want to be directed by the federal government or report on its work to the federal government, but it welcomed the collaboration of BFRL and other federal agencies in its own programs. Richard Wright and Jack Snell became members of CII's Board of Advisors, Wright served on the Strategic Planning Committee and Snell on the Breakthrough Research Committee, Robert Chapman on the Benchmarking and Metrics Committee, and William Stone on project committees concerned with automation and metrology in construction.

CII since 1983 had focused on development of best practices for design and construction and had demonstrated the value of their application for safety, and for schedule and cost control in its Benchmarking and Metrics Summary for 1997. However, CII felt best practice efforts might be approaching diminishing returns and decided to explore larger scale, breakthrough programs capable of producing major improvements in quality, safety and economy. The May 1997 Strategic Plan of CII identified Fully Integrated and Automated Project Processes (FIAPP) as a trend that will revolutionize construction. FIAPP meant the fully automated, one-time data entry, seamless integration of the project life-cycle work processes (from project inception through ongoing operation), including automated knowledge-based decision making, use of institutionalized intelligence and common databases. The Breakthrough Research Committee began work on development of a FIAPP program for CII with BFRL as an active participant.

NIST's Visiting Committee on Advanced Technology advised NIST in those times of difficult budgeting to provide closure in its mission statements - to show the consequences of not properly funding a mission. Consequently, BFRL added the word assure to its mission:

To enhance the competitiveness of U.S. industry and public safety through performance prediction methods, measurement technologies, and technical advances needed to assure improvement of the life cycle quality and economy of constructed facilities.

Disaster mitigation again became an element of BFRL's Success Strategy and BFRL participated in activities of the National Disaster Reduction Subcommittee of the National Science and Technology Council:

- National Mitigation Strategy
- US/Japan Earthquake Mitigation Partnership
- US/Japan Earthquake Policy Symposium
- Lifeline Policy Makers' Workshop
- Wind Peril Workshop

The focus on major products was strengthened to almost 2/3 of BFRL's directly appropriated funding. The major products became:

- Partnership for high performance concrete technology
- Performance standard system for dwellings
- Fire-Safe Polymers/Composites
- Fire Safety Performance Evaluation System
- Computer-Integrated Construction Environment
- Cybernetic Building Systems

In addition to major products, with their 3 year to 5 year time frame for results and 5 year to 10 year time frame for impacts, it was essential to prepare for the principal issues and major products of future years.

Greg Linteris, fire research engineer and NIST's first astronaut, is performing materials and combustion science research in the orbiting STS-94 Microgravity Space Science Laboratory.

Richard Gann headed a task force that included BFRL's NIST fellows (Emil Simiu, David Didion, and Howard Baum) and some of its liveliest younger researchers (Edward Garboczi, Anthony Hamins and William Pitts) to identify topics likely to become the ruling technologies in ten or so years. BFRL planned to invest 10 percent to 15 percent of its directly appropriated funding and focus its recruitment in preparing for leadership in the most important of these topics.

Gregory Linteris was NIST's first astronaut with two space flights (STS-83 in April and STS-94 in July) in the Microgravity Science Laboratory Mission. The first flight was curtailed after a few days because of mechanical problems, but because of the importance of the mission it flew again in July. Linteris conducted highly successful studies of soot formation, spherical flame structures, and combustion of atomized fuels.

Barbara Lippiatt developed and beta-tested a powerful technique for assessing the environmental and economic performance of building products called BEES (Building for Environmental and Economic Sustainability) to help manufacturers demonstrate the sustainability of their products and to help owners, designers, and builders make economical and sustainable choices.

Douglas Burch released an enhanced version of MOIST, a computer program that predicts the transfer of heat and moisture in walls, flat roof and cathedral ceilings. MOIST determined whether ventilation strategies achieved acceptable moisture performance to prevent build up of moisture and resultant degradation in walls or roofs, or the growth of mold on interior surfaces.

Edward Garboczi and Dale Bentz produced a pioneering "electronic monograph" available on Internet to predict concrete properties as a function on mixture design, curing and environmental exposure.

William Stone and Geraldine Cheok received the Structural Engineering Award of the American Concrete Institute for their paper Performance of Hybrid Moment Resisting Precast Beam-Column Concrete Connections Subject to Cyclic Loading which provided the basis for building code acceptance of seismically resistant multi-story precast concrete framed buildings.

6.9 1998

NIST director Ray Kammer and the Laboratory Council, which was comprised of the directors of NIST laboratories, gave substantial attention to "best in the world" programs of NIST. Presentations were made to NIST staff on the "best in the world" programs, and the question was asked implicitly, why should we have programs where we are not best in the world or striving to become that? BFRL's major products aimed squarely at best in the world. But programs, such as BFRL's role in the National Earthquake Hazards Reduction Program, where it was useful but not even best in the program, became candidates for restructuring or reprogramming. The Laboratory Council defined the goal of NIST's laboratories' research as "research planned and implemented in cooperation with industry that anticipates and addresses the most important measurement and standards needs in a timely fashion." This focused the "best in the world" concept for programs by defining the nature of their objectives.

BFRL's 1998 Strategic Plan focused on its six major products and four additional objectives for measurements and standards with potential for best in the world status:

- Service life of building materials
- Metrology for sustainable development
- Earthquake, fire and wind engineering
- Advanced fire measurements and fire fighting technologies

The major budget increase for NIST laboratories for fiscal year 1998, was $3.8 million in wind engineering - but it was earmarked for Texas Tech University by Senator Kay Bailey Hutchinson who served on the Appropriations Committee. It displaced NIST's priorities for initiatives and made duplicative NIST's own fiscal year 1999 proposal for increased funding for wind engineering at NIST. BFRL was assigned to work with Texas Tech to define a strong program of research. This was done dutifully and well; sufficiently well that by fiscal year 2001, NIST was able to share in the appropriation and strengthen its wind research.

Substantial efforts were made to obtain budget initiatives for fiscal year 2000. Three led in BFRL were submitted by

NIST to the Department of Commerce: the initiative for PATH (partnership for advancing technology in housing); an initiative for PAIR (partnership for the advancement of infrastructure and its renewal) based on work with the federal agencies in the Subcommittee on Construction and Building and with industry; and a Disaster Mitigation initiative based on collaboration with NOAA and other bureaus of the Department of Commerce. All fared well enough to be included in a Livable Communities proposal by the President's Office of Science and Technology Policy in December 1998. However, none became part of the President's proposal for his 2000 budget.

One great highlight of fiscal year 1998 was that BFRL received funding to build the smoke abatement system for the fire laboratory from NIST's appropriation for renewal of facilities. Finally, in 2001, BFRL was again able to conduct medium and large scale fire tests in its own laboratory.

BFRL's Success Strategy was cited by NIST director Ray Kammer as probably "best in NIST" for reallocation of resources. In addition to the major products, the remainder of BFRL's directly appropriated funds were allocated systematically using the Analytical Hierarchy Process standardized for ASTM by BFRL's own Office of Applied Economics. The Success Strategy received support from NIST, the Assessment Panel for BFRL, and BFRL staff, but it succeeded at best at keeping a near-level effort for BFRL in the tight budget environment after the mid term elections of 1994. "Success" was a success in maintaining a healthy BFRL, but failed to achieve laboratory growth.

In its program review for the NIST Executive Board, BFRL cited a number of $100 million scale impacts of its program:

- Guidelines for the Seismic Rehabilitation of Welded Steel Frames, developed with the American Institute of Steel Construction, to make cost effective multi-billion dollars in rehabilitations.
- Expert System for Highway Concrete to guide materials selection and repair techniques for the multi-billion dollar highway pavement market.
- Alternate Refrigeration Systems to increase U.S. markets for environmentally friendly refrigerants and equipment and to reduce energy costs.
- Building Automation Protocol to increase market for U.S. products, and to save in installation, operation and maintenance costs.
- Moisture modeling to save over $100 million annually in energy costs of wet insulation and in repairs of degradation caused by wet insulation.
- Fire Modeling to save construction and rehabilitation costs by allowing performance based design of fire safety systems.
- Environmentally friendly fire suppressant systems to prevent airplane fires and reduce costs of retrofits to environmentally friendly systems.
- Life cycle cost assessment of high performance concrete for highway bridges shows state highway engineers how to achieve annual savings of $700 million.

The Industrial Fire Simulation System, developed by David Evans and colleagues, showed the capability to model the interactions of sprinklers, draft curtains and vents in a simulation of a warehouse fire. The simulation capability is very valuable for design of fire safety systems since a single full scale test, covering only one set of variables, costs about $50,000.

William Stone and colleagues demonstrated BFRL's National Construction Automation Testbed that combined real time construction site metrology and virtual reality simulations to allow construction automation hardware and software to evaluated for on site performance. Wireless real time metrology and simulation capabilities will support automation and remote control for safety and productivity in construction.

Robert Chapman and Roderick Rennison published the first two studies of baseline and progress measurements for the National Construction Goals. These studies described data sources, data classifications and hierarchies, and the metrics for the baselines and progress for the goals on project delivery time and on life cycle operation, maintenance and energy costs.

S. Shyam Sunder, chief, Structures Division

They defined an approach applicable to all of the goals.

S. Shyam Sunder became Chief of the Structures Division. Sunder joined BFRL in 1994 as Manager of the High Performance Construction Materials and Systems Program after 14 years on the Civil Engineering faculty of MIT, and served in the Office of the NIST Director as program analyst and senior program analyst from June 1996 to December 1997. H.S. Lew, who served as division chief from 1989 to 1997, continued as senior research structural engineer with major responsibilities in earthquake engineering and national and international standardization.

Richard Marshall received the first Walter P. Moore Award of the American Society of Civil Engineers for his career contributions to wind engineering standards - a most timely recognition as Marshall entered the final stages of a mortal illness. Dale Bentz received the L'Hermite Award of RILEM for his seminal contributions to the modeling of the microstructure and properties of concrete.

6.10 1999

Richard Wright retired as director of BFRL at the end of January 1999. Jack Snell succeeded him as BFRL director and James Hill succeeded Snell as deputy director. Wright retired pleased with the accomplishments of CBT/BFRL's researchers and managers, often under adverse circumstances, in his years as director, and regretful that BFRL had not achieved the scope, size and funding needed to meet the measurement and standards needs of the construction and fire safety communities. This history overall tells the story of the accomplishments and frustrations in some detail.

The year was tight financially without new directly appropriated funding and other federal agencies also limited in their funding for BFRL. BFRL had focused directly appropriated funding increasingly on new areas such as FIATECH and Cybernetic Building Systems. BFRL developed a marketing program for its managers and senior researchers to improve prospects for funding from other federal agencies and the private sector. NIST director Ray Kammer also made central allocation funding available to support earthquake, fire, and wind engineering temporarily because initiatives were not funded by Congress.

Jack Snell's work over two years with the Breakthrough Research Committee of the Construction Industry Institute (CII) led to the organization of the FIATECH (Fully-Integrated and Automated Project Process Systems and Technologies) Consortium. FIATECH brought major owners of constructed facilities, engineering construction firms, and suppliers of information technology hardware and software into a collaborative effort with BFRL to reduce project delivery time and cost. The focus was on seamless integration of project information through the whole life cycle and by bringing real-time wireless data from the construction site into project management information systems. Richard Jackson retired as director of NIST's Manufacturing Engineering Laboratory to lead the FIATECH Consortium. The BFRL major product Computer-Integrated Construction Environment evolved into Construction Integration and Automation Technologies (CONSIAT) to align itself with a major theme of FIATECH.

The Cybernetic Building Systems major product aimed at performance measurement and evaluation tools and open systems protocols for integrated, intelligent building service systems providing optimal control, fault detection and diagnostics for energy management, real-time purchase of electricity, fire and security, transportation, and aggregation of sets of buildings. BFRL works with industry, building professionals, ASHRAE and trade organizations, university researchers and other government agencies to prepare a Virtual Cybernetic Building Testbed and conduct a full-scale demonstration of a Cybernetic Building System in a government office building complex.

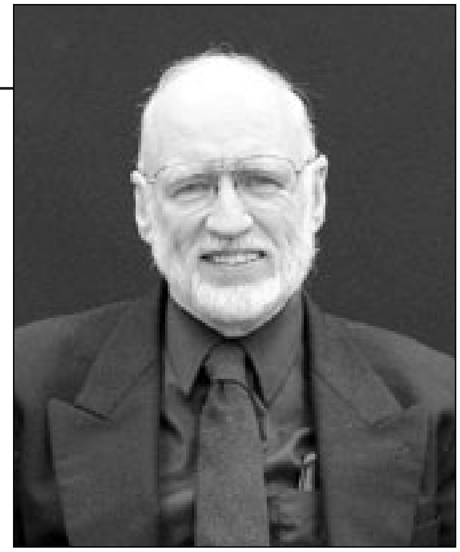
Jeffrey Gilman and Takashi Kashiwagi demonstrated that polymer-clay nanocomposites fulfill requirements for high-performance additive type flame retardant systems for polymers. Flammability is reduced while improving other properties of the polymer. A consortium of eight companies and three government agencies has been formed to study the nanocomposites' flame retardant mechanism.

Richard Gann stepped aside from Chief of the Fire Science Division, a position he had held since 1982, to focus on leading the interagency effort to remove dependence on ozone-depleting halon fire suppressants, guidance to U.S. manufacturers in exporting to countries with diverse fire test requirements, and developing a scientifically sound basis for determining when and how to include the sublethal effects of smoke in fire safety decisions.

William Grosshandler, who joined BFRL in 1991 as Leader of the Fire Sensing and Extinguishment Group after three years as Director of the Thermal Systems Program of the National Science Foundation, became chief of the Fire Science Division. At BFRL Grosshandler enthusiastically and efficiently led highly successful interdisciplinary teams in understanding the mechanisms of fire suppression and in expanding capabilities for calibration of heat flux measuring devices.

George Kelly became chief of the Building Environment Division. Kelly joined NBS in 1970 and led development of work in building automation and control systems as leader of the Mechanical Systems and Controls Group since 1980. His quiet manner hides great technical insight and imagination and unstinting efforts to meeting commitments on time, target and budget.

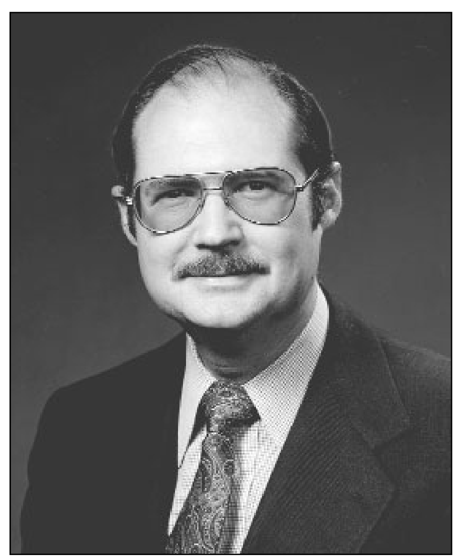
Noel Raufaste retired from BFRL as Manager, Cooperative Research Programs, at the end of December 1998 to become Managing Director, Technical and International Activities, for the American Society of Civil Engineers. Raufaste joined CBT's Office of Federal Building Technology in 1972 to develop, oversee and participate in research projects for federal agencies. He continued these efforts throughout his years with CBT and BFRL, and represented CBT/BFRL in the National Science and Technology Council's Subcommittee on Natural Disaster Reduction, the Federal Facilities Council of the National Research Council, for which he served on the Program Committee and as Vice Chair, and on the Consultative Council of the National Institute of Building Sciences, which he chaired for a term. He developed a major cooperative research program with the General Services Administration which was an important source of funds for CBT and CFR in the 80s.



George Kelly, chief, Building Environment Division.

Raufaste also led CBT's and BFRL's efforts to communicate effectively with the building and fire communities at large - supplementing the traditional communication of researchers with their peers and the direct users of their research in standardization and similar activities. He designed and developed project summaries, reports on publica-

Noel Raufaste, lead BFRL's cooperative research programs for a quarter century.



tions, newsletters and videos to inform and attract potential collaborators in and users of CBT/BFRL research. A number of these products received national awards for their quality.

He coordinated CBT's international activities during the early and mid 1970s and later coordinated collaborations with several European building and fire research laboratories He served as the U.S. side Secretary General for the U.S./Japan Panel on Wind and Seismic Effects from 1985-1999, organized and coordinated its highly productive technical committees, and arranged funding for its work by U.S. agencies. For a quarter century, Raufaste worked effectively with foreign science diplomats from about 20 foreign embassies in Washington, DC to help them learn about NBS/NIST research and to gain access to foreign research. In addition, he provided staff support for the program planning activities of CBT/BFRL. His enthusiasm and unstinting efforts earned the respect of colleagues in BFRL and collaborating organizations.

6.11 2000

BFRL initiated this last year of the 20th century with a self assessment and action plan following the criteria of the Malcolm Baldrige National Quality Award. The resulting mission and vision became:

Mission: *Meet the ongoing measurement and standards infrastructure needs of the Building and Fire Safety Communities.*

Vision: *The source of critical tools - metrics, models and knowledge - used to advance the communities we serve.*

The assessment showed that NIST, through BFRL, has growing opportunities and is driving major changes while facing shrinking resources. The outcomes envisioned were:

- Innovative Materials: enable the next generation materials for construction and building products.
- Enhanced Building Performance: provide means to assure that buildings work better throughout their useful lives.
- Fire Loss Reduction: enable engineered fire safety for people, products, facilities, and first responders.

The shrinking resources were a serious problem. BFRL management was required to announce a reduction in force affecting a number of its most renowned and productive researchers to show NIST management that without additional resources BFRL could not respond to new demands and opportunities without terminating established and productive work. NIST responded with reallocation of resources that allowed cancellation of the reduction in force.

Moreover, BFRL succeeded in gaining new funding in wind engineering and technologies for fire fighter safety through Congressional appropriation for fiscal year 2001 that put BFRL on a sound financial basis for the beginning of the new century.

At the end of the year, the Fire Safety Engineering Division and the Fire Science Division were merged into the Fire Research Division with William Grosshandler as chief. This provided a single focal point at NIST for fire research and recognized the attrition of fire research funding and staff since the Center for Fire Research was organized in 1974. However, the quality and impact of BFRL's fire research continue to grow as shown by the descriptions herein of the work.

Another evidence in 2000 of the success of BFRL fire research was the election of Howard Baum to the National Academy of Engineering in recognition of his research on fluid mechanics of fire, turbulent combustion and the development of efficient large eddy simulation methods for turbulent combustion. Baum joined NBS in 1975, received with Ronald Rehm one of the first competence project awards in 1978 for the beginning of the large eddy simulation method and was selected as NIST Fellow in 1983. His influence on fire research and practice extends far beyond his own work. Baum delights in collaboration with and development of young researchers to become independent leaders in fire science and engineering.

The work of Howard Baum and colleagues in collaboration with industry was made available to fire protection engineers, designers and investigators with release of the Fire Dynamics Simulator (www.fire.nist.gov). The NIST Fire Dynamics Simulator consists of two programs, FDS and

Smokeview. The NIST Fire Dynamics Simulator predicts smoke and/or air flow movement caused by fire, wind, ventilation systems etc. Smokeview visualizes the predictions generated by NIST FDS. FDS, solves a form of the Navier-Stokes equations appropriate for low-speed, thermally-driven flows of smoke and hot gases generated in a fire. Kevin McGrattin and Glenn Forney received the Department of Commerce Silver Medal in 2001 in recognition of this work.

David Didion was awarded the first Gustov Lorentzen Prize of the International Institute of Refrigeration for his pioneering work in refrigeration research and in the search for alternatives to CFC refrigerants. Didion joined NBS in 1971 and decided after a year in the NBS Director's Office in 1972-73 to focus on technical work rather than management. However, his great effectiveness in working with leaders of industry and other agencies, in developing young researchers including part time teaching of graduate courses and supervision of theses, in conceiving and conducting innovative research programs to produce changes in practice, and in candid assessments of managerial fads and initiatives extended his influence far beyond his own, very influential work. He conceived and initiated highly successful CBT/BFRL research in mechanical systems and controls as well as initiating and leading his prize winning research on alternative refrigerants and on refrigeration cycles to increase their efficiency.

The work of Jonathan Martin and colleagues enabled reliability-based predictions of the service lives of polymeric materials. Outdoor exposures are characterized by time series of temperature, moisture and ultra-violet exposure; laboratory and field studies define mechanisms of degradation and formulate cumulative damage models which then are used for rational, probabilistic predictions of service life.

The work of John Gross, in cooperation with the American Institute of Steel Construction (AISC) and several leading universities, to develop guidance for the rehabilitation of welded steel moment frames to improve their seismic resistance, was published as AISC Design Guide 12, Modification of Existing Welded Steel Moment Frame Connections for Seismic Resistance. In 2002, John Gross received the Department of Commerce Bronze medal for this work and the American Society of Civil Engineers (ASCE) Raymond C. Reese Research prize for a related paper.

The work of William Stone and colleagues in cooperation with Pankow Construction to develop hybrid connections for precast concrete frame systems was implemented in the building authorities' approval for construction of the tallest reinforced concrete building in California - a 39 story apartment in San Francisco. Stone, Geraldine Cheok, and H.S. Lew received the Department of Commerce Silver Medal for this work in 2001.

6.12 CONSTRUCTION AND BUILDING SUBCOMMITTEE, NATIONAL SCIENCE AND TECHNOLOGY COUNCIL

This section is included as a management topic in building and fire research history because it was a major concern of BFRL management and concerned program development rather than technical work.

At its beginning, the Clinton Administration gave priority to economic growth [9], and particularly to technologies for economic growth [10]. President Clinton established the National Science and Technology Council (NSTC) by Executive Order on November 23, 1993, to coordinate science, space and technology policies across the federal government. The President chaired NSTC; members included the Vice President, the Assistant to the President for Science and Technology, Cabinet Secretaries and Agency Heads with significant science and technology responsibilities, and other White House officials. Mary Good, Undersecretary of Commerce for Technology, chaired the NSTC's Committee on Civilian Industrial Technology (CCIT) which was charged to collaborate with industry to enhance the international competitiveness of U.S. industry through federal technology policies and programs.

BFRL's mission already was well aligned with the thrusts of NSTC and

CCIT: to enhance the competitiveness of U.S. industry and public safety through performance prediction and measurement technologies and technical advances that improve the life cycle quality of constructed facilities. At its meeting of December 7, 1993, CCIT discussed establishing a Subcommittee on Construction and Building (C&B). Richard Wright worked with Mary Good and with Henry Kelly and Cynthia Arnold-McKenna of the President's Office of Science and Technology Policy (OSTP) to organize C&B. Kelly in 1988, while with the Office of Technology Assessment, had worked with Arthur Rosenfeld, Director of the Center for Building Science of the Lawrence Berkeley Laboratory (LBL), to outline proposed National Institutes for the Built Environment, modeled on the National Institutes of Health. At the suggestion of OSTP, Wright and Rosenfeld became co-chairmen of C&B. Rosenfeld, originally a nuclear physicist, applied his drive and imagination to energy conservation technology and policy following the energy crisis of 1973 and led the development of LBL's major energy conservation program.

Rosenfeld immediately arranged substantial funding from the Department of Energy for C&B to match that provided by BFRL. Andrew Fowell of NIST accepted the secretariat of C&B. Thomas Anderson, a Fluor Daniel executive on an AAAS fellowship to RAND Corporation's Critical Technologies Institute, provided liaison for C&B to OSTP. The Civil Engineering Research Foundation (CERF), led by Harvey Bernstein, expressed interest in convening private sector interests to participate in the C&B program. A planning group including representatives of the Department of Defense, Housing and Urban Development, and National Science Foundation met on March 2, 1994, and additional inputs were obtained from the Environmental Protection Agency, Federal Highway Administration, and Health and Human Services. A proposed Program Description for C&B was submitted to CCIT on March 7, and CCIT established the subcommittee on March 18, 1994.

C&B met on March 25, to agree on its vision, mission and goals [11].

Vision

- High quality constructed facilities support the competitiveness of U.S. industry and everyone's quality of life.
- U.S. industry leads in quality and economy in the global market for construction products and services.
- The construction industry and constructed facilities are energy efficient, environmentally benign, safe and healthful, and sustainable in use of resources.
- Natural and manmade hazards do not cause disasters.
- Intelligent renewal, a process that cost effectively uses limited economic, material and human resources, is applied to rebuilding America.

Mission

Enhance the competitiveness of U.S. industry, public safety and environmental quality through research and development, in cooperation with U.S. industry, labor and academia, for improvement of the life cycle performance of constructed facilities.

Goals, which came to be known as the National Construction Goals, were made quantitative to show policy makers in industry and government the importance of the program.

1. 50 percent reduction in project delivery time.
2. 50 percent reduction in operation and maintenance.
3. 30 percent increase in productivity and comfort.
4. 50 percent fewer occupant related illnesses and injuries.
5. 50 percent less waste and pollution.
6. 50 percent more durability and flexibility.
7. 50 percent reduction in construction related illnesses and injuries.

The baseline for the goals was current construction practices, and the target was to have technologies and practices capable of meeting the goals available to the industry by 2003.

On April 5, 1994, CERF convened a broadly based focus group of industry leaders to discuss the C&B program. The program and goals were endorsed enthusiastically [12].

On May 6, 1994, Leon Panetta, Director of the Office of Management and Budget, and John Gibbons, Director of the Office of Science and

Technology Policy, issued FY 1996 Research and Development Priorities to the heads of executive departments and agencies. Three of the seven cited priorities for research related to the program of C&B:

- Construction and Building. Activities that support the residential/commercial building construction industry and its suppliers in the development of advanced technologies aimed at increasing the productivity of construction, improving product quality (including energy efficiency and improved air quality), use of renewable resources, and increased worker health and safety. Focus areas will include the development and demonstration of systems for constructed facilities exploiting advanced construction materials; advanced design, modeling and engineering tools for concurrent engineering design and life-cycle monitoring and maintenance; automated construction methods; and improved building systems such as sensors and control, fire safety systems, advanced glazing, and lighting systems.
- Materials Technology. Emphasis will be placed on materials processing for specific industry sectors, in particular automotive, electronics, construction, environmental technologies, and aeronautics.
- Physical Infrastructure for Transportation. Activities will include improved materials, monitoring instruments, tools, construction methods, and design concepts for the construction and renewal of the physical infrastructure.

Wonderful! For the first time in the experience of any of the veteran federal officials serving on C&B, an administration had given top priority to research to improve construction and constructed facilities. C&B proceeded to define a program of research to meet its goals [13], and to develop partnerships with the private sector to fund and conduct the needed research, development and demonstration [14, 15, 16]. The agencies participating in C&B planning and program development were the departments of Agriculture, Commerce, Defense, Energy, Health and Human Services, Interior, Labor, Transportation, and Veterans Affairs, and the Environmental Protection Agency, General Services Administration, National Aeronautics and Space Administration, and National Science Foundation.

Because the different sectors of the industries of construction had distinct needs and priorities, the development of collaborations with industry were divided into four sectors with an appropriate private sector organization coordinating each sector's efforts:

1. Residential, coordinated by the National Association of Homebuilders Research Foundation.
2. Commercial and Institutional, coordinated by the National Institute of Building Sciences,
3. Industrial, coordinated by the Construction Industry Institute.
4. Public Works, coordinated by the American Public Works Association.

The Administration's loss of both houses of Congress in the 1994 elections made the Administration's budget priorities for FY 1996 irrelevant to Congress. C&B received sustained priority in the Administration [17] and focused its efforts on developing collaborations with industry that would be attractive of Congressional support [18]. C&B studied existing federal research supporting the industries of construction and showed that it amounted to $500 million per year [19]. Focusing and coordinating federal R&D for construction, in cooperation with industry, to address the National Construction Goals clearly was of important public interest. A Collaborations Workshop [20] was conducted to make industry organizations aware of the mechanisms existing for collaborative research with the federal agencies.

The Residential Sector, led by Liza Bowles, president of the National Association of Homebuilders Research Foundation, moved vigorously to define a program meeting its priority goals [21]. In December of 1996, Rosenfeld and Wright agreed with Mary Good, Undersecretary of Commerce for Technology, and Henry Kelly, of the Office of Science and Technology Policy (OSTP), to organize a major program with the residential industry. David Engel of Housing and Urban Development (HUD), John Talbott of the Department of Energy (DoE), Joel Zingeser of BFRL, and Mark Bernstein of OSTP led the effort to organize the Partnership for

Advancing Technology for Housing (PATH). Bernstein used effectively the leverage of "calling from the White House" to attract participation of industry leaders, and Engel, Talbott and Zingeser, built on their agencies' extensive experiences in collaborations with industry and Congress to develop the program. PATH was announced by President Clinton on May 1998 [22], and HUD received an increase of $10 million for PATH in its FY 1999 budget to reverse a 25 year decline in HUD's funding for housing technology. NIST proposed budget increases for PATH for both FY 1999 and FY 2000, but did not give either sufficient priority with the White House to make it part of the President's Budget Proposal to Congress. However, HUD allocated a substantial portion of its budget for PATH to BFRL for technical support.

The Construction Industry Institute (CII) informed C&B that it would not collaborate formally with C&B, but would welcome participation of federal agencies in its programs addressing its goals (which were consistent with those of C&B). BFRL became a member of CII, as representing the Department of Commerce, and a number of other C&B agencies already were CII members. CII sponsored a workshop [23] to explore research needs and opportunities with C&B, and made a commitment to "breakthrough research" in its strategic plan. CII's program in Fully Integrated and Automated Project Processes (FIAPP) and its FIATECH Consortium resulted from these collaborations.

From the beginnings of its interactions with industry [12], C&B was told that barriers to innovation in construction practices and products were severe disincentives to increased private sector investments in research. Among principal barriers were 1) the multiple approvals of innovative products required by federal agencies and the regulatory authorities of state and local governments, and 2) the multiple, uncoordinated reviews and approvals imposed upon construction projects by the regulatory authorities of federal, state and local governments. To address the first barrier, C&B agencies supported the formation of nationally recognized evaluation centers: for building products by the International Code Council and CERF, and for highway, environmental and civil engineering products by CERF. To address the second barrier, C&B funded the National Conference of States on Building Codes and Standards (NCSBCS) to develop a program for Streamlining the Building Regulatory Process [24]. The Streamlining program identified, and made available nationally, best practices used successfully in various localities [25]. Because of the potential for information technologies for efficient sharing of information by project proponents and regulatory authorities, the Streamlining Project has evolved into NCSBCS's National Alliance for Building Regulatory Reform.

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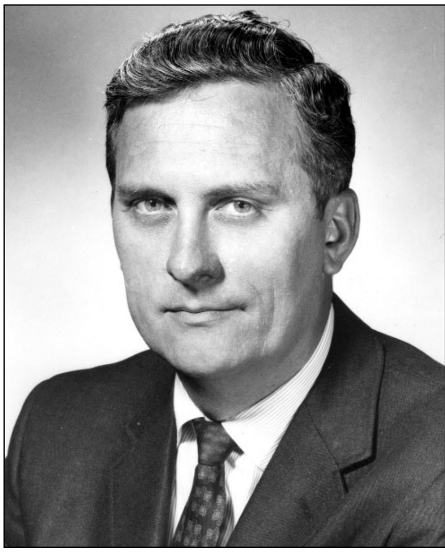
7. ARCHITECTURE, ENVIRONMENTAL PSYCHOLOGY, AND ACOUSTICS

From the time in the late 60s when John Eberhard and James Wright began to rebuild the Division of Building Research, Architectural Research and Environmental Psychology were seen as important program and growth areas. CBT was formed in 1972 with an Architectural Research Section in its Technical Evaluation and Applications Division and a Sensory Environment Section in its Building Environment Division. Most Acoustics research had been transferred to the Engineering Mechanics Division, but this returned to CBT in 1978 with the establishment of the National Engineering Laboratory and the elimination of the Engineering Mechanics Division. Eberhard was a strong advocate for advancing NBS's building technology program and worked hard to understand users needs for technologies. He said, "We don't produce cities as abstract things, but as places people can use. Yet even today (late 60s) we don't know how to relate the human to their environment (in urban areas)."

CBT management continued to believe in the importance of this work. Quantitative knowledge of how the built environment affects human health, safety and behavior is essential to providing functional, safe and economical constructed facilities. Architects are responsible for many or most of the early decisions affecting the usefulness, safety and economy of buildings. CBT should work closely with architects to identify and provide the measurements, performance prediction methods and standards they need. Throughout the 70s these areas received very little directly appropriated funding and CBT received no support from NBS for initiatives to increase their funding. Nevertheless, CBT and its staff members were recognized well in the architectural and environmental psychology communities for their leadership in research.

However, when the Reagan Administration imposed staffing cuts on NBS in the 80s, NBS felt it should focus its limited personnel resources on measurement-oriented physical sciences and engineering. CBT was directed by NBS management to eliminate its work in architectural research, environmental psychology and psychoacoustics.



John P. Eberhard, director, Institute for Applied Technology 1966-1970.

7.1 STAIR SAFETY

Stair safety was a major topic in architectural research [1,2]. Within CBT, the research was led by John Archea with collaborations from Belinda Collins, Steven Margulis, and Frederick Stahl. The team made extensive video studies of how people used stairs and the apparent causes for accidents and near accidents. The user's approach and orientation to the stairway was found critical to safety: the beginning of the stair should be clearly defined and distractions to the user's attention minimized. Stairs should be regular; the user expects tread height and depth to remain the same and is likely to be tripped up by changes. This, other CBT safety research, and research elsewhere was prepared for dissemination to architects and builders under a contract from CBT [3], although the original CBT reports continue to be requested to this day. The model building code organization, Building Officials and Code Administrators, International, cited this research as a major contribution to stair safety [4], and the results were incorporated in the 1982 edition of Architectural Graphic Standards. In January 1981, Progressive Architecture, awarded a research prize to CBT and BOSTI (Buffalo Organization for Social and Technological Innovations) for the Home Safety Guidelines for Architects and Builders.

John Archea videotaping persons ascending and descending stairs to evaluate possible barriers to slips and falls.

7.2 SECURITY

John Stroik led CBT's research on burglar resistance of doors and ASTM's development of security standards for doors [5]. Criteria were established by analysis of available data on burglars' methods, duplication of the attacks, and measurements of effects of the duplicated attacks.

7.3 HUMAN RESPONSE IN FIRES

Frederick Stahl, in support of the Center for Fire Research's research to quantify fire hazards, developed, and verified through observations of human behavior, a computer program BFIRES for simulation of human movements during building fires [6,7]. The model postulates that people construct their emergency responses and behavioral decisions dynamically in response to what they observe themselves and observe others doing. This work was incorporated in HAZARD, CFR's computer program for predicting the hazards produced by fire scenarios, and is used in its successors.

7.4 ENERGY CONSERVING DESIGN

One of the first issues for energy conservation in buildings was building fenestration - or windows. In the early 70s,the bulk of buildings used single-glazed, transparent materials, which allowed for significant energy losses in terms of excessive heat gain during the day, and heat loss at night. To solve the problem, some designers and engineers suggested reducing or eliminating windows. Others suggested analyzing all aspects of windows, including the positive lighting benefits provided by daylighting, more creative use of heat gains and losses, and consideration of any psychological benefits to building occupants.

The Center for Building Technology convened a multidisciplinary group to

S. Robert Hastings and an assistant are discussing methods to minimize unwanted solar heat gain.

evaluate all aspects of window performance. The group consisted of an architect, an economist, a psychologist, and a thermal engineer. Belinda Collins led the team. Collins, an environmental psychologist, led interdisciplinary studies of energy conservation in buildings and color rendering of lighting for safety symbols. Its publications [8, 9, 10] stimulated much greater national consideration of the benefits of daylighting, building orientation, usable solar gains, life cycle costs, and psychological responses.

As a result of the NBS research, building codes were modified to include the opportunity for daylight tradeoffs, solar and multi-layer glazing, solar controls, and utilization of beneficial solar heat gains, while minimizing unwanted heat loss. Building design became more flexible by allowing architects and designers to use building site and location more effectively, while continuing to meet occupant needs. Applications in Architectural Graphic Standards put the results on the desks of architectural designers while NBS's thermal load determination programs by CBT's Tamami Kusuda, enabled engineers to make the necessary thermal calculations and tradeoffs easily and accurately.

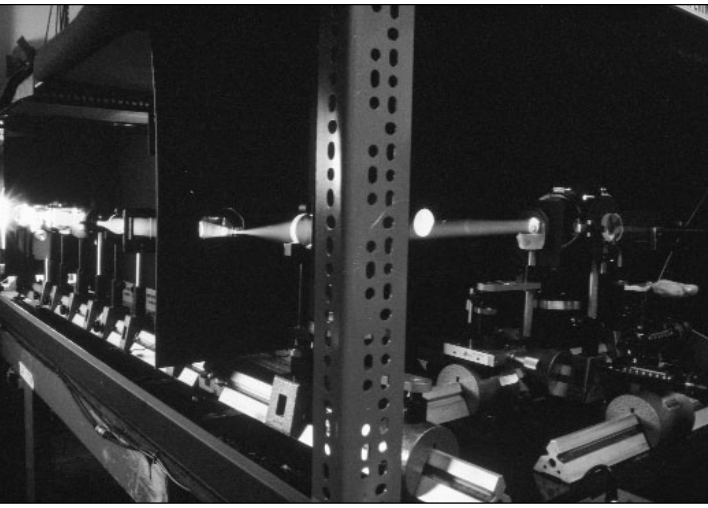
S. Robert Hastings provided architectural expertise to a variety of CBT programs for energy conservation and solar energy. His "typical houses" for assessment of energy conservation and solar energy options have been used extensively by researchers and practitioners, worldwide [11].

Edward Arens, an architect expert in wind and other environmental effects on people, collaborated with Preston McNall of the Building Environment Division and researchers from the J. B. Pierce Foundation to update the "bioclimatic" chart describing comfort as a function of clothing, activity level and the thermal environment [12]. This information was valued by researchers and designers dealing with the broader range of thermal environment encountered with passive solar energy systems.

7.5 COLOR AND SAFETY SIGNS

Kenneth Kelly continued and completed Dean Judd's many years of research at NBS to characterize color and issued the Universal Color Language and Color Names Dictionary [13].

During the late 1970s researchers became aware of the importance and effectiveness of both symbols and colors in communicating important safety-related information. The Center for Building Technology responded by directing resources toward research into the understandability of pictorial, safety symbols [14]. Research was conducted in support of programs at the Occupational Safety and Health Administration (OSHA), National Institute of Occupational Safety and Health (NIOSH), and the Bureau of Mines (BOM). In addition, CBT researchers, including Belinda Collins, Brian Pierman, and Neil Lerner worked with industry, which wanted to develop voluntary consensus standards for safety symbols to be used on equipment and in facilities. Following the initial research into symbols, Belinda Collins and her colleagues also investigated the role of both color and lighting spectrum to determine if safety colors could be detected and identified accurately under the newer, more efficient light sources being used in industrial and agricultural facilities [15]. Next, Jim Worthey and Belinda Collins extended these procedures to an evaluation of the visibility of diseases, defects and contamination in



CBT's illumination test facility is used to develop illumination/color criteria. The research facility provided a basis to better understand the interactions between the occupants and the illumination/daylighting systems of a building. It provides a realistic environment for studying color rendering (distortion) of energy-efficient lighting systems.

meat and poultry under different light sources [16]. Finally, Belinda Collins and her colleagues conducted investigations into the visibility of exit signs, symbols, and exit directional indicators in clear and smoky conditions, again to verify the understandability and visibility of different proposed standards for exit symbols and indicators [17]. The team involved research psychologists and safety engineers who conducted research in a variety of field conditions, including actual industrial facilities, meat and poultry processing facilities, and mine sites, as well as in laboratory conditions.

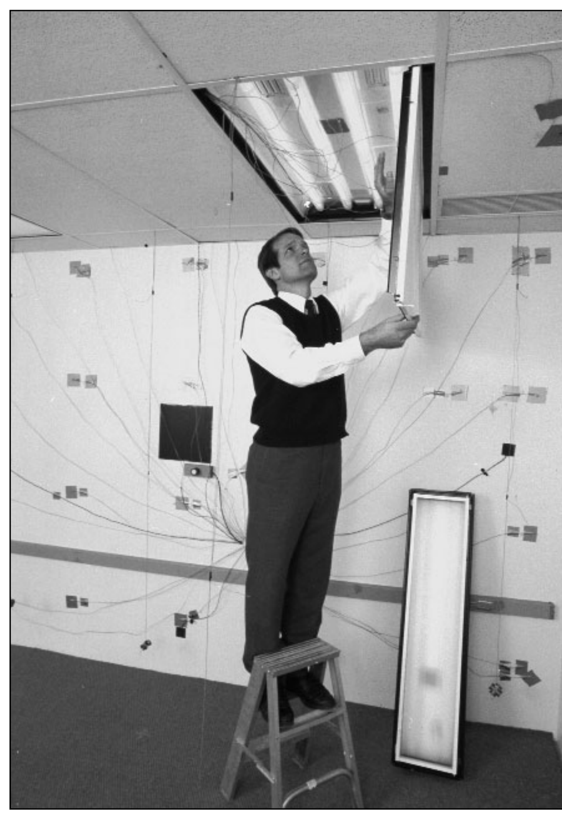
The data developed by CBT researchers were used as input into the set of ANSI Accredited Committee Z535 Standards for Safety Signs and Colors. In particular, Z535.3, 1979, Safety Color Code for Marking Physical Hazards, relied heavily on the NBS findings for the understandability of symbols in both workplaces and mines. At the same time, NBS also chaired the NFPA Committee on Life Safety Symbols, which developed a standard for life-safety symbols. That committee also relied on the NBS research on the visibility and understandability of an exit symbol - which eventually became an ISO symbol. In addition, OSHA referenced the NBS research in the Code of Federal Regulations. Finally, USDA issued regulations setting minimum color rendering guidelines for meat and poultry processing facilities based on the NIST research on detectability of defects and disease under different, energy-efficient light sources.

Belinda Collins received the Bronze Medal Award of the Department of Commerce in 1984 for her work on illumination engineering and safety symbols.

7.6 LIGHTING

Gary Yonemura [18] questioned the accepted psychophysical basis for lighting standards - the ability to just perceive an object (threshold visibility) does improve with increased illumination and led to the view "more light gives better sight." However, few visual tasks are carried out at threshold conditions. For normal, suprathreshold levels of illumination, Yonemura's work showed a definite maximum in visibility; for greater or lesser luminance more contrast being required for subjectively equal visibility. In recognition of this work and its influence on energy conserving lighting standards, Yonemura received the Presidential Award of the Illuminating Engineering Society of North America in 1981. Arthur Rubin led the work of CBT researchers with the lighting community to define the research, standardization and education efforts needed to improve lighting practices [19]; for these efforts he received the Presidential Award of the Illuminating Engineering Society on North America in 1982. Also, Richard Wright served as chairman of the Board of Directors

Steven Treado, mechanical engineer, is exchanging experimental luminaries in research to develop and verify models for the interaction between lighting and HVAC systems. Lighting quantity and quality affect safety, productivity, and the performance of HVAC systems.



of the Illuminating Engineering Research Institute and its successor the Lighting Research Institute from 1980-1983.

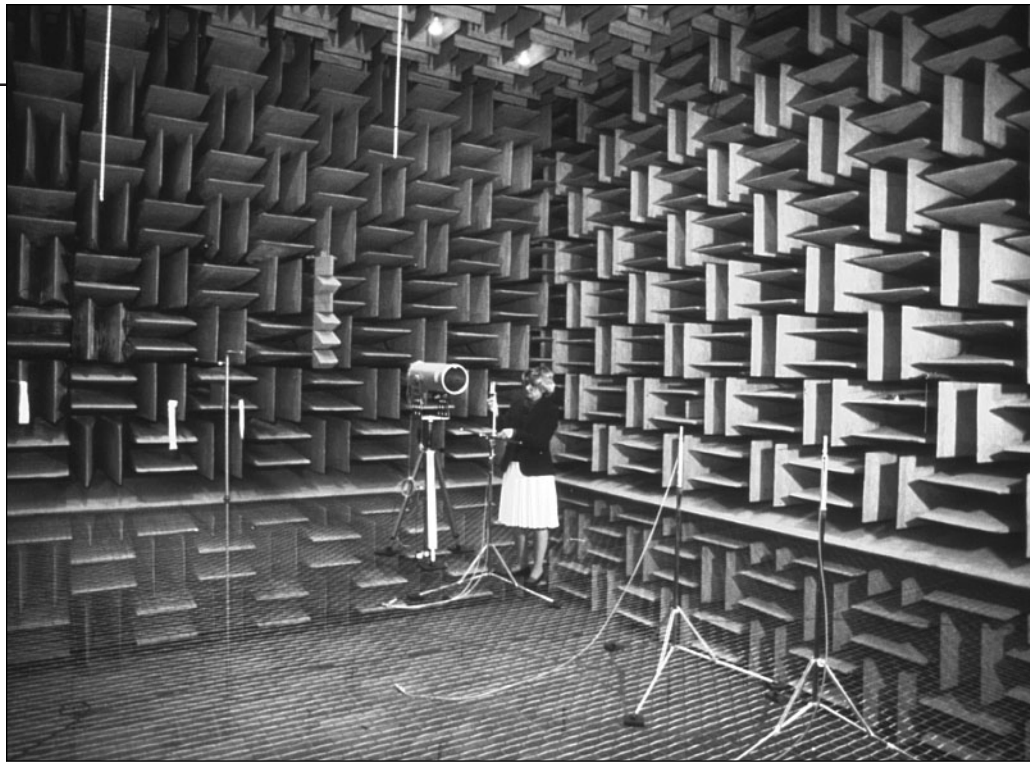
7.7 BUILDING FOR PEOPLE

Arthur Rubin and Jacqueline Elder capped many years of work with publication of the hardcover, well illustrated book *Building for People* [20]. It is a thoughtful manifesto for the potential contributions of the social sciences to the solution of building design problems. It received the 1981 Blue Pencil Publication Award from National Association of Government Communicators. However, because its intended audience of architects and architectural students generally seek actual rather than potential contributions to such solutions, the book's impact on practice seemed modest. In application of this work, in January 1982, a CBT-sponsored post occupancy evaluation of a federal office building by the University of Michigan's Institute of Social Research won a Progressive Architecture Award.

7.8 ACOUSTICS

Acoustics researchers in the Engineering Mechanics Division and architectural researcher Robert Wehrli of CBT collaborated to produce a design guide for reducing transportation noise in and around buildings [21]. It presented a unified procedure for selection of noise criteria, prediction of exterior and interior noise levels, and the evaluation of the adequacy of building designs. Collaboration in development of highway and building noise criteria [22, 23, 24, 25] continued for several years led by Daniel Flynn of the Center for Mechanical Engineering and Process Technology (a former member of the Division of Building Research) and Simone Yaniv of CBT. Results were used in ASTM standards.

John Molino, Neil Lerner and colleagues who joined CBT from the Engineering Mechanics Division [26] continued and reported psychoacoustic studies of the aversive effects of corona noise from electrical power transmission lines. Thomas Bartel used the CBT reverberation chamber to study the effects of edges on the acoustical absorption of materials [27]. This work received the "best paper" citation of the Technical Committee on Architectural Acoustics of the Acoustical Society of America. Simone Yaniv received the Bronze Medal Award of the Department of Commerce in 1986 for her work in characterizing semi-reverberant spaces.



Simone Yaniv making adjustment to test equipment in NBS Anechoic Chamber.

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8. CONSTRUCTION INTEGRATION AND AUTOMATION

8.1 INFORMATION EXCHANGE STANDARDS FOR CONSTRUCTION

In 1983 Samuel Kramer, Deputy Director of the National Engineering Laboratory (NEL), asked CBT to involve its new Computer Integrated Construction Group in the work to create the Initial Graphics Exchange Standard (IGES) of the American National Standards Institute (ANSI). This request came on the heels of strong building industry expressions of its need for data exchange standards in such forums as the First and Second Congresses on Computers/Graphics in the Building Process cosponsored by the Advisory Board on the Built Environment of the National Research Council and the National Computer Graphics Association.

IGES was intended to provide a neutral (non-proprietary) interchange language for the description of products (initially machine parts) for the automatic exchange of information between dissimilar computer systems used in design and manufacturing. The neutral interchange language was a brilliant and essential concept. Only *n* translators to and from the neutral form are required to interchange information among n dissimilar systems, rather than the *n* times (n-1) translators required for direct interchange between each pair of systems. A new system can be introduced with the development of only one neutral-language translator, rather than *n* direct translators. In addition, the developers of a proprietary system do not need to reveal anything about their data management practices to their competitors or users. Furthermore, the carefully prepared neutral interchange language can serve as an initial or default data structure in the development of proprietary or open system software. Finally, the neutral interchange language provides a natural archiving format for data that may need to be reused long after the originating system is retired.

The IGES effort took off with the stimulation of Air Force, Navy, and NASA management when NBS agreed to champion it as chair and coordinator. The IGES approach was based on technology developed in government and industry projects in the late

1970s, including work in one of Director Ambler's first competence projects in 1978. Bradford Smith of the Center for Manufacturing Engineering headed the IGES Committee that soon became the IGES/PDES Organization.

CBT management was eager to participate in IGES. Automatic exchange of information between dissimilar systems was essential to the effective exploitation of information technology in the construction industry and the whole life cycle of constructed facilities. Many distinct organizations are involved in the life cycle of a constructed facility; owner, designers (architect, structural engineer, mechanical engineer, etc.), contractors (general, site work, concrete, mechanical systems, etc.), regulators, financers (construction loans and long term finance), occupants, maintainers, rehabilitators, etc. Generally, the team of organizations involved in a specific project never has worked together before and never will work together again. It is infeasible for all involved organizations to acquire and use computer hardware and software from the same vendor, or to maintain such hardware and software for the 50 year life typical of a constructed facility. The alternative to automatic exchange of information between dissimilar computer systems is to accept the costs, delays, and mistakes involved in manual transfer of data from one computer's output to another's input.

1983, the beginning of the Administration's efforts to eliminate CBT, was a challenging year to begin a new program thrust. Funds were reprogrammed within CBT and augmented with NEL reserve. Staffing was even more difficult with new skills needed while a CBT cutting staff was unattractive to recruits. Frederick Stahl, who had founded the Computer Integrated Construction Group, departed CBT for work in industry. Kent Reed, a Ph.D. physicist, who joined CBT in 1981 to work in solar energy but had great interest in computer systems, undertook leadership of the group. Reed exemplified the NBS/NIST concept "if you have a challenging new problem, give it to a physicist." Mark Palmer, an architect and engineer experienced in commercial, institutional, and residential building projects, with an advanced degree in Computer Aided Design from the Mechanical Engineering Department of MIT, and infectious enthusiasm for knowledge of and practice in building, joined the Group in 1985. William Danner, a Ph.D. psychophysicist who had retrained himself as an acoustician in response to NBS program changes, joined the group in 1985 to exploit his capabilities in computer simulation and computer aided design. James Barnett, physicist and software engineer, was a founding and continuing member of the group.

The Group promptly organized and led the Architecture, Engineering, and Construction (AEC) effort of IGES and its successor the Product Data Exchange Specification of ANSI. First Stahl and then Reed served as co-chairman, each with a co-chairman elected from industry, of the AEC Committee of IGES/PDES. This committee had a strong influence on the formation of its AEC counterpart in the emerging international standardization effort known familiarly as the Standard for the Exchange of Product Model Data (STEP) and formally as ISO 10303—Product Data Representation and Exchange—that is the international analogue of PDES. Reed took over the editorship of IGES during the balloting of IGES V4.0 [1] and served as IGES Editor for three consecutive versions. During this time numerous capabilities essential for the AEC industry were added as new capabilities or explicated as informative appendices. Reed also served as the NBS/NIST representative to the U.S. Technical Advisory Group to ISO TC184/SC4 (External Representation of Product Definition Data). Palmer chaired the Application Validation Methodology Committee of IGES/PDES and also served on the U.S. Technical Advisory Group.

AEC information exchange is technically more challenging than that for most manufacturing [2]. A product, for instance a door, carries much more information that its dimensions, information such as acoustical properties, thermal properties, fire resistance, security capabilities, appearance, etc. Danner, Palmer, and colleagues in the IGES/PDES Organization and ISO TC184/SC4 developed the data modeling concept [3] and the Application Protocol [4] approach for its implementation to meet these AEC needs.

With support from the U.S. Navy (exchange of piping systems information is as important for ships as it is for chemical plants and buildings), BFRL led the development of the first IGES application protocol [5]. BFRL led the development of the STEP AP methodology and the corresponding Guidelines [6] by which ISO applies this methodology in the development of STEP. To sustain this methodology, Palmer served as the first AP Coordinator for ISO TC184/SC4.

The PlantSTEP Consortium was formed in 1995 by leading process plant owners, contractors, software suppliers, and BFRL to advance information exchange standardization. BFRL also worked with pdXi (Process Data Exchange Institute of AIChE), PIEBASE (Process Industry Executive for Achieving Business Advantage Using Standards for Data Exchange), NIDDESC (U.S. Navy-Industry Digital Data Exchange Standards Committee), and the International Alliance for Interoperability, advancing contributions to STEP and other data exchange standards. BFRL contributed to a number of STEP Application Protocol projects relevant to the AEC industry. In particular, BFRL led the development of STEP AP227, Plant Spatial Configuration [7].

BFRL also has been especially involved in developing methods for validating draft specifications and for testing translators for conformance to STEP standards.

William Danner and Mark Palmer received the Bronze Medal Award of the Department of Commerce in 1993 for their contributions to the international standards for automatic exchange of design and construction information. Kent Reed received the Silver Medal Award of the Department of Commerce in 1994 jointly with two colleagues in other NIST laboratories for their contributions to the initial release of ISO 10303, STEP.

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8.2 CONSTRUCTION SITE METROLOGY

In the mid 1980s, CBT and the Robotics Systems Division of the Center for Manufacturing Engineering of NBS, led by James Albus, became aware of large Japanese investments in research for automation in construction and decided to determine what research the U.S. should perform to retain technical leadership for competitiveness in construction. A workshop of fifty technical experts from universities and the industries of automation and construction was convened in February 1985 [1] to determine needs and priorities for research in measurement technologies for automation in construction and large-scale assembly (such as ship building). Top priority research on construction metrology was determined to be justified for productivity in construction even without automated equipment on the construction site and also to be essential for integrated automation of construction site activities:

1. Computerized data bases, particularly an as-built data system including standardized data elements and interfaces.
2. Automated systems for inventory management, particularly on-site part labeling and tracking of materials handling equipment.
3. On-site metrology to measure the characteristics of construction as

actually built to feed an as-built data base with data on position, dimensions and quality control.

CBT's Computer Integrated Construction group led by Kent Reed addressed the standardization of data and interfaces needed for automatic exchange of information between the information systems of construction project participants. William Stone, structural engineer and underwater explorer, built upon both sets of interests and skills to champion CBT/BFRL efforts in construction site metrology. The publications referenced in the following describe the technologies and the software produced to improve real time construction site metrology.

Pulse-synthesized, base-band electro magnetic signals were used to measure distances to targets through solid walls [2]. Accuracy to 10 mm was achieved when obstacles were well characterized (the dual problem solved was non-destructive characterization of the obstacles).

A prototype world model of a construction site was developed to demonstrate the feasibility of real-time remote control of construction operations with a simulation tracking both equipment and resources using real-time data from the site [3]. The National Construction Automation Testbed was established to assist contractors and manufacturers of sensors, controls and equipment in developing and evaluating products for construction site automation.

Auto-registered Lidar range sensing systems integrated with wireless communications, high speed networking, temporal project databases, web-based data analysis and 3D user interfaces have been demonstrated for on-site and remote control of earthworking operations [4,5].

BFRL has worked with the Construction Industry Institute to establish the FIATECH consortium to conduct research and development in partnership with construction equipment suppliers, information technology suppliers, owners of constructed facilities and contractors for fully integrated and automated project processes. BFRL's construction site metrology efforts are a key element of FIATECH. BFRL's prospective assessment of the benefits of its construction metrology research [6] indicates potential cost savings of five times BFRL's investment for applications in industrial construction projects alone.

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9. ECONOMICS

9.1 OVERVIEW OF ECONOMICS RESEARCH FOR BUILDING AND FIRE PROGRAMS

The goal of the Office of Applied Economics (OAE), of the Building and Fire Research Laboratory, has been to bring state-of-the-art economic decision tools and data to decision makers in a form that they can understand and use. The focus has been on delivering useful economics research that would provide the maximum impact for the available research budget. Several strategic principles were followed: (1) conduct research in areas of high national interest (e.g., energy economics starting in the 1970s); (2) transfer research findings and tools to users in the building community via multiple routes-through professional societies and standards organizations (e.g., American Society for Testing and Materials (ASTM)), training, and publishing; and (3) adapt the format of OAE products to the technology and customer attitudes in the current market (e.g., switching over time from technical reports to user-friendly, decision-support software).

The OAE has provided economic products and services through research and consulting to industry and government agencies in support of productivity enhancement, economic growth, and international competitiveness, with a focus on improving the life-cycle quality and economy of constructed facilities. The focus of OAE's research and technical assistance is microeconomic analysis. The OAE provides information to decision makers in the public and private sectors who are faced with choices among new technologies and policies.

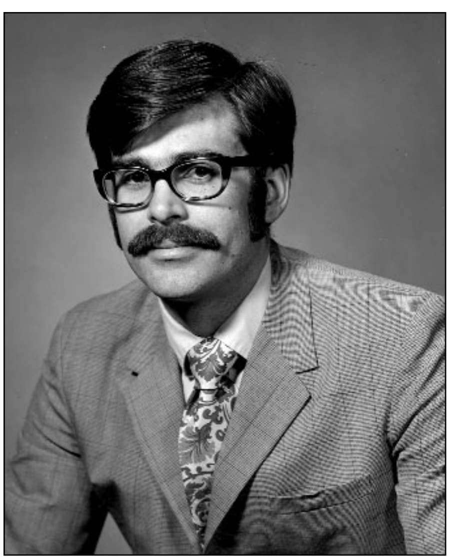
The OAE staff have competence in economics, financial analysis, operations research, cost engineering, and software development. Benefit-cost analysis, life-cycle costing, multicriteria decision analysis, risk analysis, linear programming, statistical modeling, and econometrics are techniques the OAE has used in evaluating new technologies, processes, governmental programs, legislation, and codes and standards to determine efficient alternatives. Research areas include energy conservation in buildings, fire safety, automation, seismic design, and building economics. Products include

Office of Applied Economics, October 2001

reports and articles on research findings; standard methods and guidelines for making economic evaluations; audiovisuals that teach and illustrate methods in practice; training programs; and decision-support software with documentation.

During the period 1967-1973, several economists and cost engineers supported various programs in the Center for Building Technology (CBT). The establishment of a separate building economics group, however, came with the hiring of economist Harold Marshall as Group Leader in 1973. Over the next 27-years, the group varied in size, increasing to 20 persons prior to the Reagan administration personnel cuts, and becoming stable in recent years at about 10-12 permanent employees. The group used two strategies to attract and retain productive employees. It organized the group by discipline to encourage economists to join and stay with the research team, and it provided research opportunities in areas of national importance that excited employees about the chance to do meaningful work.

Harold Marshall, leader, Office of Applied Economics.



The name of the group changed from Building Economics to Office of Applied Economics (OAE), and the group moved in 1981 to the Computing and Applied Mathematics Laboratory for a 14-year period. While the OAE had the charter to work in any industrial sector, the staff's expertise and client history continued to focus research on the building industry area. The group returned to the Building and Fire Research Laboratory in 1995.

Funds for the operation of the OAE come in part from Federally appropriated money through NIST and in part from other government agencies that enter into agreements with OAE for research services. While virtually all of OAE funds come from Federal sources, in some years as much as 85 percent has come from non-NIST agencies.

Examples of other agency sponsors of OAE work are the Department of Energy, Public Health Service, General Services Administration, National Institute of Justice, Environmental Protection Agency, and the Department of Housing and Urban Development. The OAE also provides economic support for other major operating units within NIST, the two largest efforts being for the Advanced Technology Program and the Manufacturing Extension Partnership Program.

All work done by the OAE is in the public domain. While some private sector clients want proprietary control over their research, and are therefore reluctant to fund OAE research directly, OAE does collaborate with private interests in identifying industry needs and in creating research agendas. In addition, since many of the products are economic evaluation methods and user-friendly software, non-government, as well as government, organizations benefit directly from OAE research.

The OAE has collaborated with researchers from every Office and Group within BFRL. Economists typically work with professionals from other disciplines, so it was natural to capitalize on multidisciplinary, and ultimately interdisciplinary, arrangements to treat building industry problems from multiple perspectives. This ability to work with other disciplines made it possible for the OAE to find other agency clients to support OAE research consistent with the BFRL and NIST missions. Moreover, the collaboration required of other agency work has helped focus OAE efforts on areas of high national interest that offer significant research payoffs.

Overviews of Major Projects

Nine major projects epitomize OAE's responsiveness to significant economic measurement needs of the building community. Following is a brief overview of each of the nine projects that describes project accomplishments and identifies the principal investigators. In the sections that follow the overviews are more detailed descriptions of each of the nine projects.

Economics of Energy Conservation–The energy crisis in the 1970s spurred the OAE to address the problem of how to measure and evaluate the appropriate level of investment in energy conservation in buildings. Scarcity and rising prices of energy forced the world to revise traditional approaches to construction, maintenance, and operation of buildings. Stephen Petersen's pathbreaking report on retrofitting existing housing for energy conservation redirected the U.S. Department of Energy's (DOE's) policy from promoting Btu budgets exclusively to seeking economically efficient levels of energy conservation investment. His BLCC 4.0 computer program for evaluating energy conservation investments has been used nationwide. For 20 years, Harold Marshall, Rosalie Ruegg, and Stephen Petersen developed and taught life-cycle cost workshops and produced reports in support of DOE's energy conservation program. Sieglinde Fuller and Amy Rushing continue that tradition today; in 2000 an enhanced, graphical version of BLCC was completed and has become the premier life-cycle costing software in energy conservation.

Standard Economic Methods in Building Economics–This project started with BFRL's suggestion to ASTM's Building Performance and Constructions Committee that a new subcommittee called Building Economics be established. Harold Marshall became the first chairman in 1979 and remains so today. For 20 years this subcommittee has helped shape the research agenda for the OAE and provided a forum for presenting to the building industry OAE research results. Robert Chapman, Harold Marshall, Stephen Petersen, and Rosalie Ruegg made substantial contributions to economic measurement by drafting for and guiding through the ASTM balloting process 13 standard economic methods, guides, and adjuncts based on their research. The subcommittee continues today to be an excellent link to industry, academia, and government users of OAE products.

Cost-Effective Compliance with Life Safety Codes–The Life Safety Code for fire protection in buildings is a prescriptive code that specifies solutions. It allows, however, for equivalent solutions to be substituted. In 1978, NIST fire researchers Harold Nelson and A. J. Shibe developed a system of assigning points that would help the designer choose equivalent, alternative building solutions to the prescribed solution for health care occupancies. Robert Chapman and William Hall, in 1982, developed software that allowed the user to find many alternatives close to the least-cost solution that would satisfy the code requirements. Stephen Weber and Barbara Lippiatt, in 1994, enhanced the software, now called ALARM, to greatly facilitate its application. Stephen Weber and Laura Schultz extended ALARM to make it applicable to correction and detention facilities. Conservative estimates of the cost savings from applying ALARM to the design of military hospitals over a 10-year period exceed $100 million.

Economic Impacts of BFRL Research–NIST and other research institutions need quantitative measures of research impacts to efficiently allocate their budgets among competing research projects and to evaluate the success of past projects. Harold Marshall and Rosalie Ruegg published the first such impact study in CBT in 1979. Four subsequent reports, authored by Robert Chapman, Stephen Weber, and Sieglinde Fuller, were published between 1996 and 2000. Robert Chapman's application of these methods to the estimation of cost savings to the public from BFRL investments in cybernetic building systems, for example, showed cost savings of almost eight dollars for every dollar of BFRL investment. In addition to showing significant net dollar impacts from selected NIST research projects, this series of reports provided (1) a standard framework for categorizing research benefits and costs and (2) standard methods for measuring and evaluating those benefits and costs.

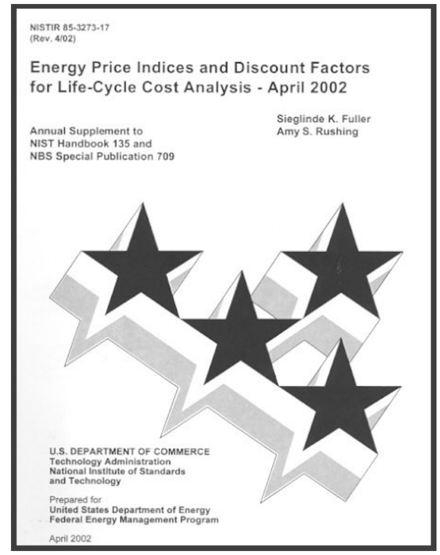
Applications of the Analytical Hierarchy Process (AHP)–The AHP is a method that considers nonfinancial characteristics and economic measures in evaluating investments. Economists in OAE have applied the AHP method to decisions in automated manufacturing, fire sprinklers in residences, green-building investments (BEES), and in the choices of building design and location. Robert Chapman and Harold Marshall worked with ASTM and Expert Choice, Inc. to produce an AHP software product that supports ASTM standard methods for economic evaluation. For fiscal years FY 1998-2000, BFRL management used the AHP with a series of resource allocation models developed by Robert Chapman to rate budget proposals and to allocate the BFRL research budget.

BEES: Building for Environmental and Economic Sustainability–BEES, developed by Barbara Lippiatt, is a cradle-to-grave life-cycle assessment tool that helps users measure and evaluate the environmental and economic performance of building products over their lifetimes. A traditional life-cycle cost comparison of products may reveal the most cost-effective choice, but it fails to account for related environmental impacts such as resource depletion, global warming, and acid rain. BEES fills this gap by providing the developer, owner, manufacturer, and architect with software for measuring and comparing both environmental and economic performance of building products using a single performance score. Two hundred building products can now be evaluated with the software, and additional products continue to be added.

UNIFORMAT II Elemental Classification for Building Specifications, Cost Estimating, and Cost Analysis–Building elements are major components, common to all buildings, that perform a given function regardless of design specifications, construction, method, or materials. Examples of elements are foundations, exterior walls, and lighting. A standard elemental classification of buildings is needed to provide a consistent reference for the description, economic analysis, and management of buildings during all phases of their life cycle. Harold Marshall, in collaboration with consultants Robert Charette and Brian Bowen, developed a standard set of elements called UNIFORMAT II. It became an ASTM standard classification and has been embraced widely in the United States by the Construction Specifications Institute, the Design-Build Institute of America, R.S. Means Company, Inc., Whitestone Research, and government agencies responsible for constructing buildings. Since elemental cost estimates are faster and less costly to make, UNIFORMAT II is making possible cost savings from informed design tradeoffs early in the planning process when the greatest savings from design choices are possible.

Baselines and Measures for the National Construction Goals–The Subcommittee on Construction and Building of the National Science and Technology Council developed seven National Construction Goals at its founding in 1994. The goals were intended to attract the support and cooperation of policy makers in federal agencies and in the private sector to the subcommittee's efforts to focus and coordinate federal R&D, to enhance the competitiveness of U.S. industry, and to promote public safety and environmental quality through research and development to improve the life-cycle performance of constructed facilities. Robert Chapman drew upon his experience assisting the Construction Industry Institute to establish baselines and measures for progress on its related goals to define baselines and measures for the National Construction Goals.

BridgeLCC–BridgeLCC, developed by Mark Ehlen, is a user-friendly, life-cycle costing software tool. It is used



BLCC version 5.1, and the discount factors annual supplement to the software.

to evaluate the economic performance of new/alternative construction materials as compared with conventional materials in the construction of bridges. While the tool is specially tailored to compare new and conventional bridge materials, such as high-performance concrete vs. conventional concrete, it can also be used to compare alternative conventional materials and for the analysis of civil infrastructure other than bridges.

9.2 ECONOMICS OF ENERGY CONSERVATION

The energy crisis of the early 1970s focused the attention of the building community on the high consumption of energy rather than on simply providing adequate cooling and heating, lighting, water heating, and other energy-related building services. Energy shortages, increasing energy prices, and significant media coverage encouraged conservation nationwide. Government and private sector facility managers as well as homeowners needed guidance regarding what conservation investments were economically justified given higher energy costs and forecasts of more increases to come. When the Building Economics Group (the forerunner of the Office of Applied Economics) was established in BFRL in 1973, its first major undertaking was to take a leadership role under the sponsorship of DOE in working with researchers from other disciplines to measure the life-cycle net savings from alternative approaches to energy conservation in buildings. The National Energy Conservation Policy Act, signed by President Carter in 1978, called upon the Secretary of The Department of Energy (DOE), in consultation with NBS, "...to (1) establish practical and effective methods for estimating and comparing life-cycle costs for Federal buildings, and (2) develop and prescribe the procedures to be followed in applying and implementing the methods so established."

The first challenge was how to provide useful, unbiased, information to building owners, the building trades, and government agencies on the economic tradeoffs between energy conservation and energy consumption in the design and retrofit of new and existing buildings.

Stephen Petersen's BSS 64 report *Retrofitting Existing Housing for Energy Conservation* [1] provided specific guidelines for determining economically optimal retrofit strategies for installing insulation and storm windows in existing houses based on site-specific energy prices, climate factors, heating and cooling equipment efficiencies, and retrofit costs. This report, with an initial dissemination of over 1,000 copies, showed energy policy makers that significantly larger investments in energy conservation (than had been made up to that time in most housing units) were cost effective based on a life-cycle cost analysis.

Making the Most of Your Energy Dollars, a consumer-oriented pamphlet [2] by Madeleine Jacobs and Petersen, was adapted from the BSS 64 report. The pamphlet, with a distribution of over a half-million copies, helped homeowners determine the best combination of energy conservation improvements for their home's unique design, climate, and fuel costs so as to provide the highest, long-run, net savings in home heating and cooling costs.

Petersen's *Building Life-Cycle Cost* (BLCC) computer program [3], expanding on the economic methodology used in BSS 64, helped owners and managers of all building types make more cost-effective choices related to energy conservation and energy use in buildings. The BLCC computer program, ultimately adopted by ASTM as a product in their software series, implemented the life-cycle cost methods introduced in BSS 64. The DOE, along with a number of public and private sector software vendors, distributed annually up to 5,000 copies of the software. The Java version, BLCC 5.1, is now available directly on the internet.

Petersen's Zip-Code Insulation Program [4] provided specific recommendations for insulation levels in houses based on local energy prices and climate factors (keyed to Postal Zip Codes) for the entire country.

A second challenge was to redirect DOE away from promoting BTU energy budgets to seeking economically efficient levels of energy conservation. BSS 64 made it clear that overinvestment as well as underinvestment in energy conservation was economically inefficient.

In the late 1970s, solar economics became a part of the group's research. Rosalie Ruegg, and Jeanne Powell published reports [5,6] on the economic evaluation of solar heating and cooling technologies for home and commercial environments. OAE's solar work was well received and widely used during the period when alternative energy sources were explored intensely.

In the early 1990's, DOE added renewable energy projects and water conservation to its portfolio of conservation strategies. The economics group at the OAE adapted its life-cycle cost methods, software, and instructional materials to accommodate new legislation and user requirements.

Another significant effort for DOE provided by the economics group was the teaching of 2-3 day life-cycle cost (LCC) workshops around the U.S. and abroad. In support of those workshops, Harold Marshall, Rosalie Ruegg, and Stephen Petersen developed reports, workbooks, case studies, and three instructional videos for helping government facility planners and private consultants evaluate the cost effectiveness of alternative energy-conservation investments and policies [7]. In recent years, Sieglinde Fuller and Amy Rushing continue to support DOE with reports, workshops, and a BLCC software product programmed in Java [8].

OAE workshops, taught in person around the world and via teleconferencing, have presented to users these methodologies, tools, and data for evaluating energy conservation investments to well over 2000 seminar attendees over the last 20 years. The internet makes OAE products even more accessible.

OAE participation in ASTM has been particularly effective in transmitting standard economic methods and software to the building community concerned with energy and water conservation and renewable energy. The first standard published by the ASTM's Building Economics Subcommittee was the Life-Cycle Cost standard. It was drafted by OAE staff in response to the subcommittee's plea for a way of evaluating energy conservation investments.

A major impact of economics work in energy conservation was a shift in philosophy from merely minimizing building energy consumption to optimizing on economic grounds the level of energy conservation investment and energy consumption. The public policy result was a shift from codes and standards based solely on energy budgets to a more flexible policy that takes into account the dollar cost of energy.
NBS Director Richard Roberts, in his annual "state of the NBS" address in 1975, declared the CIS pamphlet on Energy Dollars to be the outstanding NBS publication for the year because it successfully addressed the energy crisis in the large stock of U.S. housing. It received the Society for Technical Communication Award for "outstanding government publication" in 1976.

Stephen Petersen (1976) and Rosalie Ruegg (1977) each received the Department of Commerce Silver Medal Award for their outstanding work in the economics of energy conservation. In 1998 Sieglinde Fuller was selected by DOE as an "Energy Champion" for the Department of Commerce for her work in developing and updating the life-cycle cost methodology and software for the Federal Energy Management Program.

NIST has become the de facto authority in software (BLCC), Life-Cycle Cost training, and methods for economic analysis of energy conservation investments, as indicated by the widespread adoption of OAE products by ASHRAE, ASTM, private companies, the federal government, numerous state governments, and other countries, such as Canada and Australia.

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9.3 STANDARD ECONOMIC METHODS

The building community needs standard methods for evaluating the economic performance of investments in buildings and building systems. For example, typical decisions facing investors are whether to accept or reject a building investment, what design or size to choose for a building system, and how to establish priority among investment choices when budgets are limited. Users of economic methods want to know that the methods have been tested, approved, and accepted in the standards process by all stakeholders in the building industry. While sophisticated economic methods are needed to guide these users towards cost-effective building choices, the methods must be understandable to the non-economists who typically use them. Thus two major challenges in implementing standard economic methods are (1) developing technically sound methods in a format that building professionals can understand and (2) educating industry representatives on the standards committee so that they will endorse and adopt the recommended standard methods.

Harold E. Marshall, Rosalie T. Ruegg, Stephen R. Petersen, and Robert E. Chapman of the Office of Applied Economics in BFRL played major authorship, educational, and leadership roles in writing and shepherding successfully 16 standards and two software products through the ASTM standardization process. ASTM has published all of the economics standards in a compilation of building economics standards [1]. BFRL management targeted ASTM as the organization for development of the economic standards because it had the consensus balloting process important in creating widespread acceptance and it dominated the standards field (current membership includes 32,000 members from over 100 countries). BFRL proposed an ASTM subcommittee on Building Economics and succeeded in having it formally established in 1979. Harold Marshall was named the original chairman and remains so today.

BFRL economists wrote NIST reports that were the bases for standard methods on life-cycle cost [2], benefit-to-cost and savings-to-investment ratios [3], internal rates of return [4], net benefits [4], multi-attribute decision analysis [5], and payback [6]. They wrote two guides: one recommending techniques for treating uncertainty and risk [7], and one to help users match technically appropriate economic methods with the different types of design and system decisions that require economic analysis [8]. They wrote a standard classification of building elements [9, 10] to facilitate cost analysis and the electronic tracking of buildings. Finally, ASTM based its Life-Cycle Cost and Analytical Hierarchy Process software products on BFRL work [11].

The ASTM Subcommittee on Building Economics has been the preeminent forum for BFRL's Office of Applied Economics to identify industry's economic measurement needs, to create collaboratively with industry the standard measurement practices to answer those needs, and to implement standard measurement practices through the voluntary consensus standards process. Users of such standards include manufacturers and producers; federal, state, and local government agencies; builders; building code bodies; architectural and engineering firms; consumer groups; trade associations; research groups; consulting firms; and universities. Examples of specific applications of the standards are (1) manufacturers using the Life-Cycle Cost Standard Practice to customize energy-conservation products to economically efficient performance levels (e.g., insulation batt resistance levels and heat pump efficiencies); (2) building owners and designers using the UNIFORMAT II Elemental Classification Standard as the basis for bidding, tracking, and analyzing costs in all phases of the building's life cycle; and (3) federal and state governments using the Savings-to-Investment Ratio and Adjusted Internal Rate of Return to choose among multiple building investment options when the available budget is insufficient to fund all economically feasible projects.

Reduced life-cycle cost for any given level of building performance is the significant impact resulting from BFRL developing economic measurement methods and supporting them through the ASTM standards process.

1. Consumers (private and public) save money by purchasing building products (roofs, heating and cooling equipment, multiple-pane glazing) that are life-cycle cost effective.
2. Manufacturers can increase profits by designing and offering for sale building products that are most cost effective for their customers.
3. While the standards focus on buildings and building components, they have also been used widely to reduce life-cycle costs in nonbuilding investments. Economic evaluation algorithms in commercial spreadsheet software that are based on the standard economic methods, for example, help their users achieve life-cycle savings when choosing among investment alternatives.

Harold Marshall received the Department of Commerce Silver Medal Award in 1978 for his leadership in developing the building economics program and pioneering the development of standard methods in building economics.

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9.4 COST-EFFECTIVE COMPLIANCE WITH LIFE SAFETY CODES

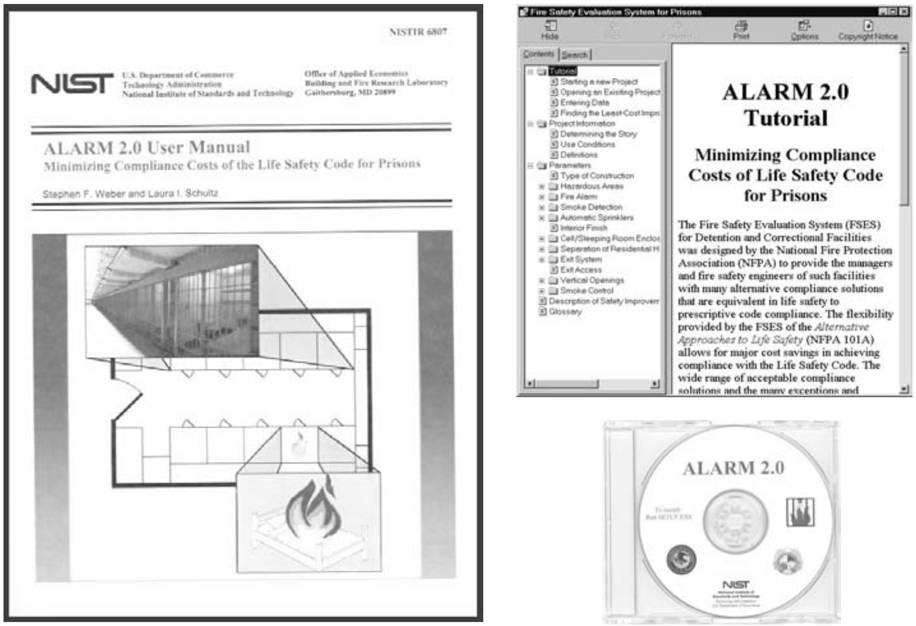
Although the Life Safety Code (LSC) for fire protection in buildings published by the National Fire Protection Association (NFPA) is primarily a prescriptive code specifying explicitly defined solutions to assure compliance, a special provision of the code has long allowed for substitution of equivalent solutions. In the late 1970s, Center for Fire Research (CFR) scientists worked with a panel of fire safety experts using the Delphi method to develop a point scoring system to assure that proposed safety improvements would provide a level of safety equivalent to the prescriptive code. This system was called the Fire Safety Evaluation System (FSES) and was first developed for health care facilities. The flexibility of the FSES made possible major cost savings when achieving compliance with the LSC. Because the FSES offers so many qualifying solutions, however, the most cost-effective solutions cannot be found by simple trial and error. What was needed was a method for finding a practical set of low-cost, safety-equivalent solutions from which facility managers could choose. The objective of this research was to develop systematic procedures for finding low-cost, safety-equivalent solutions compliant with the LSC for various building occupancies and to incorporate those procedures into software.

In 1978 Harold Nelson and A. J. Shibe of CFR led the effort to develop the first FSES [1], a flexible alternative to the prescriptive provisions of the LSC for health care facilities. Application of this alternative was initially made possible by language in the code allowing for equivalent solutions. Later the 1981 edition of the LSC formally adopted the FSES for health care facilities as an explicit part of the LSC. All editions since then have included the original FSES as well as others developed for a wide variety of building types, including offices and prisons.

Optimization based on the FSES scoring table of alternative safety states for each safety parameter is most directly formulated as a zero-one integer programming problem [2]. In 1982, Robert Chapman and William Hall developed an alternative formulation [3] based on solving the linear programming relaxation of the zero-one problem for the FSES of the 1981 edition of the LSC. The software exploited the “staircase” structure of the problem, a structure, which guaranteed that almost all variables in the solution would take on values of one or zero, and the advanced starting feature of the revised simplex algorithm. A post processor was used to select a single state when the solution fell between two states and to address any interdependencies caused by the footnotes to the FSES scoring table. The software, now called ALARM, contained a procedure for systematically finding many alternative, near least-cost solutions and then organizing them to ensure design compatibility across fire zones. The procedure usually produced about five to fifteen consistent strategies for the entire building. To facilitate comparisons, the costs of all alternatives are compared to and ranked against the costs of prescriptive compliance. Robert Chapman received the NIST Bronze Medal Award in 1982 for this work.

In 1994 Stephen Weber and Barbara Lippiatt [4] updated the cost data and cost algorithms, incorporated the changes in the point scores, and introduced new interdependent footnotes in the 1994 edition of the LSC. They also developed a menu-driven user interface for ALARM to assist users in preparing data files for the optimizer.

From 1998 to 2000, the National Institute of Justice funded Stephen Weber and Laura Schultz to extend the Alarm technology to cover the FSES for Correction and Detention facilities. They incorporated a new optimization model using zero-one integer programming to directly find the least-cost solution without the need to integerize the floating point solution of the simplex method [5]. They also developed an explicit Boolean model of all of the interdependencies in the footnotes and integrated it into the integer programming model. This model has the advantage of finding the true cost minimizing solution, taking into account all interdependencies, with a single optimization run without any post processing. They then developed ALARM 2.0, a 32-bit Windows software program with a user interface that intuitively leads the user through



ALARM 2.0 User Manual, screen shot, and software CD.

the FSES process. The interface graphically presents the main FSES scoring table with all the safety parameters and safety states and uses pop-up menus and color coding to guide the user in identifying current safety states, considering possible safety improvements, entering quantity data, and optimizing costs. The beta version of ALARM 2.0 was released in 2001.

The original version of the cost minimizer was used extensively by the U.S. Public Health Service (PHS). Between 1985 and 1995, fire safety engineers of the PHS conducted on-site surveys of 89 hospitals (53 Air Force, 33 Army, one Indian Health Service, and two community hospitals). They applied the cost minimizer software to all of these hospitals and used the results to prepare recommendations for safety improvements to the facility managers. The Alarm 1.0 software was published in 1994 and widely distributed by the NFPA through their One-Stop Data Shop.

The NIST Office of Applied Economics has published a detailed study of the economic impacts of this research in the hospital sector [6]. The economists based their impact estimates on the 86 military hospitals analyzed by PHS from 1985 to 1995, expert judgments of the use of the FSES for each type of hospital, and national statistics on the number of hospitals and beds in each type. The average cost savings of the optimized FSES solution found by the software compared with the prescriptive solution was about $2,200 per bed. Using a conservative twenty-year study period (1975-1995) and a thorough sensitivity analysis, the economists found that the present value of the net savings in hospitals from the FSES and the cost minimization software ranged from $119 million to $1,335 million. Large savings for FSES applications in prisons and commercial office facilities are anticipated in the future.

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9.5 ECONOMIC IMPACTS OF BFRL RESEARCH

A formal resource allocation process for funding future research is needed in both the public and private sectors. Research managers need guidelines for research planning so that they can maximize the payoffs from their limited resources. Furthermore, quantitative descriptions of research impacts have become a basic requirement in many organizations for evaluating budget requests. Economic impact studies help management set priorities and define new research opportunities. By revealing the "voice of the customer," such studies strengthen BFRL's ties to industry and identify opportunities for leveraging its federal research investments. Improved methods for measuring economic impacts are essential for BFRL to select the "best" among competing research programs, to evaluate the cost effectiveness of existing research programs, and to defend or terminate programs on the basis of their economic impact.

BFRL has long recognized the value of measuring the impacts of its research programs. A seminal study by Harold Marshall and Rosalie Ruegg in 1979 [1] demonstrated that even modest research efforts within BFRL are capable of producing significant impacts. More recently, BFRL has committed to a formal program for evaluating the impacts of not only past research efforts but also ongoing and planned research efforts as well.

A series of four reports published between 1996 and 2000 by Robert Chapman, Stephen Weber, and Sieglinde Fuller [2, 3, 4, 5] illustrate how to apply standardized methods to evaluate and compare the economic impacts of alternative research investments. The standardized methods employed in these reports make use of standard practices published by ASTM. In addition, the results of the economic impact assessments are summarized in a structured format, which ASTM has adopted as a standard format.

Two of the four economic impact studies deal with past BFRL research efforts for which a well-defined stream of benefits had been historically documented. These studies generated considerable interest from NIST senior management on how to apply the same approach to ongoing and planned research efforts. The two most recently published economic impact studies, and those planned for the future, are prospective in that the bulk of the impacts will occur in the future. These studies are designed to help BFRL shape its research efforts to better serve its constituency and to move its research results towards the marketplace.

The four recent economic impact studies have documented BFRL's role in some of the most significant research challenges facing the construction industry: energy conservation standards, fire safety in healthcare facilities, building automation and control functions, and construction systems integration and automation technologies. BFRL has successfully employed professional societies, standards and codes organizations, and public-private partnerships to move its research from the laboratory to a multitude of users.

BFRL's research is having a lasting impact on the construction industry. Without BFRL's customer-focused research, promising technologies would not have moved into the commercial marketplace as quickly as key construction industry stakeholders desired. The four recent reports document reductions in time-to-market for a variety of promising technologies of at least two years in all cases. The timelier introduction of new and innovative technologies into the construction industry has resulted in hundreds of millions of dollars of cost savings to construction industry stakeholders. For example:

1. Products and services based on BFRL's cybernetic building systems (CBS) research efforts are expected to result in cost savings in excess of $1.1 billion to owners, managers, and occupants of office buildings. BFRL's role in moving these products and services into the commercial marketplace in a timelier manner is valued at approximately $90 million. These expected gains are a direct result of the public sector's CBS-related research investment of approximately $11.5 million. In this case, every public dollar invested in BFRL's CBS-related research is expected to generate $7.90 in cost savings to the public.
2. BFRL's research on construction systems integration and automation technologies (CONSIAT) will generate substantial cost savings to

industrial facility owners and managers and to contractors engaged in the construction of those facilities. The present value of these cost savings is expected to be approximately $150 million. These cost savings measure the value of BFRL's contribution for its CONSIAT-related investment costs of approximately $30 million.

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9.6 APPLICATIONS OF THE ANALYTICAL HIERARCHY PROCESS

Many research and building investment alternatives differ in characteristics that decision makers consider important but that are not readily expressed in monetary terms. To choose the best means for achieving the desired outcome or goal when non-financial characteristics are important, decision makers need a method that accounts for these characteristics when choosing among investment alternatives. A class of methods that accommodates non-financial characteristics is multi-attribute decision analysis (MADA). The analytical hierarchy process (AHP) is a MADA method that considers non-financial characteristics, in addition to common economic evaluation measures, when evaluating investment alternatives against a stated goal. In the context of the AHP, non-financial characteristics, economic evaluation measures, and other key factors are referred to as criteria. For complex decision problems, the criteria are divided into their constituent parts, referred to as sub-criteria.

Economists in the Office of Applied Economics have produced innovative AHP applications for a broad class of users in the construction industry, the research community, and in manufacturing.

Sieglinde Fuller explored the use of the AHP [1] by integrating quantifiable and qualitative variables to arrive at a preference ordering of fire protection systems in residential dwellings. The AHP hierarchy was structured to allow homeowners to include their personal risk attitudes and risk exposures, compared with an 'average' level of fire risk as indicated by U.S. fire statistics, when deciding whether or not to invest in a sprinkler system. The study included recommendations for developing customized decision-support software to meet the special needs of homeowner decisions. The AHP application to fire protection systems was met with interest by builders, municipalities, and fire research labs in the U.S., England, and Australia, whose task it is to promote the implementation of fire protection measures.

Stephen Weber and Barbara Lippiatt developed the AutoMan software [2, 3] designed to support multi-criteria decisions about automated manufacturing investments. The program permits users to combine quantitative and qualitative criteria in evaluating investment alternatives. Quantitative criteria could include such traditional financial measures as Life-Cycle Cost and Net Present Value as well as such engineering performance measures as throughput and setup time. Qualitative criteria could include criteria requiring judgments like flexibility and product quality. AutoMan includes a graphical system for conducting sensitivity analysis so users can easily visualize how results vary as criteria weights are changed. For two years, AutoMan made the NTIS list of Best-Selling Software from the U.S. Government. AutoMan also made the bestseller list of the Defense Technical Information Center, which began distributing AutoMan 2.0 in June 1992. The Institute for Management Accountants widely distributed AutoMan 2.0. The DoD Director for Defense Information adopted AutoMan as a tool for investment decisions on information systems. The software company, Foresight Science and Technology, signed a CRADA with NIST to incorporate AutoMan decision technology into an expert system for automation planning.

In 1995, Gregory Norris and Harold Marshall published a technical report that reviewed 14 classes of methods for performing MADA [4]. The report summarizes each method's usefulness for screening, ranking, and choosing among projects; its data input requirements; and its method for scoring project alternatives. The section of the report dealing with the AHP was used as the basis for ASTM Standard Practice E 1765.

Harold Marshall and Robert Chapman, in collaboration with ASTM and Expert Choice, Inc., produced a software product [5], which contains a comprehensive list of building-related attributes. These attributes are drawn from standards produced by ASTM Subcommittees E06.25, Whole Buildings and Facilities, and E06.81, Building Economics. Marshall and Chapman revised ASTM's AHP Standard Practice E 1765 to incorporate enhancements resulting from the production of an ASTM-supported, AHP-based software product. The revisions promoted a broader use of both ASTM Standard Practice E 1765 and the software product.

Robert Chapman, Karthy Kasi, and Julia Rhoten employed the AHP to produce a series of resource allocation models that were used by BFRL management to rate and produce budget allocations for BFRL projects in FY 1998, FY 1999, and FY 2000. Evaluation criteria and sub-criteria that were deemed important by BFRL's Management Council and Management Group were used with the models and were described in white papers. The NIST Visiting Committee recognized BFRL's use of AHP-based resource allocation models as an exemplary process that offers potential for significant and sustained performance improvements. BFRL Director Jack Snell described the process to several other NIST Laboratory Directors and their management teams, recommending its use as a contribution towards NIST compliance with the Government Performance and Results Act.

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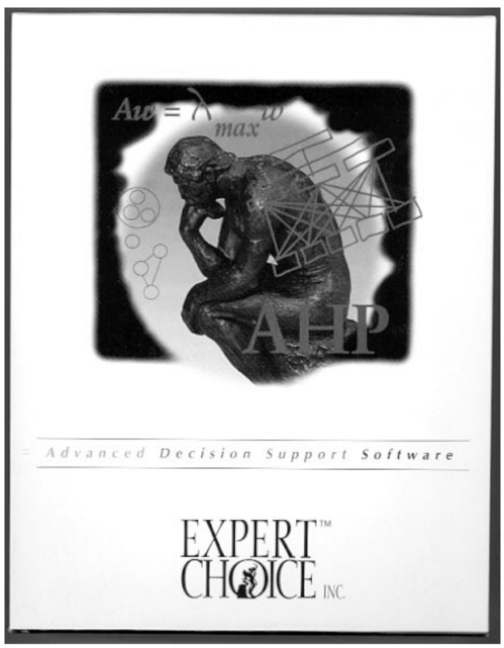

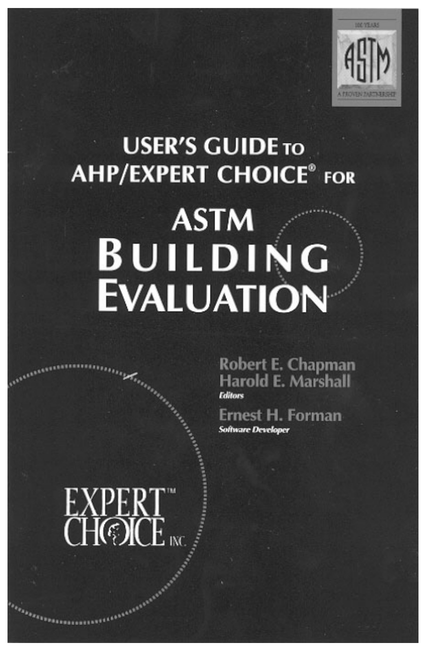

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9.7 BEES: BUILDING FOR ENVIRONMENTAL AND ECONOMIC SUSTAINABILITY

The building industry needs a tool to measure and balance the environmental and economic performance of building products, covering multiple environmental and economic impacts over the entire life of the product. Many product claims and strategies are now based on a single life-cycle stage or a single impact. A product is claimed to be green simply because it has recycled content, or cost-effective simply because it has a low first cost. These single-attribute claims may be misleading because they ignore the possibility that other life-cycle stages, or other environmental impacts, may yield offsetting impacts. For example, the recycled content product may have a high embodied energy content, leading to resource depletion, global warming, and acid rain impacts during the raw materials acquisition, manufacturing, and transportation life-cycle stages. Or the low-first-cost product may have a short, maintenance-intensive life, leading to a high life-cycle cost.

The BEES methodology, first developed by Barbara Lippiatt in the summer of 1994, takes a multidimensional, life-cycle approach [1, 2]. It is relatively straightforward to select products based on minimum life-cycle economic impacts because building products are bought and sold in the marketplace. But how do we include life-cycle environmental impacts in our purchase decisions? Environmental impacts such as global warming, water pollution, and resource depletion are for the most part economic externalities. That is, their costs are not reflected in the market prices of the products that generated the impacts. Moreover, even if there were a mandate today to include environmental "costs" in market prices, it would be nearly impossible to do so due to difficulties in assessing these impacts in economic terms. How do you put a price on clean air and clean water? What is the value of human life? Economists have debated these questions for decades, and consensus does not appear likely.

While environmental performance cannot be measured on a monetary scale, it can be quantified using the evolving, multi-disciplinary approach known as environmental life-cycle assessment (LCA). The BEES methodology measures environmental performance using an LCA approach, following guidance in the International Standards Organization 14040 series of standards for LCA. LCA is a "cradle-to-grave," systems approach for measuring environmental performance. The approach is based on the belief that all stages in the life of a product generate environmental impacts and must therefore be analyzed, including raw materials acquisition, product manufacture, transportation, installation, operation and maintenance, and ultimately recycling and waste management. An analysis that excludes any of these stages is limited because it ignores the full range of upstream and downstream impacts of stage-specific processes. LCA thus broadens the environmental discussion by accounting for shifts of environmental problems from one life-cycle stage to another, or one environmental medium (land, air, water) to another. The benefit of the LCA approach is in implementing a trade-off analysis to achieve a genuine reduction in overall environmental impact, rather than a simple shift of impact.

Economic performance is separately measured using ASTM standard E 917 life-cycle cost (LCC) approach. The environmental and economic performance measures are then synthesized into an overall performance measure using ASTM standard E 1765 for Multi-attribute Decision Analysis. For the entire BEES analysis, building products are defined and classified based on UNIFORMAT II, the ASTM E 1557 standard classification for building elements.

The BEES approach is applied to 200 building products in the Windows-based decision support software, BEES 3.0 [3]. It evaluates generic products for 23 building elements, including framing, exterior and interior wall finishes, wall and roof sheathing, ceiling and wall insulation, and roof and floor

Barbara Lippiatt, developer of BEES.

BEES and its logo are registered trademarks.

coverings. Each product category contains detailed performance data for competing products. For example, the "floor covering" category surveys cork flooring, ceramic tile, linoleum, vinyl tile, and different types of carpets, marble, and terrazzo. Environmental performance data are collected under contract by Environmental Strategies and Solutions, Inc. and PricewaterhouseCoopers.

The environmental impact analysis measures the product's impact on global warming, acidification, eutrophication (the unwanted addition of mineral nutrients to the soil and water), indoor air quality, fossil fuel depletion, habitat alteration, criteria air pollutants, water intake, ozone depletion, smog, and ecological toxicity. The BEES user specifies the relative importance weights used to combine environmental and economic performance scores and may test the sensitivity of the overall scores to different sets of relative importance weights.

In the first week after BEES 3.0 was released, over 1,000 copies were requested. Users represent a broad spectrum on interests including design, construction, manufacturing, research, Federal/state/local government, and education. BEES is prominently listed and described as a key tool for carrying out Executive Order 13101, "Greening the Federal Government" in the Final Guidance issued by the EPA Environmentally Preferable Purchasing Program. This guidance document applies to the $200 billion in annual Federal purchases. In addition, BEES is currently taught at the University of Michigan, University of Florida, Georgia Tech, Texas A&M, Air Force Institute, and in Korea, Saudi Arabia, and Indonesia.

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9.8 UNIFORMAT II ELEMENTAL CLASSIFICATION FOR BUILDING SPECIFICATIONS, COST ESTIMATION, AND COST ANALYSIS

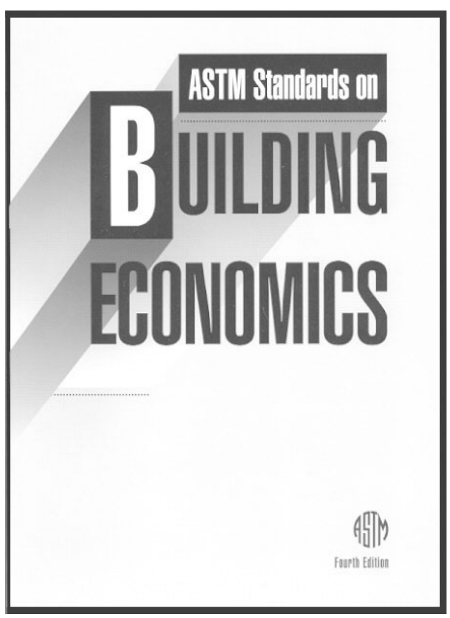
The building community needs a classification framework to provide a consistent reference for the description, economic analysis, and management of buildings during all phases of their life cycle. This includes planning, programming, design, construction, operation, and disposal. An elemental classification best meets these needs. Elements are major components, common to all buildings, that usually perform a given function regardless of design specification, construction method, or materials. Examples of elements are foundations, exterior walls, sprinkler systems, and lighting. The need for an elemental classification is most apparent in the economic evaluation of building alternatives at the design stage. Cost estimates based on lists of products and materials are time consuming and costly in early design. Yet it is in the early stages of design that economic analysis is most helpful in establishing economically efficient choices among building alternatives. An elemental classification can provide needed cost information in the most cost-effective manner.

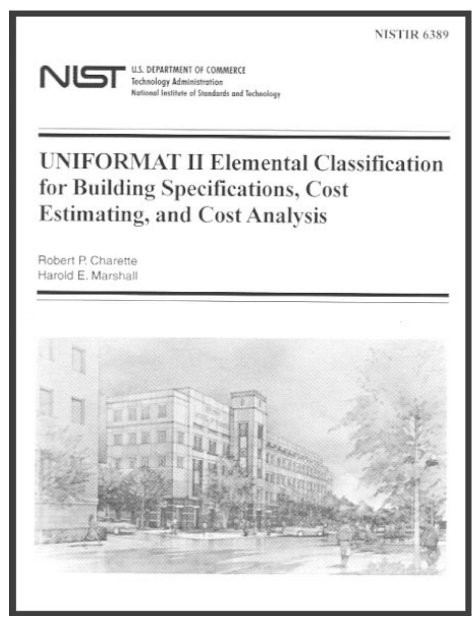
The major challenge to implementing an elemental format for building evaluations is to move the industry beyond the traditional practice of estimating costs of alternative designs via detailed quantity takeoffs of all materials and tasks associated with construction. For example, MasterFormat 95™, a classification published by the Construction Specifications Institute (CSI), is based on products and materials. While this is a logical format when preparing detailed cost estimates of the final design choice, it is time consuming and costly to apply early in the design process when establishing economically efficient choices among building alternatives. An alternative format is needed that is elemental-based and widely accepted in the construction industry.

Robert Charette, a Value Engineering Specialist in Canada, Harold Marshall of the Office of Applied Economics in BFRL, and Brian Bowen of Hanscomb Ltd. teamed up to develop an elemental classification of building elements for ASTM's consideration as a standard classification. ASTM was chosen as the organization for delivery of the new format because it has the consensus balloting process important in creating widespread acceptance, a standing committee on building economics with interest in the standard, and a prospective customer base of 32,000 members from over 100 countries.

The authors call their three-level hierarchical format UNIFORMAT II. It is based in part on a 1973 elemental classification developed for the General Services Administration (GSA) and the American Institute of Architects (AIA), in part on formats used by U.S. defense agencies, and in part on the team's judgment as to what kind of classification is needed in the modern electronic era. The team's initial NIST report [1] became the basis for ASTM's UNIFORMAT II standard classification, E 1557 [2] first issued in 1993. Representatives from CSI, AIA, R. S. Means, Department of Defense, GSA, and the American Association of Cost Engineers were invited to the ASTM work sessions to ensure that the standard met their needs. CSI became the secretariat to the ASTM task Group on UNIFORMAT II to ensure that CSI's forthcoming UniFormat™ would be compatible with ASTM's UNIFORMAT II.

The ASTM UNIFORMAT II standard classification has been adopted by the U.S. State Department for embassy bids worldwide; Whitestone Research in its Building Maintenance and Repair Cost Manuals; Hydro Quebec for the condition assessment of its 700 buildings; state governments such as Kansas and Massachusetts for building budgeting and programming; R. S. Means for Structuring its Assemblies Cost Data





UNIFORMAT II, co-authored by Harold Marshall, was adopted as an ASTM standard.

(in 2002); and by software products dealing with costs of construction-NIST's Building for Environmental and Economic Sustainability (BEES), NIST's BridgeLCC, and HPT-Buildwrite's Schematic Phase Elemental Project Template. The GSA has adopted a slightly modified version for cost estimates of U. S. government office buildings. CSI and the Design-Build Institute of America have developed jointly a software product for design-build estimating called PerSpective™ that is based on a slightly modified UNIFORMAT II and CSI's UniFormat™ hardcopy and software versions are generally consistent with UNIFORMAT II.

Adoption of UNIFORMAT II is reducing life-cycle costs in all phases of the building life cycle. And as owners and builders use commercial cost databases, e.g., from R. S. Means, that are structured according to UNIFORMAT II, these cost reductions will magnify. Some specific benefits from UNIFORMAT II are as follows:

1. Elemental cost estimates are faster and less costly to generate than detailed estimates. This yields savings in preparing the estimates and encourages the consideration of design tradeoffs early in the design process, when the greatest savings are possible from efficient design choices.
2. Data entered in a consistent format will never have to be reentered again, allowing cradle-to-grave electronic tracking of the building and its components.
3. All stakeholders in the construction process will share better information, generated at lower cost, because data are linked to a common, standardized structure.
4. Using a standardized format for collecting and analyzing historical data for use in budgeting and estimating future projects will save time and produce better estimates.
5. Tracking building condition assessments will help facility managers be more efficient in maintaining buildings.
6. Making performance specifications in standard elemental terms promotes the use of design-build contracts by making them more understandable to the participating parties.

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9.9 BASELINE MEASURES FOR THE NATIONAL CONSTRUCTION GOALS

The National Science and Technology Council, a cabinet-level group chaired by the president, is charged with setting federal technology policy and coordinating R&D strategies across a broad cross-section of public and private interests. It has established nine research and development committees, including the Committee on Technology, to collaborate with the private sector in developing a comprehensive national technology policy. The purpose of the Committee on Technology is to enhance the international competitiveness of U.S. industry through federal technology policies and programs. The Subcommittee on Construction and Building of the Committee on Technology coordinates and defines priorities for federal research, development, and deployment related to the industries that produce, operate, and maintain constructed facilities, including buildings and infrastructure.

The mission of the Subcommittee on Construction and Building-in cooperation with U.S. industry, labor, and academia-is to enhance the competitiveness of U.S. industry and promote public safety and environmental quality through research and development, and to improve the life-cycle performance of constructed facilities. To accomplish its mission, the Subcommittee on Construction and Building has established seven National Construction Goals in collaboration with a broad cross-section of the construction industry. The goals are focused on the four major sectors of the construction industry-residential, commercial/institutional, industrial, and public works.

Data describing current practices of the U.S. construction industry are needed to establish baselines against which the industry can measure its progress towards achieving the seven National Construction Goals. The seven National Construction Goals are concerned with: (1) reductions in the delivery time of constructed facilities; (2) reductions in operations, maintenance, and energy costs; (3) increases in occupant productivity and comfort; (4) reductions in occupant-related illnesses and injuries; (5) reductions in waste and pollution; (6) increases in the durability and flexibility of constructed facilities; and (7) reductions in construction worker illnesses and injuries.

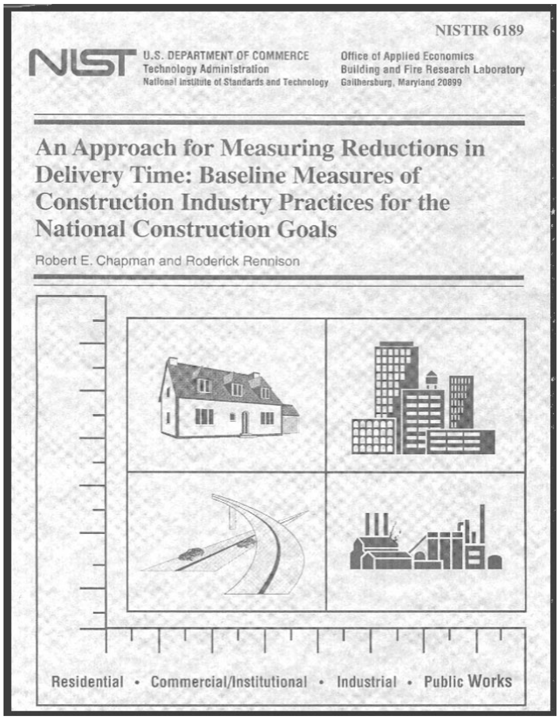
Goals 1, 2, and 7 were identified as the highest priority National Construction Goals by the construction industry. Robert Chapman and Roderick Rennison, a visiting researcher from the UK firm of WS Atkins PLC, with funding from the Subcommittee on Construction and Building, produced three reports that provide baseline measures and characterize current industry performance for Goals 1, 2, and 7. Industry performance in 1994 was used as the reference point from which the values of the baseline measures are calculated.

Delivery time is defined as the elapsed time from the decision to construct a new facility until its readiness for service. The report [1] on delivery time explains how delivery time issues affect both industrial competitiveness and project costs. During the initial planning, design, procurement, construction, and start-up process, the needs of the client are not being met. Furthermore, the client's needs evolve over time, so a facility long in delivery may be uncompetitive or partially unsuitable when finally finished. Delays almost always translate into increased project costs due to inflationary effects, higher financial holding costs, and reduced productivity. Furthermore, the investments in producing the facility cannot be recouped until the facility is operational. Owners, users, designers, and constructors are among the groups who will benefit from technologies and practices that reduce delivery time.

The report describes how a well-defined set of metrics is used to develop the baseline measures and measures of progress. Two data classification schemes are used to construct data hierarchies from which key metrics are derived and used to develop baseline measures for the residential sector and three non-residential sectors-commercial/institutional, industrial, and public works. These measures are based primarily on aggregated, project-level data made available by the Construction Industry Institute. A discontinued data series published by the U.S. Bureau of the Census is included as a reference point and for purposes of comparison.

The report [2] on operations, maintenance, and energy (OM&E) costs shows that OM&E is a major factor in the life-cycle costs of a constructed facility. In some cases, OM&E costs over the life of a facility exceed its first cost. However, because reductions in OM&E costs are often associated with increased first costs, facility owners and managers may under-invest in cost-saving technologies. Furthermore, undue attention on minimizing first costs may result in a facility which is expensive to operate and maintain, wastes energy resources, is inflexible, and rapidly becomes obsolete. Finally, because OM&E costs tend to increase more rapidly than the general rate of inflation, facility owners and operators are often forced to reallocate funds to cover OM&E costs. Reductions in OM&E costs produce two types of benefits. First, constructed facilities become more affordable because facility owners and operators are making more cost-effective choices among investments (e.g., design configurations) that affect life-cycle costs. Second, these same facilities better conserve scarce energy resources.

Like the delivery time report, this report describes how a well-defined set of metrics is used to develop the baseline measures and measures of progress. Two data classification schemes are used to construct data hierarchies from which key metrics are derived and used to develop the baseline measures for each of four construction industry sectors: residential sector, commercial/institutional sector, industrial sector, and public works sector. The overview of each sector examines sector size, changes in the sector, and key sector characteristics. Detailed



NISTIR 6189, co-authored by Robert Chapman.

baseline measures examine operations, maintenance, and energy categories separately. The key OM&E baseline measures for each sector are summarized in tabular form at the end of that sector's chapter.

The third report [3] is on health and safety issues. It shows that health and safety exert a major effect on the competitiveness of the U.S. construction industry. Construction workers die as a result of work-related trauma at a rate higher than all other industries except mining and agriculture. Construction workers also experience a higher incidence of lost workday injuries than workers in other industries do. Although the construction workforce represents less than five percent of the nation's workforce, it is estimated that the construction industry pays about 15 percent of the nation's workers' compensation.

The report describes a well-defined set of metrics used to develop baseline measures, which are based on data published by the Bureau of Labor Statistics. The data cover both nonfatal construction worker illnesses and injuries and construction-related fatalities. The report introduces the concept of a safety practice and gives several examples of safety practices currently in use within the construction industry. An analysis of the impact of safety practice use on reducing nonfatal construction worker illnesses and injuries is based on data provided to NIST by the Construction Industry Institute. The report concludes with a discussion of why the aggressive use of safety practices is a key instrument for achieving the 50 percent reduction in construction worker illnesses and injuries set forth in National Construction Goal 7.

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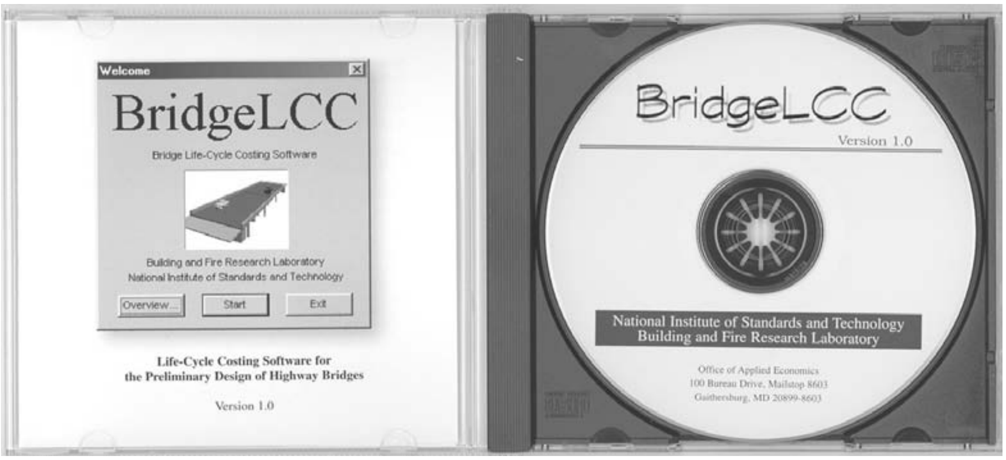
9.10 BRIDGE LCC

Engineers, designers, and builders need a user-friendly software tool to compare the life-cycle cost of new and alternative construction materials with conventional materials. Mark Ehlen and Harold Marshall developed the theoretical basis for such a tool in a 1996 report [1] on the economics of new technology materials. BridgeLCC [2] was developed in 1999 by Mark Ehlen to provide this type of decision support in software form. Even though the software was specially tailored to compare new and conventional bridge materials, it can be used in comparing alternative conventional materials and for the analysis of civil infrastructures other than bridges.

The first step of a BridgeLCC analysis is for the user to determine construction, maintenance, and disposal costs for the alternatives being evaluated. The user enters this information into BridgeLCC and the software calculates life-cycle costs. Graphs of life-cycle costs by bearer, life-cycle period, and project component can be displayed. This allows for a comprehensive assessment of the advantages and disadvantages, in life-cycle cost terms, of each alternative. If one or more costs are highly uncertain, individual costs can be assigned probability distributions and Monte Carlo simulations performed to examine the likelihood that one of the alternative structures will be cost effective over the range of possible cost outcomes.



BridgeLCC, version 1.0, helps designers evaluate the cost-effectiveness of new construction materials such as high-performance steel and fiber-reinforced-polymer composites.

BridgeLCC 1.0 was released in May 1999. The program had registered users in approximately 40 states and 16 countries. Mark Ehlen received the Department of Commerce Bronze Medal Award in 2000 for his development of BridgeLCC.

BridgeLCC 2.0, by Amy Rushing and Mark Ehlen, is an expanded version of the software. It includes improved Monte Carlo simulation capability, context-sensitive help, a concrete service life prediction tool, and the addition of a Terrorist Risk Management module. BridgeLCC 2.0 is available for download under "software" at http://www.bfrl.nist.gov/oae/oae.html.

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10. ENVIRONMENTAL SYSTEMS

10.1 INSULATION

Accurate knowledge of the insulating properties of building materials is important to thermal comfort, energy efficiency, and fire endurance for buildings. Development of measurement methods for the properties of thermal insulation has been an early and continuing concern for NBS and NIST. This section describes the work conducted in CBT and BFRL from 1975 through 2000 based substantially on accounts prepared by Robert Zarr who has led CBT/BFRL's work since the mid 1980s [1, 2].

The energy crisis of the 70s made economical insulations much thicker than the 25 mm thickness that could be measured by then-available standard apparatuses. Because of the complexity of heat flow through insulating materials, involving conduction, convection and radiation, heat flow varies with orientation and non-linearly with thickness. Because heat flow is small through large thicknesses of high-quality insulations, it is very challenging to measure the heat actually flowing through and not that flowing around the specimen. Fortunately, Henry Robinson, leader of NBS's insulation metrology research in the 50s and 60s, had developed an innovative measurement approach applicable to large thickness [3] - the line heat source guarded hotplate. A prototype apparatus was completed in 1978 and determined to perform as predicted [4].

By the mid 70s the Federal Trade Commission (FTC) was pressing the insulation industry to justify its labeling of the insulation value of thick insulations. Frank Powell represented CBT effectively in interactions with industry, FTC, and the Department of Energy (DOE), and led the planning of development of a One Meter Line-Heat-Source apparatus capable of direct measurements of insulating value at arbitrary orientations and thickness up to 380 mm [5]. With encouragement from industry, FTC and DOE, CBT organized a team led by Robert Jones, who was appreciated for his ability to achieve team results on schedule and within budget, to construct the apparatus, which was put into service in 1980. Mahn-Hee Hahn, who also had guided the early design of the prototype apparatus a decade earlier, championed the techni-

Robert Zarr, research mechanical engineer inserting an insulation sample in NIST's Line Heat Source Guarded Hot Plate, a large-capacity device for measuring the thermal resistance of insulation and other low-density materials up to 380 mm thick and 1 m in diameter. The Hot Plate provides calibrated specimens for guarded hot plates in other laboratories.

cal design and construction for the apparatus. The apparatus immediately was used to supply reference samples for calibration of industry's heat flow meters to allow industry to comply with the FTC's order for performing insulation measurements at representative thickness [6]. Jones received the Department of Commerce Bronze Medal Award and the NBS Measurement Service Award in 1981 for his efforts and those of his team. This effective response of CBT to an important national need was very valuable when the elimination of CBT was proposed by the President in 1983. Representatives of the U.S. Chamber of Commerce testified to Congress [7] that the improved insulation measurements made possible by the one meter apparatus saved U.S. consumers $90 million annually in insulation costs. The apparatus continues to provide NIST-traceable standards to industry through the development of thermal insulation NIST Standard Reference Materials (SRMs).

Heat transfer measurements also were needed on complex, compound walls to verify computational models. Reese Achenbach, in a final performance of his long, significant career at NBS, led in the design and construction of a large, calibrated hot box capable of measuring heat, air and moisture transfer for room-sized (3 m by 4.5 m) specimens for transient heat, moisture and pressure conditions on both sides (to represent internal and external conditions) [8]. The design and construction of the calibrated hot box was funded by the DOE through its Oak Ridge National Laboratory. Significant tests were conducted of super-insulated wood framed walls [9], and innovative masonry walls [10].

In the 90s, attention turned to measurement needs for advanced insulation technologies being developed to reduce the energy consumption associated with refrigerators, freezers, and the transport of refrigerated products. Among the insulation concepts being explored are powder, foam, glass-fiber-filled evacuated panels, and low-conductivity gas-filled panels. These advanced insulation panels offer the potential for significant reductions in energy consumption and greater flexibility in product design. Unfortunately, the equipment used to determine the thermal resistance of traditional building insulation materials was not well suited for measuring the thermal resistance of advanced insulation panels. A team led by Hunter Fanney developed a calorimetric apparatus and computational procedures to measure the thermal resistance of advanced insulation materials [11]. The procedures used to determine the thermal resistance of advanced insulation panels from calorimetric results were verified by measurements with the guarded hot plate for extruded polystyrene specimens. The measurements agreed to within 3 percent over a mean temperature range of 280 K to 295 K.

In the 90s, requests from the American Society of Heating, Refrigerating, and Air Conditioning (ASHRAE) prompted BFRL to address missing references for the thermal and vapor transmission data in their handbook. Over the decades, BFRL had accumulated a valuable and comprehensive collection of guarded hot plate data on a variety of insulating and building materials. In response, BFRL and NIST's Office of Standard Reference Data developed a new online database [12] that contained over 2000 of the NBS guarded hot plate measurements from 1932 to 1983. The database reconstructs one of the original reference authorities for the handbook data on design heat transmission coefficients for insulating and building materials, and currently receives about 5000 requests a month from the public.

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10.2 WEATHERIZATION

Between 1975 and 1982, NBS undertook three significant efforts in support of Congressional mandates to assist home owners in making their houses more energy efficient. These mandates were driven by the realization that residences consumed approximately 22 percent of total U.S. Energy use , that, for the foreseeable future, much of the current residential stock will remain occupied. Weatherization applied the results of building energy conservation research to support other agencies in their mandate to assist in the cost effective weatherization of homes. Weatherization also provided the energy conservation in buildings program with feedback and identified research needs and opportunities that would not have been recognized otherwise. Heinz Trechsel led the Weatherization Program for NBS with outstanding attention to high quality, timely and useful results, responsiveness to sponsors and external collaborators, and interdisciplinary teamwork.

The three components of Weatherization were:

1. Criteria for Retrofit Materials and Products for Weatherization of Residences.
2. CSA Weatherization Demonstration - Optimal Weatherization of Low-Income Housing In The USA
3. Criteria for the Installation of Energy Conservation Measures

10.2.1 CRITERIA FOR RETROFIT MATERIALS AND PRODUCTS FOR WEATHERIZATION OF RESIDENCES

Although started in anticipation of energy conservation tax credits, this work was completed in support of the Department of Energy's program to assist low income home owners. The intent was to establish guidelines for the selection of materials that can be expected to provide energy savings when correctly installed in residences. The first goal was to establish the types of measures that would provide significant energy savings. Materials that provide primarily other benefits, such as a more pleasing interior (such as carpets) or enhanced privacy (such as curtains and drapes) were excluded, although it was recognized that such measures also might provide energy savings. The second effort was to develop specific criteria to be met by each of the generic measures. The measures selected were: thermal insulation, storm windows and doors, caulks and sealants, weatherstripping, vapor barriers, and clock thermostats. The recommended criteria were based on thermal performance, fire safety, structural integrity, durability, quality, conformance to building codes, and ease of installation. Specific criteria included conformance to Nationally recognized standards, such as Federal Standards and standards promulgated by voluntary consensus organizations, such as ASTM International. For some products, where recognized standards did not exist, it was determined that simple availability of commercial products was a sufficient requirement. The criteria developed by this effort [1,2,3] also were used as a basis for selecting retrofit measures to be included in the CSA Weatherization Demonstration.

10.2.2 CSA WEATHERIZATION DEMONSTRATION

In 1976, the Community Services Administration approached NBS with a request for assistance in determining the optimal cost savings achievable through weatherization of low income housing to better allocate its resources. The goal was to determine which weatherization measures are the most cost effective, and what level of funding for each residence would provide an optimal rate of return in terms of energy savings.

In response, NBS developed an experimental and demonstration plan for conducting field measurements before and after retrofit of selected housing units. A pilot plan was tested in a Portland, Maine. After finalizing the plan, the demonstration/experiment was carried out in 16 locations covering all major climatic areas of the USA, of which 12 submitted data: Tacoma, WA; Oakland, CA; Colorado Springs, CO; Fargo, ND; Minneapolis, MN; Chicago, IL; St Louis, MO; Atlanta, GA; Charleston, SC; Washington, DC; Easton, PA; and Portland, ME.

In each location, from four (Washington, DC) to 19 (St. Louis, MO) houses were included in the sample, for a total of 183 houses, of which 141 were experimentally retrofitted for optimal weatherization, and 41 served as control houses. The houses ranged in age from 10 years to 80 years, with a median age of about 45 years. The sample included detached and row-type attached one to three story frame and masonry houses. To qualify, all houses had to be in reasonably good repair.

The weatherization measures considered were: sealing of cracks and holes, window and door treatments, roof and wall insulation, basement wall and floor insulation, and mechanical options, heating and hot water systems improvements. The measures were selected for each house based on economic cost/benefit analysis.

The installation of the various measures was done either by contractor's personnel or by persons trained under the Comprehensive Employment and Training Act (CETA). All metering and data collection was done by local Community Action Agency (CAA) personnel trained by NBS for the purpose. Overall, an average of $1,610 was expended for each house. Payback periods through fuel savings averaged 8 years and savings in fuel consumption averaged 31 percent.

The project leader was Richard Crenshaw. In addition to the authors of the publications referenced, Scheryle Schroyer, Judy Calabrese, and Lawrence Kaetzel were computer consultants to the project. Steve Weber, Kimberly Barnes, Barbara Lippiatt, Michael Boehm, Ann Hillstrom, and Phil Chen assisted with economic analysis. Richard Grot received the Bronze Medal Award of the Department of Commerce in 1980 for development of the field measurement techniques.

The project spawned some 15 technical reports on demonstration planning, results, economic analysis, and on field measurement techniques. References [4,5,6] provide a broad overview of the project, its planning, and its results.

10.2.3 CRITERIA FOR THE INSTALLATION OF ENERGY CONSERVATION MEASURES

In 1979, in response to the National Energy Conservation and Policy Act (NECPA), the Department of Energy established the Residential Conservation Service program (RCS). RCS required large utility companies and participating heating oil suppliers to offer auditing services to their residential customers to encourage the installation of energy conserving and renewable resource measures, to assist their customers in selecting appropriate cost-effective energy conservation measures, and to aid in contracting for the procurement and installation of selected measures. NECPA also provided for DOE to establish material and installation standards to assure the effective and safe installation of energy conservation measures. NBS assisted DOE in the development of the required installation standards.

NBS had primary responsible for preparing the installation standards for thermal insulations, caulks and sealants, storm windows and doors. Installation standards for insulating domestic hot water heaters, replacement of oil burners, automatic vent dampers, and intermittent pilot ignition systems were prepared by others. In developing the installation standards, NBS needed to address several technical and safety issues, primarily control of condensation in walls and attics retrofitted with insulation and potential fire hazards from electrical wiring surrounded by thermal insulation and from recessed and surface mounted lighting fixtures.

As format, DOE and NBS chose that of ASTM standards. Not only did this provide a proven format, but it also eased the eventual conversion of the standards into voluntary consensus standards. This was determined to be desirable as a long-term strategy; DOE would hardly want to be in the business of periodic updating the standards, as would be required for them to remain current. Some of the standards originally established for the RCS program and included in the publications listed below were withdrawn by DOE in 1981, but it is a measure of success that many RCS Installation Standards for thermal insulation and those for storm windows and doors eventually were converted into ASTM standards by the respective committees, mostly with only minor changes.

The ASTM Standards based on the RCS Installation Standards were:

C 1015	Installation of Cellulosic and Mineral Fiber Loose-Fill Thermal Insulation;
C 1049	Installation of Granular Loose-Fill Thermal Insulation;
C 1320	Installation of Mineral Fiber Batt and Blanket Thermal Insulation for Light Frame Construction;
C 1158	Installation and use of Radiant Barrier Systems (RBS) in Building Construction.

The project leader was Heinz Trechsel. He received the Bronze Medal Award of the Department of Commerce in 1981 for these and other contributions to residential energy conservation. In addition to the authors of the publications referenced [7, 8], the following contributed significantly to the development of installation practices:

- Robert Hastings contributed much in the area of replacement thermal windows and storm windows,
- Reece Achenbach, Frank Powell, Bradley Peavy, and Doug Burch in the area of thermal insulations,
- Larry Galowin and Robert Beausoliel provided expertise on the effect of thermal insulation on electrical wiring.

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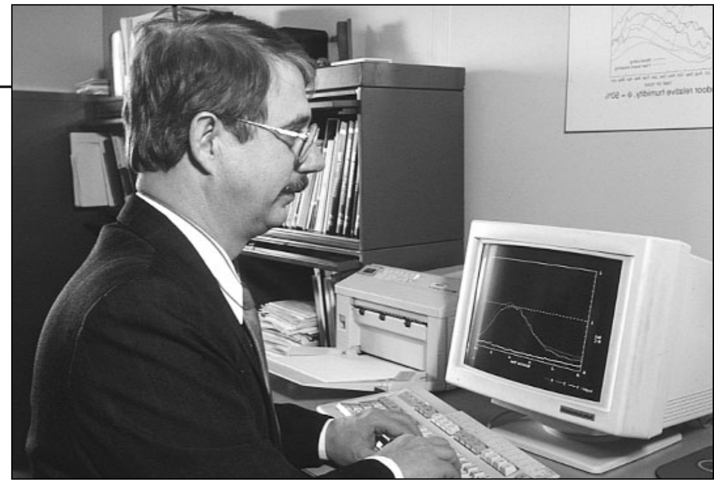

Douglas Burch, mechanical engineer, co-developer of the CBT MOIST Program, with William Thomas of Virginia Polytechnic Institute and State University testing the software to predict moisture accumulation in walls and ceilings.

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10.3 MOISTURE

Moisture accumulation in or on building walls and roofs creates substantial problems: reduction of insulations effectiveness, mold and mildew on interior surfaces, and rotting or corrosion of wall or roof materials. Walls and roofs are complex, multi-layered systems, with differing heat and moisture storage and transfer properties for the various layers.

The energy impact associated with moisture accumulating within the building envelope is enormous. The impact associated with just low-slope roofs and residential walls is approximately $200 million per year at an assumed oil price of $20 per barrel. The total economic impact is anticipated to be much greater since the impact of moisture in crawl spaces, conventional attic, and commercial walls, is not included in this estimate.

In the mid 80s, Douglas Burch of CBT and guest researcher William Thomas, professor of Mechanical Engineering at Virginia Polytechnic Institute and State University, began to address the problem of predicting the combined flow of heat and moisture through multi-layered walls. They determined that it would be necessary to develop measurements for diffusion coefficients for various wall materials and to measure the thermal conductivity of various materials as affected by moisture content, as well as to develop and verify a computer model for heat and moisture transfer in multi-layer walls and roofs. Sponsorship for the work was provided by NBS, the Department of Energy, and the Department of Housing and Urban Development (HUD).

The computer modeling proceeded well and the MOIST program was made generally available [1], but extensive research and testing were required to define the materials properties needed for general use [2,3,4]. Version 2.0 of MOIST [5] was made available incorporating these materials properties. An immediate area of application, conducted for HUD with the Forest Products Laboratory, was to address moisture problems commonly encountered in manufactured homes in both cold and warm climates [6]. These studies led to improvements in the HUD standard for manufactured homes. The research also addressed the severe problems encountered with mold and mildew in air conditioned buildings in hot and humid climates [7] and recommended avoidance of interior vapor barriers.

Subsequent research extended MOIST to deal with transient interior temperatures and humidity, and to provide a user-friendlier program for designers, builders and investigators of moisture problems [8].

In 2001, ASTM published a document [9] that included MOIST on an accompanying CD ROM. This combination of materials offered a basic understanding of the mechanisms involved in moisture movement, condensation, and accumulation. The inclusion of MOIST allowed analysis to be conducted on building walls and roofs.

The U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy has widely disseminated the MOIST program by means of their Building Energy Software web site http://www.eren.doe.gov/buildings/tools_directory/software/moist.htm [10]. This site emphasizes the use of renewable energy and achieving energy efficiency through proper building envelope design and the judicious selection of space conditioning equipment. MOIST is included within their web site as one of the programs available to analyze the performance of building envelopes.

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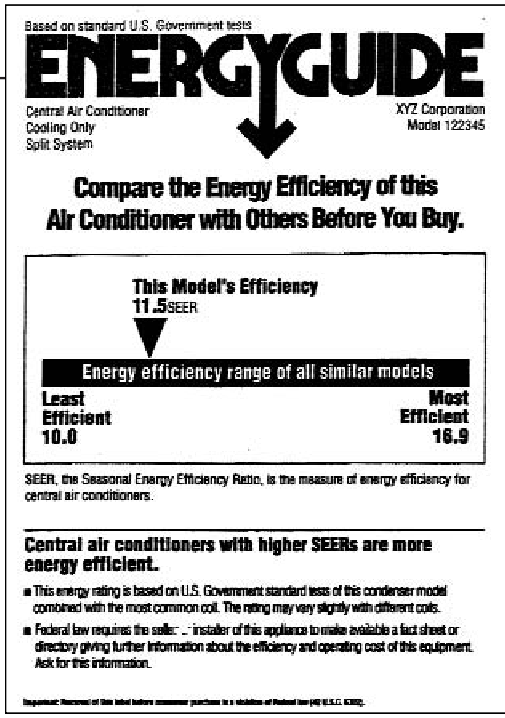
10.4 APPLIANCE TEST PROCEDURES AND LABELING

Following the nationwide gasoline shortage in the early 1970s, the U.S. Congress enacted the Energy Policy and Conservation Act (EPCA, Public Law 94-163). The energy used by household appliances was considered a major factor in the national energy conservation effort. The law was subsequently amended three times, in 1978, 1987 and 1988. The 1987 amendment, the National Appliance Energy Conservation Act of 1987 (NAECA), established the mandated energy conservation standards for the covered appliances. Under the law, DOE was required to establish energy conservation standards with respect to minimum efficiency and/or maximum energy use for all covered residential products. NBS was required to assist DOE to develop the test procedures that would be used by the appliance industries as the uniform test procedure for the measurement and reporting of the energy efficiency or energy consumption. The Federal Trade Commission (FTC) was tasked with the administration of the labeling of the energy efficiency/consumption of the covered products to provide information to and encourage consumers in the purchase the more energy efficient appliances.

At the beginning of the appliance energy efficiency program, DOE decided that providing information to consumers on the relative energy consumption of different models, would be more acceptable than direct regulation by setting maximum energy consumption for various appliances. This approach would allow competition between manufacturers on the basis of energy consumption. In addition to the development of the test methods for the covered appliances, NBS also was asked to design labels that would provide information on the annual energy consumption at the point of sale. The label was bright yellow and named the EnergyGuide. In addition to the annual cost of energy, the label showed where the particular model was positioned in the range of competitive products. Purchasers were able to make decisions on the payback time for any added cost for appliances that used less energy, and were able to compare different fuels. The FTC issued guidelines for the label in a rule promulgated in 1979. In 1994, the FTC issued a final rule that revised the EnergyGuide labels. Rather than the



NBS developed test method for appliances' energy consumption that were used by the Federal Trade Commission as Energy Guide appliance labels as illustrated for Furnace-Natural Gas appliance.

average annual operating cost that may change from year to year depending on fuel cost, the labels now contain the annual energy use (in kWh) as the main comparative indicator. The 1987 amendment requires that as the technology to improve the equipment efficiency advances, DOE periodically re-evaluate the standards, and, after public hearings, establish new minimum standards

The challenge to NBS was to develop a test method for each appliance that would measure annual energy consumption under normal use conditions and provide the information to purchasers in a meaningful way. This not only involved the development of a standard, repeatable method of measuring energy use, but also determination of normal use patterns for each specific appliance. The development of a standard test method was comparatively straightforward for the so called "white" appliances of the covered products, those used for cooking, cleaning, refrigerating food, etc. For those appliances, the performance and annual cost of operation are primarily dependent on the use pattern or schedule. Once normal use patterns/schedules were known, the existing industry steady state test method for the appliance could be combined with the specific daily use pattern/schedule to determine the performance and annual cost of operation.

Industry experts were helpful in explaining normal use patterns, but surveys were also used. In some instances it was necessary to observe people using appliances to establish use pattern. For example, most users could not say how many times they opened an oven door to check while cooking a meal, which burners they used on the range top, or which size pots they used on each burner. To solve these problems a kitchen was set up with one way mirrors in a test house known as the Bowman House, on NBS grounds, and volunteers were recruited to cook meals while being monitored by NBS staff.

At the time of the enactment of EPCA, steady state tests were used in the industry for central space heating and cooling equipment. However, in actual operation, the equipment cycles on and off frequently throughout the day. This cyclic operation causes significant energy losses or inefficiencies associated with the warm up and cool down of the heating equipment such as furnaces and boilers, or migration of refrigerant in the cooling equipment such as air-conditioner and heat pump. In addition, these appliances do not have a constant year-round daily use pattern but rather depend primarily on the outside weather conditions. Therefore, steady state tests were deemed not a sufficient procedure for the determination of the annual energy consumption. As a result, NBS staff developed new procedures to determine a seasonal (heating or cooling) efficiency for this type of equipment that includes both steady state and cycling tests coupled with calculation procedures that account for the changing weather conditions throughout the heating and cooling seasons. The resulting seasonal efficiency descriptors were the Annual Fuel Utilization Efficiency (AFUE) for furnaces and boilers, and the Seasonal Energy Efficiency Ratio (SEER) for air-conditioners and the SEER and Heating Season Performance Factor (HSPF) for heat pumps. The average annual energy consumption of these appliances on the basis of these energy efficiency descriptors was then calculated for the yellow labels.

After the initial tasks of development of the appliance test methods and labels, NBS concentrated on the improvement of the test procedures for the covered appliances to account for the advances in the energy efficiency design features spurred by the energy conservation efforts. Revised and additional test procedures were developed or under study for [1] condensing and modulating furnaces and boilers, [2] variable-speed compressor and mix-matched systems in cooling systems, [3] heat pump water heaters and improved procedure for the first hour rating of storage water heaters, [4] standardized load sample cloth and multiple load control feature in cloth washers, [5] dishwashers employing adaptive control and soil/particle sensors for performance and energy efficiency, [6] test procedures for fluorescence lamp ballast, and [7] test procedures for plumbing fixtures.

Many reports were provided to the Department of Energy including recommended label design, test methods, and the results of surveys. References [1-10] are the principal reports and publications, and [11] is a description of the outstanding technical work in the NBS/NIST Centennial Publication.

NBS provided information to DOE to enable it to hold public hearings on the test procedures, which after incorporating public comments as appropriate, were then adopted by DOE as final rules for the covered products. They were published as the federal rules in the Codes of Federal Regulations, No. 10, Part 430, Subpart B, Test Procedures, Appendix A through Appendix P. The energy efficiency and annual energy consumption values for the covered appliances were reported by the manufacturers to DOE and FTC, and listed on the appliance labels as specified in the FTC's Federal Trade Commission, Energy Guide (16 CFR Part 305).

Residential equipment accounts for 20 percent of U.S national energy consumption. The test procedures, the labeling program, and the required mandatory minimum standards stimulated competition, and have resulted in substantial improvement in equipment efficiency by manufacturers. The main impact on the public of the appliance labeling program is the visibility of the "energy labels" affixed to appliances in stores, and the fact that many purchasers are influenced by the information on the label. The American Council for an Energy Efficiency Economy (ACEEE) reported average efficiency increase from 1972 to 1987 of 96 percent for refrigerator-freezers, 35 percent for central air conditioners and heat pumps, 30 percent for room air conditioners, and 18 percent for gas furnaces. The energy cost saving makes it worthwhile to replace an old refrigerator (1970s) even though it may be working. EPCA has been amended by the Energy Policy Act of 1992, P.L. 102-486, to cover certain commercial equipment and NIST is assisting the Department of Energy to develop energy efficiency test methods for commercial water heaters, furnaces, boilers, air conditioners and heat pumps.

Initially the appliance program at NBS was lead by the Center for Consumer Product Technology (CCPT) with CBT handling the work on furnaces and central air conditioners. The human factors aspects including label design, user surveys, and cooking studies were the responsibility of the CCPT's Consumer Sciences Division headed by Mel Myerson, appliance test methods were developed by CCPT's Product Performance Engineering Division headed by Andrew Fowell, and the home heating and cooling product test methods were developed by CBT's Building Environment Division headed by Preston McNall. Key people in the early part of the program included Charles "Chuck" Howard, Ken Yee, Charles Gordon, Escher Kweller, Robert Wise, James Harris, Alan Davies, King Mon Tu, George Kelly, Joseph Chi, Walter Parken, Mark Kuklewicz, William Mulroy, and James Hill. In 1981 CCPT was disbanded and the appliance program was absorbed by CBT. Staff of CBT (now BFRL) who continued the work in the appliance program include Escher Kweller, Hunter Fanney, Brian Dougherty, Stanley Liu, William Healy, and Stuart Dols in water heaters, Esher Kweller, George Kelly, Cheol Park, Stanley Liu, and James Barnett in furnaces and boilers, David Didion, Piotr Domanski, Walter Parken, William Mulroy and Brian Dougherty in air conditioners and heat pumps, James Kao, Natascha Castro, and Andrew Persily in clothes washers, Natascha Castro in dishwashers, Steve Nabinger in Kitchen range and ovens, and Steve Treado in fluorescent lamp ballasts, plumbing fixtures and sampling procedure in performance testing and enforcement for all covered appliances.

George Kelly and David Didion received Department of Commerce Silver Medal Awards in 1978 and 1981, respectively, for their research on test methods for accurate and efficient energy labeling of heat pumps and air-conditioners. Warren Hurley received the Bronze Medal Award of the Department of Commerce in 1982 for development of data acquisition methods for appliance testing. Brian Dougherty received the Bronze Medal Award in 1999 for updating test methods for heat pumps and air-conditioners.

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10.5 TOTAL ENERGY SYSTEMS

Total Energy is a name given to the concept of recovering the waste energy from generation of electricity for use in heating and/or cooling. The best efficiency for generating electricity is about 40 percent. By using the waste energy from electricity generation to provide usable energy for heating and/or cooling, the overall efficiency typically can be 60 percent or higher, ideally as much as 85 percent.

Total Energy has other names, such as cogenerated heat and power, combined heat and power, integrated energy, district energy, etc. It is not a new concept. In the early 1900s electric power plants (typically coal-fired plants producing steam to run turbine-driven generators) were smaller and usually located close to the buildings they served. It was relatively easy to pipe heat recovered from the turbine exhaust steam to nearby buildings or homes. As the utility plants grew larger and tended to locate more remotely, the piping of recovered heat was less practical so the cogeneration of heat and power by most of these utilities gradually disappeared.

In the 1960s and early 1970s, the natural gas industry promoted natural gas-engine-driven total energy systems for supplying electric power and heating to one or more buildings. 500 or more of these systems were installed by 1971. The electric capacity ranged from less than one to about 3 MWe, with most in the lower range below 2 MWe. Many of these were hastily conceived, poorly matched to site needs, and not maintained properly. As the energy crisis eased many were discontinued.

HUD in the 1970s, was in the final phase of their 'Operation Breakthrough' program (development of performance-based building design)

This Jersey City, NJ apartment building site of the mid 1970s featured use of prefabricated modules for medium-rise construction and an on-site energy cogeneration plant. NBS monitored the energy flow from the plant's electricity generated site recovery system including recovering heat from diesel generators that contributed to heating the building units. HUD was interested to know if the cogeneration design was energy efficient and worthy of replication.

and wanted to demonstrate that the concept of total energy, properly designed, installed and maintained, would make a valuable contribution to the reduction of energy use for multiple-building installations. HUD requested NBS/CBT to determine feasibility of installing total energy at one of the 'Operation Breakthrough' building demonstration sites. Because of its energy conservation potential, CBT had been studying total energy and, in response to HUD's request, recommended the 'Operation Breakthrough' residential apartment building project site in Jersey City, NJ - Summit Plaza - for the 'installation, evaluation, and field study for the demonstration total energy system. The site used off-site fabricated modules that were stacked to form the buildings. Heating and air conditioning utilities for the buildings were generated in a small power plant located within the apartment complex. Heat generated by the diesel engines was recovered and used to offset the energy needed to supply the apartments' heating and air conditioning needs. CBT instrumented the power plant and each apartment building to monitor energy generation and use. HUD was interested to know if the cogeneration design was energy efficient and worthy of replication.

CBT prepared the performance specification for the total energy installation at the site. Installation of the total energy plant was started in 1971 and went on line serving the site in December 1973. The plant is still operating supplying electric power, heating and cooling for Summit Plaza [1].

CBT designed, installed and operated an extensive data acquisition and evaluation system for the total energy plant and developed the computer-based data reduction processes needed for performance analysis and reporting. Full-time automatic data acquisition and processing was on-line from April 1975 through December 1977 and selected data were collected and monitored, manually or automatically, from December 1973 through October 1978. A complete description of the Jersey City total energy plant, its functional and energy performance, and noise, emissions, and air quality performance, is presented in a NBS report authored by C. Warren Hurley, et al [1].

Concurrent with interest in total energy and its demonstration, HUD established their Modular Integrated Utility Systems (MIUS) program to study and encourage not only integration of electric power and heating/cooling to reduce construction cost and energy use in buildings and communities, but also the overall economics, institutional factors relative to integration of utilities, including in addition to alternative energy systems, potable water, liquid waste treatment and solid waste management systems.

HUD requested CBT and several other agencies, including, principally, the Energy Research and Development Administration, the Environmental Protection Agency, Oak Ridge National Laboratory, and the National Aeronautics and Space Administration, to conduct specific MIUS studies. CBT was requested to provide coordinated technical review for the reporting of all of these studies. The MIUS reports from all program participants, including those on total energy, totaled 213 publications [2, 3]. CBT produced 35 technical reports; 19 total energy-related publications and 16 reports of MIUS-related studies such as economic objectives, waste water management, institutional factors, comparison of MIUS with 5 alternative systems, evaluation and performance guidelines [4], and usage of electricity in non-industrial applications.

CBT, at the request of HUD and the Energy Research and Development Administration (ERDA), participated in the organization, in 1974, of the MIUS Study Group of the North Atlantic Treaty Organization's Committee on Challenges to Modern Society. CBT organized and conducted the international meetings of this study group, consisting of about 35 technical representatives from seven countries, in Belgium (1975), The Netherlands (1975), France (1976), Germany (1976), and Italy (1977). The study group mission was to exchange technical data on implementation of MIUS systems in the several countries and included development of an international projects 'catalog', a glossary of MIUS terms, sharing of MIUS feasibility computer programs, and several member-contributed papers [5].

Beginning in 1975 at HUD's request and subsequently supported by ERDA, and later by the Buildings and Communities Office of the Department of Energy, CBT organized and conducted monthly technical exchange meetings from 1977 to 1983 for Federal, state, county and city government agencies, city planners, investors, consultants, and contractors concerned with Integrated Energy Systems (IES). The meetings, with typical attendance of 50-75, were first held at NBS, then at the Department of Commerce, and finally at the U. S. Conference of Mayors headquarters in Washington, D. C.

When the National Engineering Laboratory was organized in 1978, the Total Energy Program was transferred with key personnel to the Center for Mechanical Engineering and Process Technology, but continued to involve many CBT staff. NBS participation in HUD's total energy program, its MIUS program and the DOE IES program, concluded in 1983. Throughout its history, NBS' Total Energy Program was led by Clinton W. Phillips whose enthusiasm and warmth achieved outstanding collaborations within NBS, nationally and internationally. Phillips began work as a technician with a CBT predecessor organization in the 40s, rose to lead work on modular, integrated utility systems for buildings, and was elected president of the American Society of Heating, Refrigerating and Air-Conditioning Engineers in 1982. He inspired colleagues with his enthusiasm for his and their work and his many charitable activities.

John Ryan received the Department of Commerce Bronze Medal Award in 1975 for his contributions to performance analysis of total energy systems.

Clinton Phillips served as President of the American Society of Heating, Refrigerating and Air-Conditioning Engineers 1982-1983.

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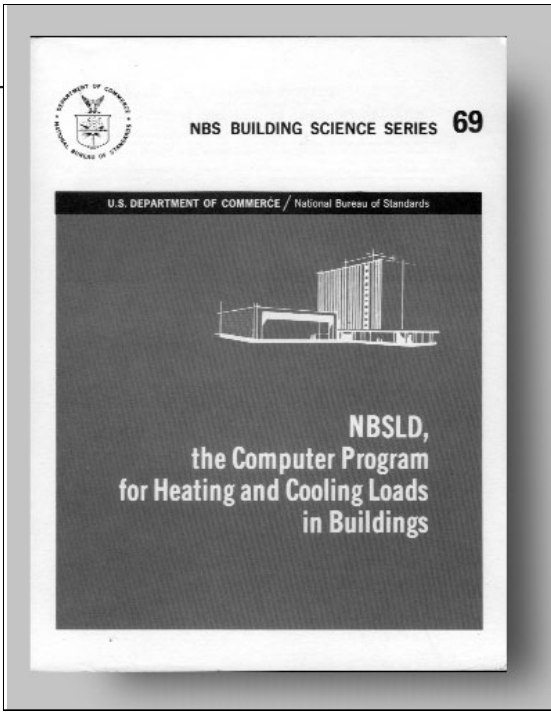
10.6 BUILDING THERMAL ENVIRONMENT ANALYSES

Before the 1970s, building environmental engineering was mostly represented by HVAC (heating, ventilating and air conditioning) engineers whose main interest was to design and select heating and cooling equipment under a set of design conditions (mainly outdoor temperature and humidity) through the so called "catalogue engineering." Very few of the HVAC engineers had any interest in, or were capable of predicting or evaluating the performance of heating and cooling equipment and systems, which they had designed or selected, under off-design conditions, which constitute a majority of the operating hours of HVAC systems and equipment. There were in fact no methodologies for estimating the performance of building indoor environment, HVAC equipment and systems under off-design conditions, since performance prediction required different and more complex mathematical approaches. Computers were also expensive and not many were found in HVAC engineers' offices.

Because of advanced computer facilities as well as the programming and mathematical talents available at NBS, some CBT researchers were very active in the use of computers for analyzing various aspects of environmental engineering for buildings, especially building heat transfer problems. Bradley Peavy [1], for example, was active in developing advanced mathematical techniques to deal with complex heat conduction problems involving the prediction of temperature in deep underground fallout shelters under the sponsorship of the Office of Civil Defense (the predecessor of FEMA). Through these activities he had developed efficient computer programs for several types of advanced computer programs involving complex Bessel functions.

Tamami Kusuda extended the fallout shelter thermal environment calculation program into an hour by hour building thermal environment calculation program in order to evaluate the performance of the Operation Breakthrough buildings of the Department of Housing and Urban Development. In this effort, he incorporated the thermal response factor method developed by Stephenson and Mitalas [2] to deal with transient heat conduction and storage in the multi-layered building envelope in lieu of finite difference calculations, which took up a large segment of the precious computer memory and involved lengthy computation time. Eventually, this computer program was expanded to include detailed heat balance calculation algorithms [3] to address the radiative heat exchange among interior surfaces of the room; the Goff and Gratch formulation of psychrometric data [4]; solar heat gain calculation procedures developed by Stephenson [5]; cloud cover modifier by Kimura/Stephenson; a comprehensive shadow program of Terry Sun [6]; an infiltration routine based on Achenbach/Coblenz equation [7] (later replaced by the Sherman/Grimsrud equation [8]); the thermal comfort equations of Fanger [9]; and ground contact heat transfer based on thermal response factors [10].

The program originally developed for a one-room building was called the NBSLD [11], the accuracy and reliability of which were validated concurrently with many different types of buildings whose thermal and energy performance were carefully measured mostly under the leadership of Frank Powell and Douglas Burch [12 - 15] (some buildings were tested inside the large environmental chamber). These measurements on test buildings included an inside-out construction (insulation placed outside of building walls), a log- cabin, a mobile home, massive masonry wall buildings, attic ventilation homes, different types of passive solar houses, houses with a whole-house fan, daylight utilization systems, thermostat setback operations, and large office buildings (e.g. the GSA Manchester demonstration building [16]). Approaches and subroutines used by NBSLD stimulated many young researchers and new research programs, and formed the starting point for the energy calculation algorithms recommended by the ASHRAE Task Group on Energy Requirements [17] as well as similar activities in many parts of the world. It laid the foundation for more sophisticated and well-known building energy simulation programs, such as DOE-2 [18], BLAST [19], TARP [20], etc., that followed. These programs played an important role in the USA when the country was developing building energy standards, during the aftermath of oil crisis of early 1970s, under the leadership of NBS, DOE, and ASHRAE.



NBS Building Science Series 69, NBSLD. Tamami Kusuda developed a dynamic computer calculation program called the National Bureau of Standards Load Determination Program (NBSLD) that provided hourly weather data covering all seasons of the year in any location and the dynamic profile of hourly energy required by a proposed building design for a full year.

Tamami Kusuda, pioneer for thermal environmental analysis.

Kusuda's contribution during this period was recognized by the 1980 Gold Medal of the Department of Commerce, the distinguished Fellow award of ASHRAE in l985, as well as by an ASHRAE symposium paper of 2000 held in Cincinnati entitled "The Role of the National Institute of Standards and Technology in Development of Energy Calculation Programs" by Professor Eugene Stamper [21] of the New Jersey Institute of Technology, who headed the ASHRAE Technical Committee on Energy Calculations.

Recognizing the need for assessing the use of computers for building environmental analyses, Achenbach and Kusuda organized the first international symposium on the use of computers for environmental engineering related to buildings [22] in1971 that attracted over 400 enthusiastic building environmental engineers from all over the world. This symposium was followed in Paris (1974), Banff (1978), Tokyo (1983), and in Seattle (1985), before it was taken over by the IBPSA (International Building Performance Simulation Association). IBPSA continues to conduct international symposia biennially ever since, and recognized Kusuda with its distinguished service award at its1993 meeting held in Adelaide, Australia. In its 1999 Kyoto, Japan, meeting of IBPSA, Kusuda was invited as the keynote speaker [23] to talk about the early history of building performance simulation activities as well as its future prospects.

In 1995, IBPSA gave its Award for Distinguished Service to Building Simulation to George Walton for his sustained contributions to the building simulation field. His work in building heat transfer and network analysis has resulted in simulation programs used worldwide including TARP, AIRNET and CONTAM. Walton received the Bronze Medal Award of the Department of Commerce in 1983 in earlier recognition of this work. Also, Douglas Burch received the Bronze Medal in 1980 for his work on attic insulation and attic ventilation.

One interesting application of NBSLD was the introduction of the predicted building habitability index (PIHI) as an integrated evaluation criterion for building performance. The PIHI concept was developed by James Hill and Tamami Kusuda in l975 [24] in which the simulated hourly energy consumption, comfort index, and system economic factors were weighted (in accordance with specific application requirements) and algebraically summed-up to arrive at an index for determining building air conditioning needs. This PIHI concept can be extended to include the energy performance of other building elements such as lighting, acoustics, moisture condensation, plumbing, etc.

Kusuda also worked on and published several papers on various subjects including the dynamic characteristics of air infiltration [25], room air convection calculations based on the numerical solution of turbulent Navier-Stokes equations [26], heat transfer of underground heat and chilled water systems [27], slab-on-grade heat transfer [28], and daylighting calculations [29]. The paper on the dynamic characteristics of air infiltration mentioned above was published jointly with James Hill and won ASHRAE's best technical paper award of 1975. The concept explored in the paper was later investigated further by John Klote [30] in his 1985 doctoral thesis at George Washington University at which Kusuda served as an adjutant professor.

The building environment simulation work started by Kusuda has been ably succeeded by other NIST researchers including George Walton, Stephen Treado, George Kelly, Cheol Park, and others in advanced building environmental simulation, the details of which are given in other sections of this report.

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10.7 SIMULATION OF MECHANICAL SYSTEMS PERFORMANCE

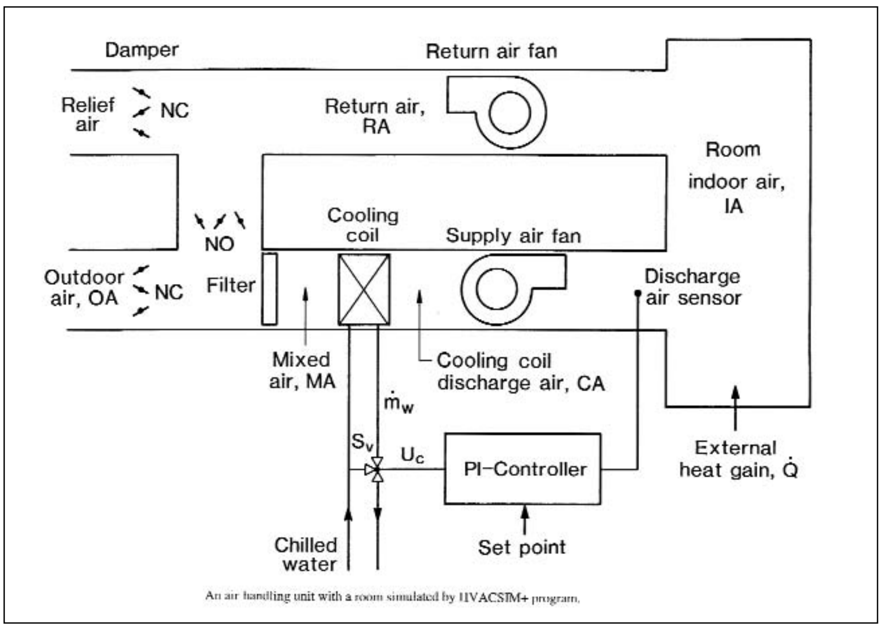
The HVAC simulation work within BFRL has focused on understanding the dynamic performance of buildings and the mechanical systems within them. These dynamics take place on a time scale on the order of seconds for control actions involving local control loops to a time scale on the order of minutes for changes in zone conditions

In an effort to understand dynamic interaction between building systems, initial development of a non-proprietary building system simulation computer program was begun at NBS in 1982. That program is called HVACSIM+, which stands for HVAC SIMulation PLUS other systems. The work built upon CBT’s pioneering work in the 60s and early 70s for the National Bureau of Standards Load Determination Program [1].

HVACSIM+ [2-7] employs advanced equation solving techniques and a hierarchical, modular approach. The simulation of an entire building/HVAC/control system involves the simultaneous solution of a large number of nonlinear algebraic and differential equations over large time periods using time steps on the order of seconds or smaller. The modular approach is based upon the methodology used in the TRNSYS program. Variable time step and variable order integration techniques are also used for reducing the amount of computation time required for dynamic simulation. Stiff ordinary differential equations are solved using a solving method based upon the famous Gear algorithm.

The HVACSIM+ program consisted of a main simulation routine, a library of HVAC system component models, a building shell model, an interactive

An air-handling unit with a room simulated by HVACSIM+ program.



front end program, and post processing routines. Most of the programs were written in Fortran 77, with the Fortran 90 code used for some specific routines.

The program HVACSIM+ is intended as a tool for conducting analytical research on building systems and subsystems and not as software which can be easily used by the general public. However, the simulation techniques, equation solving routines, and component models contained in HVACSIM+ should facilitate the development of such application programs for the general public by government laboratories, universities, or the private sector.

The HVACSIM+ dynamic building/HVAC/Control systems simulation program was used in a number of projects. Some of them are briefly described below.

A large office building system, which includes the HVAC systems, building system controls, and building shell, was simulated using the HVACSIM+ program. The building used for simulation was the NIST Administration building. EMCS (Energy Management and Control System) control schemes, such as start/stop control and nighttime purging, were evaluated [8].

An advanced air-handling unit (AHU) sequencing control algorithm was also simulated (12) and evaluated. AHU controllers commonly use simple sequencing logic to determine the most economic way to use the components of the AHU to maintain the supply air temperature at a set point value. Advanced control logic was compared with a traditional approach using HVACSIM+ to simulate the AHU components and the control logic.

As a part of a joint research effort conducted by participants of the Internal Energy Agency (IEA) Annex17 committee, NIST developed an "emulator." A building emulator is analogues to a flight simulator in the aircraft industry. Just as a flight simulator simulates an airplane in real time, a building emulator simulated a building, the weather, the HVAC system, and the heating/cooling plant in real time. Real EMCS control hardware was connected to a computer via a data acquisition system. The building system was simulated using HVACSIM+. The EMCS then controlled the simulated system as if it were an actual building. The emulator also evaluated the EMCS's performance in terms of the energy consumed, degree of comfort maintained in the simulated space, and accuracy of control [9-11].

Participants of IEA Annex 25 committee for real time simulation of HVAC systems for building optimization, fault detection, and diagnosis used the HVACSIM+ program in joint exercises to evaluate their fault detection methodologies. NIST distributed the program and data for the exercises.

One of several "major products" currently under development within BFRL is called Cybernetic Building Systems (CBS). The Virtual Cybernetic Building Testbed (VCBT) is a project within CBS. Experiences obtained from previous emulator projects have been incorporated in to the VCBT work. In the VCBT, the building and the HVAC system are simulated using HVACSIM+, which communicates with actual controllers supplied by different manufacturers. A fire simulation model is used to simulate the development of fire within one of the building zones and the spread of smoke through open doorways.

Besides being used within BFRL for various projects, the HVACSIM+ program was used in the International Energy Agency (IEA) Annexes 17 and 25 and with the debugging of controller performance and control strategy development by industry. Other researchers outside of U.S. have also participated in upgrades to HVACSIM+. Many universities in different countries have used the HVACSIM+ program as a teaching tool for graduate and undergraduate students.

George Kelly conceived of the idea to develop a program for simulating building/HVAC/control system dynamics. C. Ray Hill initially developed the main part of the HVACSIM+ program while he was at NIST as a research associate. Daniel Clark developed most of the HVAC system component models. Cheol Park contributed to the building shell model development, improved the main program, and maintained and distributed HVACSIM+. Bob May developed the interactive front-end program and David Harris did most of the programming. Outside of NIST, Philip Haves, when he was at the Loughborough University in England, participated in the improvement of HVACSIM+ and on the development of the emulator described above. Many other people have also been involved in development HVACSIM+, building emulators, and experimental works on the verification of HVACSIM+ and its component models.

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10.8 CONTROLS AND CYBERNETIC BUILDING SYSTEMS

Building controls research at NIST has focused on improving and lowering the cost of buildings services by fostering the development and use of more intelligent, integrated, and optimized mechanical systems and controls. Key aspects of this effort have been the development of a standard communication protocol for exchanging information between building management and control systems and pioneering the concept of Cybernetic Building Systems for improved productivity, life-cycle cost savings, energy conservation, improved occupant satisfaction, and U.S. market leadership.

During the past twenty-five years, our understanding of buildings and how to operate them has undergone a gradual evolution involving a shift away from considering buildings as static units to considering them as dynamic, integrated, and distributed systems. During this same period, rapid advances in technology (such as inexpensive microprocessors, large scale integrated circuits, and new approaches to telecommunications) has made it possible to develop Building Control Systems that not only can account for dynamic interactions to optimize performance but promise to be extremely cost effective due to their ability to be integrated with other building services. In this rapidly changing environment, the Building Controls Program within CBT/BFRL has worked to: 1) document the current state-of-the-art in the design, control, and operation of building service systems, 2) promote improved building services through the evaluation, development, and application of advanced concepts and technologies, 3) develop system design and performance evaluation techniques, such as advanced simulation models, emulators, and test procedures, 4) promote the development of standards, protocols, and guidelines, and

5) assist in technology transfer through publications, conferences, workshops, and demonstration projects.

In the late 1970s, BFRL was involved with two field evaluation projects: the Jersey City Total Energy Site [1] and Norris Cotton Federal Office Building [2]. In 1980, the Mechanical Systems and Controls Group was formed. One of the early projects of this Group was to evaluate the energy saving potential of the most commonly employed HVAC control strategies using BLAST 2. Different control strategies were studied for a variety of HVAC systems in a small office building, a large retail store, a large office building, and an education building in different regions of the country [3].

A Building Management and Controls Laboratory was developed. It involved the design, building, and installation of a distributed Energy Management and Control System (EMCS) to control and monitor a large air handler in the CBT building, an HVAC/Controls test facility in the laboratory, and the 11-story NIST Administration Building. The Laboratory was used to study direct digital control, control dynamics, and to verify and refine dynamic models for HVAC system components. Research involved the evaluation of different building/HVAC control strategies, the verification and refinement of control algorithms, and the development of guidelines for the operation of different building systems. Research on EMCS Algorithms was centered on the development and verification of an adaptive algorithm for local loop control and various public domain application algorithms. The latter covered economizer algorithms, demand limiting algorithms, scheduled start/stop and duty cycling, optimal start/stop, and algorithms for a variety of reset control strategies. Work also involved the investigation of the performance of EMCS instrumentation, steam flow measuring systems, and hygrometers; the development of procedures and recommendations for the on?site calibration of temperature, flow and humidity measurement systems; and evaluating and documenting the effect of EMSC sensor errors on building energy consumption [4].

During the 1980s, manufacturers were developing proprietary communication protocols for their EMCS that made expansion and upgrading of these systems both difficult and expensive. As a result of these problems, ASHRAE began in January 1987 to develop an industry standard communication protocol for building automation and control systems. Standard Project Committee 135P (SPC 135P) was formed to accomplish this task and NIST played a key role in the effort [5]. The membership of SPC 135P was selected to provide a broad and balanced representation of the building control industry. The individuals came from manufacturers, consulting engineering firms, universities, and governmental agencies from Canada and the United States.

The first meeting of SPC 135P occurred in June of 1987. In August of 1991 the first public review draft of the proposed BACnet standard was published for comment [6]. A revised version of the draft standard was published for a second public review in March of 1994. Modifications were made and a third, and final, public review version was published for comment in March of 1995. The final draft version was approved for publication as an ASHRAE standard in June of 1995, eight and a half years after the formal standardization process was begun. BACnet was approved by the American National Standards Institute (ANSI) as a national standard in December, 1995. Since 1995 BACnet has been maintained and enhanced by ASHRAE Standing Standards Project Committee 135 (SSPC 135). BACnet has been translated into Chinese, Japanese, and Korean. It has been adopted as a Korean national standard and a European Community pre-standard. It has also been proposed as an ISO standard.

In 1996, the Phillip Burton Federal Building and U.S. Courthouse located at 450 Golden Gate Avenue in San Francisco was selected as the site for the world's first large-scale commercial demonstration of the BACnet standard. The site, a 22-story 130,000 m^2 office building, is the second largest office building in San Francisco and the largest Federal office building west of the Mississippi River. It was selected for this demonstration, in part,

Cover images of the English, Chinese, Japanese, and Korean versions of the BACnet Standard

because it had little pre-existing EMCS controls and recent renovations have made it comparable to typical commercial office buildings. The EMCS retrofit also represented a significant energy-efficiency opportunity for the building with projected annual utility savings of over $500,000. The project tested multiple EMCS-manufacturers' equipment in one facility and their ability to cooperatively monitor and control building systems by utilizing the BACnet standard. In addition, extensive energy monitoring instrumentation, an operator workstation network, and communications equipment were incorporated into the EMS design to facilitate future energy assessment and research activity within the building [7].

Contract awards for the first two BACnet compliant vendors were made in August 1996. Associated construction activities were completed in January 1998, and the project remained on schedule and on budget. A follow-on project involved an extensive central plant renovation and integration of the central plant controls with the existing BACnet control system. The fire alarm system was also integrated with the HVAC controls through an BACnet gateway. At the present time, the BACnet demonstration project is being expanded to include linking eleven federal office buildings located in California, Arizona, and Nevada together with a regional operations control center in the Philip Burton Federal Building. This regional operations center will be used to monitor and supervise energy conservation measures and to improve operations and maintenance activities. It will also serve as a research and demonstration platform for developing automated commissioning procedures, automated fault detection and diagnostics, and utility/building control system interactions.

In 1993, a BACnet Interoperability Testing Consortium was formed to develop test methods and software tools to automate the compliance testing of BACnet systems [8]. Originally consisting of 12 members, it grew to 23 members before being replaced by the BACnet Manufacturers Association (BMA) in 2000. The BMA is an industry run organization whose purpose is to encourage the successful use of BACnet in building automation and control systems through interoperability testing, educational programs, and promotional activities.

While BACnet was being developed, the Mechanical Systems and Controls Group was also involved in three successive International Energy Agency (IEA) Annexes. Annex 17, which was entitled "Building Energy Management Systems (BEMS) Evaluation and Emulation Techniques," ran from February 1988 until February 1993 [9]. It focused on the use of simulation and emulation for evaluating BEMS performance. Subtask A used simulation to assess the "a priori" energy savings achievable through the use of building energy management systems (BEMS). Subtask B involved experiments on heating and cooling coils to develop and validate dynamic coil models. Other work has included experimental validation of a methodology for determining control strategies for a heating system. Subtask C, which was led by Finland and the United Kingdom, involved the analysis and development of Emulators for BEMS. The concept of BEMS Emulators was based upon research conducted at NIST several years previously. This Subtask involved construction of actual emulators by the participating countries, carrying out various emulation exercises, and developing a BEMS testing methodology using Emulators and completing a “round robin” testing program using different Emulators and BEMS systems. Emulators were developed by the U.S., United Kingdom, Belgium, Finland, The Netherlands, and France and exercises involving commercially available BEMS were conducted in each country. Guidelines for selecting and evaluating BEMS and for building emulators were also developed based upon experience and knowledge gained from the joint exercises.

Steven Bushby, leader, Mechanical Systems and Control Group, checks wiring connections for controllers in the BACnetTM Virtual Building.

Annex 25, entitled Real Time Simulation of HVAC-systems for Building Optimization, Fault Detection, and Diagnostics (BOFD), ran from April 1991 until April 1996. Its objectives were to evaluate alternative model identification methods, determining which real time simulation models are most suitable for BOFD-systems, performing qualitative availability analyses on various HVAC systems to determine the likelihood of different faults, developing a database on the most important problems and diagnostic procedures, and demonstrating the implementation of BOFD concepts through joint exercises. NIST led the Annex activities related to air-handling units and performed detailed comparison of techniques for classifying AHU operations (i.e., normal, faulty, and type of fault).

Annex 34, Computer-aided Evaluation of HVAC System Performance: The Practical Application of Fault Detection and Diagnosis Techniques In Real Buildings, ran from September 1996 until September 2000. The main objective of this Annex was to work with control manufacturers, industrial partners, and/or building owners and operators to demonstrate the benefits of fault detection and diagnostics in real building applications. The fault detection and diagnostic (FDD) methods developed in Annex 25 were combined into robust FDD systems and incorporated into either stand-alone PC based supervisors or into outstations of a future generation of “smart” building control systems. NIST activities in Annex 34 were primarily focused on field tests of a rule-based tool for detecting faults in AHUs that underscored the prevalence of control performance problems in buildings.

In the fall of 1998, several of the projects in the Mechanical Systems and Controls Group, along with two projects in the Fire Safety and Fire Science Divisions, were combined in to a Major Product called Cybernetic Building Systems (CBS). The objectives of this Major Product were to develop, test, integrate, and demonstrate open Cybernetic Building Systems for improved productivity, life cycle cost savings, energy conservation, improved occupant satisfaction, and market leadership. This work was to be carried out in close cooperation with the U.S. building industry, industrial partners, building owners/operators, and newly developing service companies.

The word “cybernetics” comes from the Greek work “steersman” and is defined as the science of control and communication of complex systems. Unlike the field of artificial intelligence, AI, which tends to focus on how information is stored and manipulated, cybernetics takes the “constructivist” point of view that information (and intelligence) is the attribute of system interactions (communications) and is not a commodity that is stored in a computer. In the field of cybernetics, “intelligence” is determined by the “observed conversations” (i.e., interactions) among the various components making up the (cybernetic) system. In other words, if a complex system “looks, acts, and is observed communicating intelligent information” it is “intelligent,” regardless of how the information is stored and manipulated internally.

A Cybernetic Building System involves energy management, fire detection, security, and transport systems, energy providers, one or more utilities, an aggregator, and numerous service providers, and information handling and complex control at many different levels.

The BFRL is currently working with industry, building professionals, ASHRAE and Trade Organizations, university researchers, and other government agencies to develop and demonstrate CBS. The work involves the following tasks and will include a full scale demonstration of one or more Cybernetic Building Systems:

1. Develop standard communication protocols which facilitate the open exchange of information among energy providers, utilities, EMCS, fire detection and smoke control systems, security systems, elevator controls, building operators, building occupants, and (newly developing) service provider companies;
2. Develop enabling technologies, such as fault detection and diagnostic (FDD) methods, a hierarchical framework for control decision making, advanced operating strategies for single and aggregated buildings, automated commissioning, and the application of fire modeling to a cybernetic building response to fires;
3. Develop advanced measurement technologies, including smart multi-functional sensors.
4. Develop performance evaluation tools for protocol compliance testing, real time monitoring, and the evaluation and documentation of interactions among cybernetic building systems;
5. Develop a standard-based program infrastructure supporting the design, analysis, specification, procurement, installation, operation, and maintenance or heating, ventilation, air-conditioning, and refrigeration (HVAC/R) systems;
6. Construct a Virtual Cybernetic Building System in the laboratory to facilitate the development and evaluation of new products and systems by manufacturers (including BACnet speaking EMCS, stand alone/integrated FDD systems, intelligent fire panels, and smart sensors) and external service providers;
7. Develop a CBS Product Data Model (PDM) capable of accurately describing, in a standard format, a building(s), its mechanical systems and controls, the desired operating strategies, and the internal/external services provided.
8. Conduct basic research on the dynamic interactions of a fire, HVAC/distribution, and the zones of a commercial building through utilization of existing and new simulation models and validate this new simulation program through both laboratory and field studies.
9. Develop a Consortium consisting of manufacturers and service providers interested in producing, testing, demonstrating, and selling Cybernetic Building Systems; and
10. Conduct a full scale demonstration of a Cybernetic Building System in a government owned office building complex consisting of five or more buildings in the southwest region of the country. This will involve the integration of energy management, fire detection, smoke control, smart fire panels, multi-functional sensors, building transport, fault detection and diagnosis, aggregation of multiple building loads, and real time communication with energy providers, the utility, an aggregator, and numerous service providers.

Work conducted under the Cybernetic Building Systems Program will improve productivity, life cycle cost savings, energy conservation, occupant satisfaction, and will increase U.S. market leadership through the commercial application of tested, integrated, and open Cybernetic Building Systems and concepts. Based upon an very conservative FY 99 impact assessment done by BFRL’s Office of Applied Economics [10], this work is expected to result in a nationwide present value cost savings of $1.1 billion and a return-on-investment benefit of $7.90 for each $1 spent on BFRL's CBS-related research.

C. Warren Hurley, William Rippey, Robert May and others were involved in the Jersey City Total Energy Site and the Norris Cotton Federal Office Building studies, respectively. George Kelly became the first Leader of the Mechanical Systems and Controls Group in the summer of 1980. James Kao and Walter Parken used BLAST to study different control strategies in four commercial buildings. Robert May, C. Warren Hurley, and Bent Borresen from the University of Trondheim, Norway developed and used the Building Management and Controls Laboratory.

Steven Bushby evaluated the application of direct digital control in NIST's eleven story Administration Building. James Kao developed design criteria and guidelines for direct digital control based building automation systems. Alexander David, Robert May, and Cheol Park developed public domain algorithms for adaptive control and various energy management strategies. James Kao and Warren Hurley defined the characteristics and expected performance of EMCS Sensors. James Kao did a study on the effect of EMCS sensor errors on building energy consumption. From 1987 on, Steven Bushby single handedly led the effort to develop the BACnet communication protocol. He was secretary of ASHRAE SPC 135 committee that developed the BACnet standard and later Chairman of the SSPC 135 committee that was formed to maintain the standard after it was adopted. He also created the BACnet Interoperability Testing Consortium and was instrumental in the creation of the BACnet Manufacturers Association.

George Kelly was the leader of the U.S. teams that participated in IEA Annexes 17 and 25, while John House was the U.S. team leader in Annex 34. George Kelly, Robert May, Cheol Park, and Gaylon Decious developed the building/HVAC emulator concept and participated in the "round robin" emulator exercises conducted by Annex 17 participants. Won-Yong Lee from the Korean Institute of Energy Research, John House, Cheol Park, and George Kelly were involved in the development and evaluation of different fault detection and diagnostic (FDD) methods in Annex 25. John House, Natascha Castro, and John Seem from Johnson Controls, Inc. demonstrated the application of different FDD methods in real building applications as a part of the Annex 34 activities.

In the fall of 1998, George Kelly proposed the CBS concept as a Major Product within BFRL. People who have worked on the CBS Major Project include George Kelly, Steven Bushby, John House, Natascha Castro, Jeanne Palmer, Cheol Park, and Mike Galler from the Building Environment Division; William Davis and Glenn Forney from the Fire Safety Engineering Division; Bill Grosshandler and Tom Cleary from the Fire Science Division; and Robert Chapman from BFRL's Office of Applied Economics. In February 1999, Steven Bushby became the new Leader of the Mechanical Systems and Controls Group, while George Kelly became the Chief of the Building Environment Division and continued as Project Manager of the CBS Major Product development effort.

Steven Bushby received the Department of Commerce Bronze Medal Award in 1992, and the NIST Slichter Award in 1996 for his contributions to BACnet. Steven Bushby and other project team members received the Vice Presidents "Hammer Award" for the 450 Golden Gate Project.

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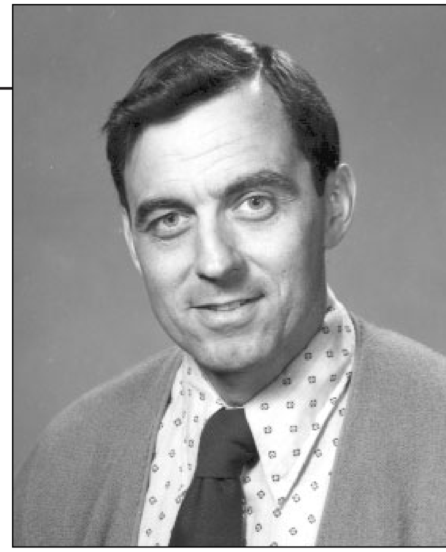
10.9 ALTERNATIVE REFRIGERANTS

The NIST refrigerants program began in 1981 as an outgrowth of the Thermal Machinery Group's research into methods of improving residential heat pump performance. For the previous five years the Group's main programmatic focus was on a U.S. Department of Energy sponsored effort to develop performance test procedures for residential heating and cooling appliances. Since energy conservation was still a national priority, heat pumps were selected, from among all residential heating systems because their current production model performance was furthest from ideal and they appeared to have the largest market growth. Coincidentally at this time the relatively new industrial agency, The Electric Power Research Institute (EPRI), was inviting proposals for advanced energy conservation concepts.

David Didion, the group leader, thought that an appropriate program would have to be both fundamental and practical. The first because it was in keeping with Laboratory's mission to lead the industry into new areas without competing with their own research organizations. The second because any success would have to be reasonably close to current system designs, if the industry was to accept it. The idea of using refrigerant mixtures as a working fluid was not new. The original idea was conceived by Lorentz, in 1894, and ever since Europeans had written about its theoretical advantages and performed an occasional experiment in one machine or another. Also, in 1981, General Electric was researching the use of mixture in home refrigerators and DuPont was also exploring candidate zeotropic (a.k.a. nonazeotropic) mixtures with an appropriate temperature glide for use in air conditioners. However, there was no record of any systematic quantitative study as to the potential improvement that mixtures could do for refrigeration systems.

Even at the proposal writing stage, it was obvious that the success of such a program would depend strongly on our knowledge of the thermodynamic properties of possible mixtures. For this reason a physical chemist, Graham Morrison, from the NIST's Thermophysics Division was asked to join the program for the purpose of



David Didion, leader, Thermal Machinery Group and world leader for environmentally benign refrigeration technology.

selecting an appropriate equation-of-state that could be used in the modification of the Group's vapor compression cycle model. This model had been under development by Piotr Domanski for the DoE efficiency labeling program. The fact that this model was based on first principles, as opposed to the Industrial type which is usually an empirically based component performance model, made it amendable to such a radical conversion. It was also obvious that a parallel study into the convection coefficient degradation, that mixtures were known to have, would have to be conducted. This was because the possibility existed that the theoretical thermodynamic benefits that the Lorentz cycle offered would be offset by the poorer heat transfer in the mixture two phase flow.

The EPRI proposal constituted the initiation of the NIST refrigeration program. It stated that based on the NIST expertise in heat pump evaluation and thermodynamic equations-of-state, along with its laboratory facilities supporting both, that NIST would begin to investigate the potential of the

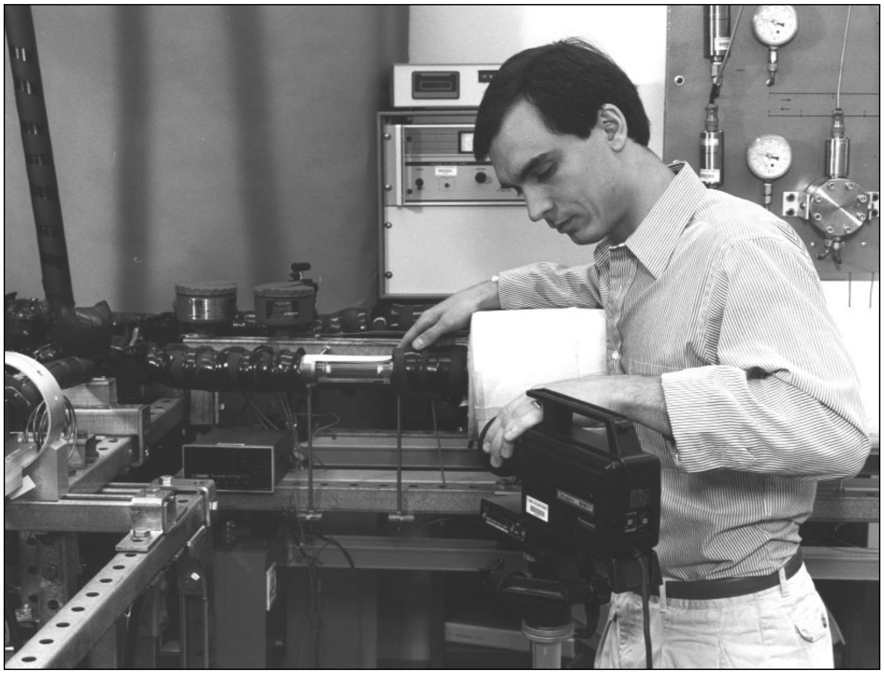
Lorentz concept for improving heat pump performance. NIST would share equally in the funding of the effort and take the most fundamental approach possible; that is, to attribute causes of system performance differences back to fluid and/or cycle properties, wherever possible.

Selecting a zeotropic mixture whose temperature glide (i.e., the difference between its dew and bubble points) can match the sensible fluids temperature gradient is the very essence of the Lorentz Cycle's performance merits. In order to determine the maximum system performance benefits it was necessary to construct heat exchangers that were grossly oversized and purely counter-flow. This experimental work was done in the first of several newly constructed vapor compression rigs called breadboard heat pumps because the four thermally important components (i.e., evaporator, compressor, condenser, expansion device) were spread out so that instrumentation accuracy was not compromised.

Tests of different mixtures soon began to demonstrate that the binary zeotropes' temperature gradients were typically nonlinear. About this time Mark McLinden, a Chemical Engineer, joined the Group. He provided a quantitative explanation that the enthalpy of phase change was a function of composition, which of course was changing during the evaporation and condensation processes. And that the degree of non-linearity was somewhat a function of the differences in normal boiling points of the components [1]. The practical ramification of this non-linearity was a pinch-point between the refrigerant mixture and the secondary heat transfer fluid in either the evaporator or the condenser was likely to occur with insignificant heat transfer down stream of the pinch point. A solution to this problem was determined to be the interjection of a third component whose normal boiling point is between the other two.

In parallel with the above thermodynamic work, a two phase heat transfer laboratory was created and developed for the specific purpose of explaining and quantifying the degradation of the zeotrope's heat transfer coefficient relative to the weighted average of the components' coefficients. The degradation was caused by a lack of the higher pressure component at the two phase interface, whether it be at a nucleate bubble or the liquid-vapor boundary of annular flow. Although the number of different mixtures measured was limited, Morrison concluded that the magnitude of the degradation may be a function of the difference in molecular size of the components. This evaporative flow work was taken over by a new full-time addition to the Group, Mark Kedzierski, at about the time the entire program was to change its objective due to the advent of the ozone crisis. One of his first assignments was to review the past two phase flow work

Mark Kedzierski, mechanical engineer, investigating the fundamental properties of pool boiling of alternative refrigerants.



we had been doing and make qualitative conclusions [2].

Early in the program a third laboratory path was initiated. Zeotropic mixture drop-in tests were conducted in several commercial heat pumps. It was realized that it was unlikely that the full performance benefits could be seen in a unit, since the Lorentz cycle's smaller average temperature difference between the refrigerant and the secondary heat transfer fluid necessarily requires a larger heat exchanger surface. So the indoor coil was replaced with one that had several banks of coils to approximate a cross-counter flow condition between the zeotropic phase change glide and that of the moist air stream. Although the efficiency never reached that for the original refrigerant, this work did provide some practical estimates of component sizes needed, particularly for cooling and dehumidification purposes. Included in this phase of the program was an investigation to explore the possibility of improving performance through the use of multistage distillation. This work showed the cost effectiveness of developing a heat pump that could essentially operate on one composition in the cooling mode and a significantly different one in the heating mode.

Not since the 1930s, when the halogens were introduced to the industry as a stable, safe (i.e., nonflammable and nontoxic) efficient family of refrigerants, had there been proposed such a widespread change in the industry's working fluids as that which resulted from the acknowledgement that chlorine was degrading the earth's ozone layer. Very little was known about chlorine-free refrigerants because the CFCs were the most stable and the best performers. By 1987, NIST researchers were in a truly unique position in their knowledge of how fluid properties effect the basic refrigeration cycle performance. Realizing the need for the industry's engineers to understand the fundamentals of using different refrigerants, McLinden and Didion wrote a seminal paper on the halogen family refrigerants [3]. This paper established NIST as an authority on the subject and paved the way for a decade of funding from government and industry.

ASHRAE immediately recognized the impact of this ozone/refrigerants issue and offered to play an important central role, as did ARI, for inter-industry communication. A series of special conferences were held with NIST and the Herrick Labs of Purdue University, in alternate years. The first was at NIST where the Building Environment Division hosted an invited speakers conference of thirteen papers on the alternative refrigerants. It was titled "CFCS: Today's Options - Tomorrows Solutions." Its was subtitled ASHRAE's 1989 CFC Technology Conference indicating how intimately CFCs were intertwined with the very concept of a refrigerant. The second ASHRAE/NIST refrigerants conference, in 1993, was "R-22/R-502 Alternatives." This subject was in response to the 1992 revisions to the Montreal Protocol, which called for the eventual phase out of all HCFCs. The 1997 conference was entitled Refrigerants for the 21st Century, and over half of the sixteen invited papers were on the natural refrigerants; that is, ammonia. carbon dioxide, air, water, hydrocarbons.

One of the most significant accomplishments during this phase of the program was that of Piotr Domanski's continuing modifications to the computer simulation model (CYCLE-11) to handle the ever-changing data-base [4] that NIST's Thermophysics Division was developing in the form that is now called REFPROP [5]. As these developments occurred the model was shared with selected industries. This enabled NIST to have a better understanding of industry needs while not having the huge burden of support documentation and making it user-friendly in a Windows format. However, due to public requests, a simplified version called CYCLE D was developed in a Windows format and issued for sale through NIST's Standard Reference Database 49 [6]. This program enables the user to compare fundamental cycle performances among virtually any working fluid, single component or mixture, that is contained within REFPROP. Further developments to CYCLE-11 allowed simulations with counter-flow, cross-flow and parallel-flow heat exchangers with consideration of the refrigerant circuitry design and its impact on pressure drop and heat transfer coefficient.

Flammable HFCs were being introduced into different zeotropes. It was necessary to mix non-flammable refrigerants with them such that the mixture was non-flammable under all feasible conditions. All of these developments were taking place at the same time ASHRAE was wrestling with how to determine flammability. McLinden and Didion worked with ASHRAE SSPC34 to determine how to measure flammability and to define the most flammable composition likely to occur in the field. The committee decided that would be a series of five slow leaks of 20 percent of the original quantity with subsequent recharges of the original composition. Establishing this composition experimentally turned out to be a procedure that took several days. Realizing REFPROP's ability to predict the composition of a mixture at any given thermodynamic state, NIST developed a quasi-steady state computer simulation procedure to act as an alternative to the tedious experimental procedure. The result was NIST Standard Reference Database 73 REFLEAK [7] that can predict the composition change of any mixture that can be created in REFPROP up to five recharge cycles and for either isothermal (slow) or adiabatic (fast) leaks.

Another critical need of industry was to understand and measure the heat transfer characteristics of alternative and mixed refrigerants with lubricants. Mark Kedzierski, soon after his arrival, began simultaneous construction on a pool boiling and on a convective boiling/condensation rig to meet these needs. These were both significant undertakings due to the unique rig designs and consequently required several years to build. An existing quartz tube rig was modified and operated so that some experimental results could be made available to industry while construction was underway. High-speed films at 6000 frames per second were taken of the low quality refrigerant flowing in the tube. The refrigerant/lubricant boiling was dramatically different from the pure refrigerant boiling [8]. Rather than relatively large discrete bubbles characterized by pure refrigerants, the refrigerant/lubricant boiled in a misty cloud of micro bubbles. The lubricant caused the bubbles to be much smaller and more numerous than the pure refrigerant bubbles. The lubricant effect on bubble size, bubble frequency, and the site density were quantified with the high-speed films. These data not only helped industry to redesign surfaces for the new refrigerants, but also were indispensable for the understanding of the influence of lubricant on boiling.

The uniqueness of the pool-boiling rig was that it was designed specifically to obtain measurements with low uncertainties with fluid heating. For example, the rig had the unique capability of using either electric heating or fluid heating for the same test section independent of the data acquisition method. A comparison of several enhancements showed that the heat flux obtained by fluid heating can be as much as 30 percent greater than that as obtained by electric heating. This casts a shadow on the use of electric heating as a valid test method for boiling. Kedzierski parametrically investigated the influence of lubricant viscosity, miscibility and composition with specially designed lubricant. A model was derived to predict the influence of each lubricant property on the heat transfer performance [9]. In general, it is possible to attain 100 percent enhancement relative to the pure refrigerant heat flux with a small quantity of high viscosity lubricant that is partially miscible in the refrigerant.

The profound contributions of this work to the world's knowledge of refrigeration technology, protection of the environment, and competitiveness of U.S. industry have been recognized by use of the results by industry and by numerous awards. These include the Department of Commerce Gold Medal for Didion in 1987, NIST Condon Award for Didion and McLinden in 1988, the NIST Applied Research Award for Didion in 1987, the Department of Commerce Bronze Medal Award for Domanski in 1991, the NIST Slichter Award for Didion, Kedzierski and Domanski in 1995, the Department of Commerce Bronze Medal Award for Kedzierski in 1995, the first Lorentzen Prize of the International Institute of Refrigeration for Didion in 1999, and the Hall Gold Medal from the United Kingdom's Institute of Refrigeration for Didion in 2001.

It is difficult to note all of the contributors who were involved in the program over twenty years. However there are a few who made especially significant contributions through dedicated service, unusual talent or both. Two were full time employees, William Mulroy and Peter Rothfleisch, and one was a guest worker from Seoul National University, Min Soo Kim.

This summary of CBT and BFRL work in alternative refrigerants has been excerpted from more comprehensive papers published by ASHRAE [10, 11].

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10.10 INDOOR AIR QUALITY

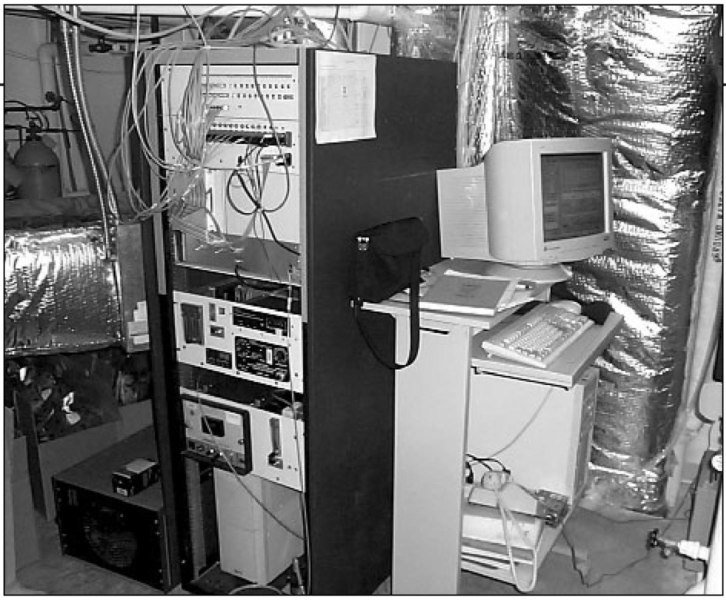
About the same time that energy efficiency research and demonstration projects were advancing in the mid-1970s, concerns about indoor air pollution were also increasing. These concerns were based upon energy efficiency measures of increased envelope airtightness, leading to reduced infiltration rates, along with reductions in outdoor air ventilation rates. In combination with new materials being used indoors, these measures could increase indoor contaminant levels to the point that occupant health and comfort may be compromised.

Some of the earliest NBS work in this area was done by Tamami Kusuda [1] in an effort to look for ways to reduce ventilation rates and the associated energy consumption while still maintaining acceptable indoor air quality through the use of occupant-generated carbon dioxide levels to control the ventilation system. Most of the other work at NBS over the next 5 to 10 years focused on the development and application of tracer gas methods to determine ventilation rates in buildings. However, a major program to develop predictive models for building airflow and contaminant levels was initiated in the early 1980s [2]. This led to the development of the CONTAM series of computer programs that have expanded in capabilities and usability since the mid-1980s into the 21st century [3-6].

Other indoor air quality research focused on measurement methods to determine formaldehyde emissions from wood products and the development of models relating these emission rates to temperature and relative humidity [7, 8]. Another area of focus was the development of test methods to evaluate the performance of gaseous air cleaning devices [9-11]. This work built on similar research in the 1970s and before on particulate filter efficiency by Charles (Max) Hunt. The gaseous efficiency test methodology has fed directly into the ASHRAE committee developing a test for gaseous air cleaning media, which will be issued as Standard 145.

Another area of NBS and subsequently NIST indoor air quality research was in the development of methods for conducting long term field studies of ventilation and indoor contaminant levels in buildings. This work built off the tracer gas research (see section 10.11) and involved the development and deployment of automated data acquisition systems to monitor carbon monoxide, carbon dioxide, particulate and other contaminant levels. These studies were performed in a number of buildings located throughout the country and greatly expanded our knowledge of actual indoor air quality performance in office buildings and the factors that impacted that performance [12-17]. Among other results, this work produced the first comprehensive database of measured ventilation rates in mechanically ventilated office buildings, that is still unique and relied upon in many analyses of indoor air quality in U.S. office buildings [18]. The other major contribution of this work has been in the area of the measurement and interpretation of indoor carbon dioxide concentrations as they relate to building ventilation rates and indoor air quality [19]. This work led to the subsequent development of an ASTM guide on that subject, Standard D6245.

Charles (Max) Hunt received the Bronze Medal Award of the Department of Commerce in 1977 for his development of tracer gas measurement techniques. Andrew Persily received the Bronze Medal Award in 1989 for advancement of measurement techniques for indoor air quality, and Persily received the 2002 Award of Appreciation from ASTM Committee D-22, Sampling and Analysis of Atmospheres, for his leadership as Chair of the Related Factors section of Subcommittee D22.05, Indoor Air, and for his contributions to the development of new standards for the sampling and analysis of indoor atmospheres.


Automated tracer gas system for measuring building air change rates.

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10.11 BUILDING ENVELOPE PERFORMANCE

Driven by energy efficiency issues in the 1970s, a major program was started at NBS to develop measurement methods to evaluate the thermal performance of the building envelopes of office buildings. Supported by the U.S. Department of Energy and the General Services Administration's Public Building Service, NBS developed measurement methods to determine envelope airtightness and infiltration rates, in-site thermal resistance of walls, and overall thermal integrity using infrared thermography. The primary effort was in the area of tracer gas methods for measuring building infiltration rates, with a focus on automated instrumentation that would determine hourly average air change rates over periods of several months in order to characterize infiltration rates as a function of weather conditions and building system operation. This work began in the late 1970s, with the first measurements made in the NBS Administration Building [1]. More buildings were studied in the 1980s, including a 26-story office building in Newark NJ [2].

A major effort was conducted in the early 1980s for GSA, in which eight federal buildings throughout the country were studied using all the measurement methods referred to earlier [3]. These buildings were generally of fairly recent vintage and were not meeting their expected energy efficiency performance. Thermal envelope problems were suspected as being part of the reason for this discrepancy, and this research effort was carried out to first refine the test procedures and then to demonstrate them in the field while increasing our understanding of the magnitude and impacts of these thermal defects. The results of this research resulted in a great advances in the measurement knowledge and our knowledge of building envelope performance [4-6]. The results of this effort contributed to numerous ASTM test methods in the area of tracer gas techniques, building pressurization methods and in-site R-value measurement. Ultimately, NIST developed design guidelines for thermal envelope integrity for GSA that have had widespread application in the design of office building envelopes in the U.S. [7].

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10.12 PERFORMANCE CRITERIA AND STANDARDS FOR SOLAR ENERGY SYSTEMS

In September 1974, the United States Government enacted the Solar Heating and Cooling Demonstration Act [1]. The purpose of this Act was to "provide for the early development and commercial demonstration of the technology of solar heating and combined solar heating and cooling systems." Various sections of the Act assigned specific responsibilities to NBS. These responsibilities included: the development of interim performance criteria for solar heating systems and dwellings within 120 days; the development of definitive performance criteria, as soon as feasible, using data obtained from the residential solar demonstration program; preparation of test procedures by which manufacturers of solar systems and components could certify their products as to compliance with the definitive performance criteria; and monitoring the performance and operation of various solar heating and cooling demonstration projects. Working with the lead Federal agencies, U.S. Department of Housing and Urban Development (HUD) and Energy Research and Development Administration (ERDA), now the Department of Energy (DoE), and other organizations in the public and private sectors, NBS had an unique and challenging opportunity during a twelve year period (1974-1986) to conduct research activities in carrying out and meeting its responsibilities.

To develop interim performance criteria, NBS staff used: a performance statement format developed by NBS for a previous HUD program on innovative and industrialized housing systems [2]; available limited published information on solar hot water, heating and cooling systems; recommendations from consultants in solar heating and cooling system design, construction, and operation; and comments and suggestions on draft performance criteria which were developed by NBS and made available for public review in November 1974. The interim performance criteria document, which dealt with the functional, mechanical, structural, safety, durability/reliability, and maintainability performance of systems and components, was published in January 1975 [3]. Under the HUD residential solar demonstration program, over 500 projects, involving 10,000 dwelling units at a cost of $19.5 million were completed. Approximately 65 percent of these projects consisted of active solar energy systems and 35 percent consisted of passive or hybrid solar systems. The HUD program, along with the DoE National Solar Data Network Program which developed instrumented thermal performance data, provided a large data base on the performance of solar heating and cooling systems which was very valuable in identifying technical problems and issues pertinent to the development of performance criteria and standards.

NBS prepared a revised interim performance criteria document in 1978 [4], and in 1981, a draft final or "definitive" performance criteria document was prepared and made available for public review and comments [5]. Following consideration of the comments received, definitive performance criteria for solar heating and cooling systems in residential buildings were published in 1982 [6].

The 1982 document served as a technical reference and resource for the solar industry, building industry and various governmental agencies concerned with assessing the design and performance of solar heating systems in buildings. Previously, the interim performance criteria documents [3, 4] served as useful resources for the development of: performance criteria for commercial solar heating and cooling systems [7, 8] and photovoltaic systems [9]; HUD standards for solar heating and hot water systems [10], and recommended requirements for building codes [11].

Members of NBS staff who participated in the preparation of performance criteria were: F. Eugene Metz, John K. Holton, Thomas H. Boone, Leopold F. Skoda, Michael F. McCabe, Elmer P. Streed, Lawrence W. Masters, Elizabeth J. Clark, Paul W. Brown, W. Douglas Walton, David Waksman, Thomas K. Faison, Belinda C. Reeder, and Robert D. Dikkers.

A plan that identified the needs and priorities for test methods and other standards (recommended practices, specifications) for solar heating and cooling applications was first published by NBS in 1976. It was later revised in 1978 [12]. This plan was prepared in cooperation with a Steering Committee established under the auspices of the American National Standards Institute (ANSI) and was useful in establishing priorities for research and standards development projects. The purposes of this Steering Committee, which was comprised of representatives from over 20 public and private-sector organizations, were to: identify needs and formulate specific tasks leading to the development of national consensus standards for the utilization of solar heating and cooling; assign standards development projects to competent standards-writing organizations; and maintain a continuous overview of these organizations' activities in order to assure an orderly and effective process which would avoid duplication of effort and conflicting standards. With financial support from ERDA and DoE, NBS established various research projects for generating draft standards that could be subsequently utilized by standards-writing organizations as a starting basis for the accelerated generation of national consensus standards.

During the eight-year period, 1974-1982, significant accomplishments were made in the development and validation of test methods and other standards relating to solar heating and cooling systems, components, and materials. With DoE support, many organizations including the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), American Society for Testing and Materials (ASTM), ANSI, and NBS contributed to the development of twenty new national consensus standards. Most of these standards, along with improved analytical procedures and design guidelines were referenced in the various evaluation sections of the 1982 definitive performance document (6).

Specifically, NBS assisted ASHRAE in the development and evaluation of test methods to measure the thermal performance of solar collectors [13-17], storage devices [14, 18-20], and domestic water heating systems [21]. The NBS method of test for solar thermal collectors allowed characterization under both outdoor environmental conditions and indoors using a solar simulator [22-26]. The test procedure developed for solar hot water systems permitted testing under outdoor conditions, indoor testing using a solar simulator, and indoor testing using a novel thermal simulation method [21, 27-35]. The Solar Rating and Certification Corporation (SRCC), an independent non-profit organization, adopted the solar collector and hot water test methods developed by NBS in the early 1980s. To date, over 1000 solar thermal collectors and 300 solar hot water systems have been SRCC certified providing much needed information to consumers contemplating the purchase of solar equipment.

Through research and the preparation of draft standards, NBS also aided ASTM in developing specifications for rubber seals and hose [36-38]; and practices for evaluating the durability of cover plates [39,40], absorptive coatings [41], thermal insulation [42], metallic and polymeric containment materials [43,44], and solar collectors [45]. Several of these standards have been referenced for use in U.S. industry certification programs for solar collectors and hot water systems. Many of the other standards were used as valuable tools in the evaluation of new materials and components for use in solar heating and cooling systems.

The U.S. Department of Energy sponsored research at NBS from 1977 through 1987 to provide experimental data to validate and improve computer

The majority of the experimental work on solar energy equipment took place at the NIST Annex (adjacent to NIST's campus, a former US Army Nike Missile site). The solar equipment, in this photograph, is being used to develop test methods for materials, solar collectors, and solar water heating systems.

simulation models used to predict the performance of solar water heating systems. In order to meet this objective, Hunter Fanney led a team consisting of Jim Allen, Donn Ebberts, Charles Terlizzi, and latter Brian Dougherty in the construction of a solar hot water test facility. The resulting facility was the only one within the U.S. that permitted the side-by-side testing of up to six solar water heaters subjected to identical environmental and load conditions. Over the years, this facility was used to test a vast array of solar water heating systems utilizing various solar collector designs, heat transfer fluids, control strategies, and storage tank configurations. The data collected from this facility greatly improved the simulation models and as a result, Hunter Fanney was asked to join and provide data to the International Energy Agency's Solar Heating and Cooling Program. His subsequent involvement provided additional exposure to NBS' solar energy activities.

In addition to providing experimental data for model validation [46-51], the research conducted within this facility led to an improved understanding of component interactions within solar water heating systems [52-55], the development of a novel measurement technique to measure the flow rate in thermosyphon solar water heating systems [56, 57], and supported the development of a testing methodology for solar water heating systems.

As interest in the direct conversion of sunlight to electricity through the use of solar photovoltaics increased during the 1980s, NBS researchers Hunter Fanney and Brian Dougherty became intrigued with the development of a solar hot water system that utilized photovoltaic panels. This work led to a prototype system and a U.S. patent was awarded to NIST in 1994 [58,59]. During the next several years, the U.S. Air Force funded NIST to deploy and measure the performance of two of these systems at the Kadena Air Force Base in Okinawa, Japan. The Tennessee Valley Authority, in concert with the National Park Service, funded the installation and monitoring of NIST's solar photovoltaic system at the Great Smoky Mountains National Park (GSMNP) [60,61]. Since 1996 this system has met the hot water needs of the main visitor's center and provided excellent visibility for NIST's efforts.

Building integrated photovoltaics, the integration of photovoltaic cells into one or more of the exterior surfaces of the building envelope, began to receive widespread interest in the late 1990s. Several factors are supporting this current interest including increased concerns over global warming, continuing declines in photovoltaic prices, legislation that requires utilities to buy excess energy generated by on-site distributed energy sources, and the fact that buildings account for 40 percent of the U.S. energy consumption. One of the barriers to the widespread proliferation of building integrated photovoltaics is the lack of performance data and validated models that will enable designers, architects, installers, and consumers to judge the merits of building integrated photovoltaics. In order to address this need Hunter Fanney, Brian Dougherty, and Mark Davis have constructed a number of experimental facilities and undertaken a multi-year project, co-funded by the California Energy Commission to provide the data needed for model validation. The facilities include a mobile, photovoltaic test facility, a building integrated photovoltaic "test bed," and

Hunter Fanney, leader, Heat Transfer and Alternative Energy Systems Group and David Block, director, Florida Solar Energy Center, shown commissioning a photovoltaic solar water heating system at the Florida Solar Energy Center.

a meteorological station [62]. Working with the solar photovoltaic industry NIST has characterized a number of photovoltaic cell technologies [63], collected long-term experimental data for a number of building integrated photovoltaic panels [64], and is currently striving to improve the computer simulation tools [65,66].

NIST's most recent activity in solar energy took place on September 14, 2001 when a 35 kW photovoltaic system located on NIST's Administration Building began supplying electrical power into the electrical grid [67]. This system provides enough electrical energy on an annual basis to meet the total electrical needs of four to five typical homes in the Gaithersburg, MD, area. In addition to saving energy and reducing peak demand charges, over a 30 year lifetime, this solar system is projected to avoid power plant emissions of an estimated 3,211 kg of nitrogen oxides, 7,470 kg of sulfur oxides, and 1,261 t of carbon dioxide. This project represents a cooperative effort between BFRL's Heat Transfer and Alternative Energy Systems Group, led by Hunter Fanney, and NIST's Plant Division, led by Douglas Elznic. This grid-connected photovoltaic system will serve as a model for the future installation of photovoltaic systems at NIST.

James Hill, who began NBS research in 1974 on measurement methods for the performance of solar collectors and storage systems, received the Department of Commerce Silver Medal Award in 1976, for contributions to the development of efficient solar energy systems. Robert D. Dikkers, who was responsible for the management and coordination of solar heating and cooling research activities being carried out for DoE and HUD from September 1974 through September 1986, was awarded the Department of Commerce Silver Medal Award in 1979 for his significant contributions to the development of national performance criteria and standards for solar energy systems. Department of Commerce Bronze Medal awards in 1980 went to: Willard Roberts for developing durability tests for solar systems materials; Elmer Streed for developing and evaluating testing standards for solar heating and cooling equipment; and David Waksman for development of performance criteria and standards for solar heating and cooling applications. Hunter Fanney, received the Department of Commerce Bronze Medal in 1988, for development of design, testing, and rating procedures for solar domestic water heating systems for buildings. In 1996 Hunter Fanney and Brian Dougherty received the Federal Laboratory's Consortium Excellence in Technology transfer Award for their outstanding work in transferring the photovoltaic solar

Photovoltaic Array installed on the NIST Administration Building that provided NIST's first on-site renewable energy on 14 September 2001.

water heating technology to the private sector. Based upon his contributions to the field of solar energy, Hunter Fanney was selected by the National Society of Professional Engineers as the Department of Commerce's "1999 Engineer of the Year." To date, the NIST team conducting solar photovoltaic research (Hunter Fanney, Brian Dougherty, and Mark Davis) has received three American Society of Mechanical Engineers' Best Paper Awards.

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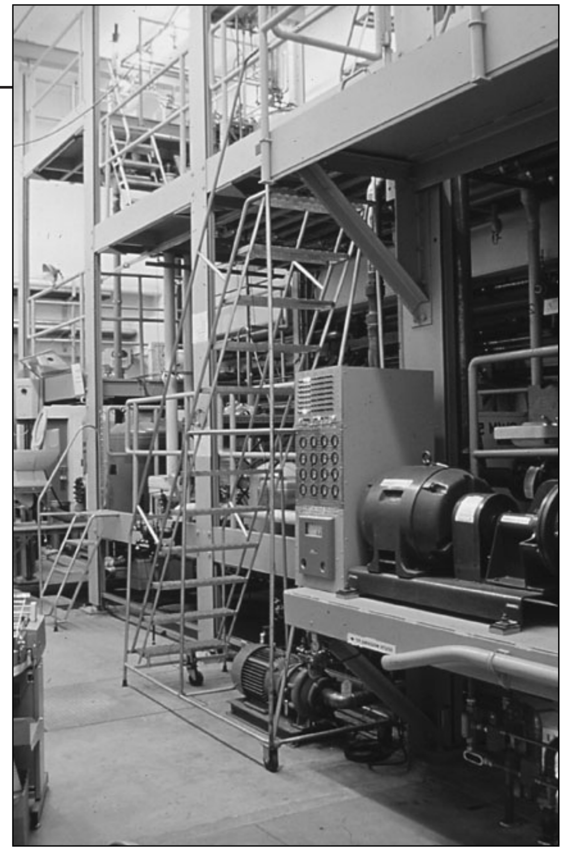
10.13 PLUMBING

In 1924 Herbert Hoover, Secretary of the Department of Commerce, reported in "Recommended Minimum Requirements for Plumbing in Dwellings and Similar Buildings," "…actual (plumbing) practice has been governed by opinions and guesswork, often involving needless costly precautions which many families could ill afford. The lack of generalized principles is responsible to a certain extent for the contradictory plumbing regulations in different localities…." NBS' Dr. Roy B. Hunter's research contributions established the basis for U.S. national plumbing codes that followed "The Hoover Codes" of 1928 and 1932 [1]. Those contributions remain in worldwide plumbing codes as adopted "Hunter Fixture Units" for design applications to full bore water supply pipe flow and partially filled pipe flow in drain-waste systems [2, 3].

FULL SCALE DYNAMIC PLUMBING TEST FACILITY - REALIZED

After NBS moved to Gaithersburg in the late 1960s the need was recognized for a plumbing test facility to investigate hydraulic phenomena of pipe networks of as-built systems. A full-scale tower installation was advocated by



CBT's seven-story plumbing tower and high-speed computerized electronic data acquisition system is used to simulate operation of full-scale plumbing systems in multistory buildings and reduced size venting and drain-waste-vent studies.

industry and code groups and constructed with the assistance of industry. Increased competence in hydraulic research event measurement was foreseen and was achieved with the introduction of computers for dynamic conditions event recording coupled with advanced instrumentation methods. The NBS plumbing test tower was constructed in 1972 in CBT under the supervision of Robert Wyly, Jack Snell, and Reece Achenbach. The facility provided capabilities for full-scale simulations of drain-waste-vent (D-W-V) plumbing systems in multi-story and town house installations.

SELECTED PLUMBING RESEARCH CONTRIBUTIONS

Several important building plumbing systems research investigations were performed using the plumbing facility in collaborations with industry and the government sectors. Working with the Copper Development Association NBS developed test procedures for test loads and measurements of a novel high rise single stack system (now the Sovent system) for U.S. applications. The work followed HUD Operation Breakthrough High Rise investigations with particularly identified research needs [4]. Installation acceptance for U.S. high rise buildings was advanced as a result of the data and information from this research; various materials are now marketed for the stacks and fittings with cost savings to contractors.

In collaboration with the National Association of Home Builders (NAHB) and DoD's Tri-Services Committee NBS developed recommendations for sizing vents at less than code specifications [5] for small residential buildings. Data were derived from test evaluations in NBS' new laboratory town house module.

With the DoD Tri-Services Committee for Building Materials, NBS supported full scale testing of a two-story townhouse configuration with reduced-size vents over a wide range of waste loading conditions in drain-waste-vent systems (D-W-V) [6]. Pipe size reductions were shown feasible without jeopardizing trap seal retention capacity. Actual air demand measurements were significantly less than assumed from current practice in plumbing codes (based on earlier NBS reports) for short stack systems with vent networks.

With the USAF, the Building Research Committee Tri-Services, and HUD, NBS determined reduced vent sizing for six new homes based on prior laboratory results. The field studies installation included automated system instrumentation (in occupied homes) for plumbing performance and user data collection for water usage [7]. NAHB encouraged their constituency of small home builders to adopt this sizing into practice by presentation of a mockup display installation. Cost savings of materials and labor indicated a potential for larger number of mortgage approvals as determined from NBS economic analyses applied to national financial minimum conditions for applicants. NAHB's economic assessment of the latter provisions indicated savings of about $500 per home in plumbing system costs. Confirmation of the sizing procedure information was submitted for plumbing code acceptance. It was not achieved primarily due to dissident opinion from sources seeking preservation of 'existing satisfactory practices'.

In a HUD sponsored research NBS performed investigation of water closet reduced consumption by control modifications of installed fixtures [8]. Laboratory testing of two-step flush control devices installed on water closets were conducted to evaluate the efficacy for water savings with reduced flush volumes. Criteria were developed for performance testing of mechanical functions and necessary performance evaluation procedures for retention of siphonic action, trap seal restoration, contaminated water exchange variability or reduction, rim wash cleansing, and adequacy of tissue extraction. Recommendations were prepared for implementation in standards.

Dynamic evaluations also were conducted in the test facility. Investigation was made of added circulation drain and vent loop modified D-W-V systems to increase system capacity in housing rehabilitation [9]. Reduced size vent applications for Veterans Administration hospitals were investigated by testing and analytical modeling for sizing [10]. Test data from dynamic measurements on multi-branch vent circuit networks were obtained for a novel installation of 'vent header' interconnects (of vertical vent stacks) in the interstitial space below the roof to avoid rain leakage from roof penetrations. Building sidewall fittings provide atmospheric pressure relief. Pressure calculations included algorithms for air pressure loss factors based on for local conditions; design sizing tables were prepared as guide to illustrate applications [10].

MODERNIZATION AND TRANSFORMATION OF PRINCIPLES

Elimination of steady flow assumptions for plumbing hydraulic phenomena became practical as the 1970s decade closed. Upgrading the test tower by Paul Kopetka, Fred Winter, and Lynn Shuman provided a unique ability to simultaneously measure time dependent phenomena and improve data precision.

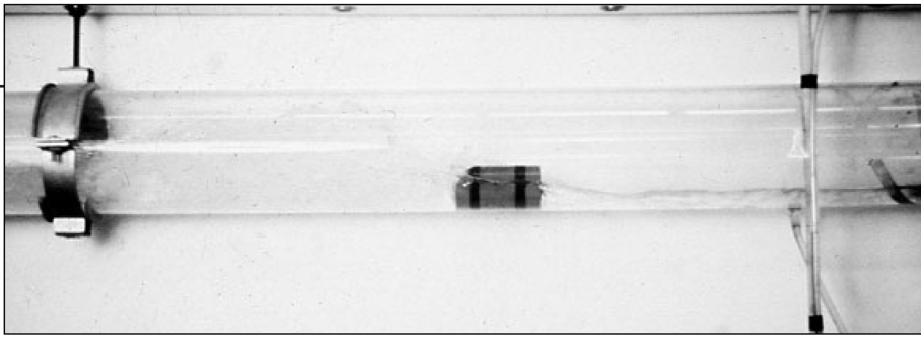
No comparable measurements in a full-scale drain-waste-vent plumbing system and fixtures had been undertaken elsewhere, or have been duplicated to date. The determination of actual transient event details became practical (water closets discharge from three to ten seconds while hydraulic jumps and flow mixing in merged flows occur within a second). Instrumentation was installed coupled with an electronic advanced sensor interface with desk top computer systems that established new competency in dynamic measurement and automated data recording with control of test events and pre-arranged loading condition sequences.

POTABLE WATER CONSERVATION PROGRAM - A COMPREHENSIVE THRUST

HUD Under Secretary Donna Shallala in 1978 approved plans for a National Potable Water Conservation program led by Lawrence Galowin with broadly inclusive participation from other participating sectors. NBS activity incorporated economics, human factors, consumer products, establishment of Stevens Institute contract, and HUD private contractor interface. Field studies of residential water demand and usage in a series of city studies on home water consumption (published by HUD) became a decade long primary resource for the American Water Works Association. The Residential Water Conservation Projects Summary Report on water conserving installations was published by HUD. It summarized three projects in Los Angeles, Denver, and the Washington areas. Robert Wyly and Lawrence Galowin assisted HUD as participants, technical advisors, and reviewers.

Results included performance of water-conserving fixtures, water supply requirements suitable for plumbing codes and consistent with water-conserving fixtures, and test procedures for the performance of water-conserving fixtures. These results permitted reliable and serviceable water-conserving residential plumbing systems with showerhead flow pressure control, user temperature requirements, pressure limiting devices and water distributions testing for performance standards [11]. Results were incorporated into the 1983 American National Standards Institute standard for water-conserving fixtures. The 1986 One and Two Family Dwelling Code of the Council of American Building Officials adopted the recommendations for drainage loads and methods for sizing water supply, drain, and vent piping. The work led to a National Potable Water Conservation Conference [12]. As a result, the American Water Works Association has encouraged water conservation.

A major result was the development (by Professor John A. Swaffield as



Horizontal solid waste drain transport for surge flow discharge

Guest Scientist at NBS) of a numerical method of characteristics solution to the governing equations for time dependent flow and waste solids transport. A computer-based engineering design procedure for the drain-waste-vent system accurately accounted for the transient transport of liquids and solids [13-20]. Fundamental theory and applications to plumbing codes were achieved which correctly reflected the hydraulics of plumbing piping systems and waste solids transport.

The dynamic modeling computer program for plumbing drainage system design has become a commercially available product in the 1990s for engineered systems and to many diverse applications for design and problem resolution. Progress continues with sustained research in doctoral degree programs in the United Kingdom that are directed by Professor Swaffield.

Larry Galowin provided enthusiastic leadership for CBT's plumbing research until it was curtailed by the cuts in CBT in the mid 80s. Galowin continued to be active in national and international plumbing research and standardization activities while assigned to other programs at NBS/NIST. As a NIST Guest Researcher he continues participation in plumbing activities. Galowin received national and international recognition for his research and recently served as a Visiting Professor and Leverhulme Fellow appointed at Heriot-Watt University, Scotland.

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11. FIRE SAFETY ENGINEERING

11.1 FLAMMABLE FABRICS

The Flammable Fabrics Act (FFA) was passed in 1953 to protect individuals from serious burns due to wearing combustible apparel. The primary impetus for passage of the law was the increased incidence of burn injuries due to brushed rayon ("torch") sweaters. The FFA was based on a standard test, up to that time voluntary, which was derived substantially from research and testing at NBS. In late 1967 the Act was amended to extend and strengthen protection from the flammability hazards of other wearing apparel and interior furnishings such as carpets, drapes and furniture.

Responsibilities for implementing the Act were split among the Department of Health, Education & Welfare (HEW), for accident case investigation; the Federal Trade Commission, for enforcement of the law; and the Department of Commerce for development and promulgation of flammability standards. The Secretary of Commerce delegated the standards development responsibility to NBS. In 1968 NBS Director Allen Astin established a Task Force to begin implementation of the new responsibilities. An Office of Flammable Fabrics was established at NBS in 1969 under Elio Passaglia. In 1970 Joseph Clark was hired to direct the office.

Joseph Clark, director, Office of Flammable Fabrics

A computerized database was developed at NBS in 1970, from accident reports provided by HEW investigators. The accident data available indicated the most frequent and severe injuries and losses to be involved with children's sleepwear and certain interior furnishings in homes. Available accident data indicated that carpets and rugs, curtains and drapes, upholstered furniture, and beds were the items most frequently involved in residential fires. Sleepwear was the first item ignited more frequently than any other item in almost 2,000 fire incident reports available at the time. Laboratory work was accelerated to develop and evaluate test methods that were related to the situations documented in the accident case reports. The law required that standards be promulgated only to protect the public from "unreasonable risks" of the occurrence of fire leading to death, injury, or significant property damage. The standards must be "reasonable, appropriate and technologically practicable." The legal concept of unreasonable risk and the technical concepts underlying appropriate tests and flame-retardant technology framed an intense set of activities ranging from basic research through policy analysis. Scientists and attorneys in and out of government frequently found themselves in public debates, media appearances, and congressional testimony. A particularly troublesome issue involved the potential toxicity of the combustion products of some chemicals added to fibers and fabrics to increase their flame retardance.

Development of a test method for surface flammability of carpets and rugs proved relatively straightforward, so promulgation of this standard came about first, in 1970. All carpet and rugs 1.2 m x 1.8 m or larger were required to meet the requirements of standard FF1-70 (flammable fabrics). This requirement states that no more than one out of eight specimens shall burn a distance of 75 mm from the point of ignition when tested according to the prescribed method. The test method, known as the "pill test," involves subjecting a 290 mm x 290 mm specimen, which has been dried in an oven, to the flame from a standard igniting source in the form of a methenamine tablet. The tablet, or "pill," is placed on top of the pile in the center of the specimen and ignited with a match, providing a standardized flame source for a period of about 2 minutes. If the flame spread on the carpet is more than 75 mm from the point of ignition, the specimen fails; and if more than one specimen of eight fails, the style of carpet cannot be legally manufactured for sale. The burden of compliance with FF1-70 rests with the carpet manufacturer. Smaller carpets and rugs were subject to the same test, but since the risk from these items is smaller, it is required only that they be labeled as flammable. The standard for carpets and rugs smaller than 1.2 m x 1.8 m is designated FF2-70.

In 1971, the Secretary of Commerce proposed a flammability standard (FF3-71) for children's sleepwear in sizes 0 through 6X. The standard was issued to protect young children from death and serious burn injuries that had been associated with ignition of sleepwear garments, such as nightgowns and pajamas, by small open-flame sources. The test requires that vertically hung specimens of fabrics, seams, and trim of children's sleepwear garments must self-extinguish after three seconds exposure to a small open flame. Manufacturers of children's sleepwear must test prototypes of sleepwear garments with acceptable results before beginning production. Manufacturers must also sample and test garments from regular production. The standard does not require or prohibit the use of any particular type of fabric or garment design as long as the manufacturer successfully completes the prescribed prototype and production testing.

While work was proceeding on the children's sleepwear standard, investigation of interior furnishings continued to progress. The accident data indicated that smoldering cigarettes and other smoking materials provide the ignition source in most residential fires. Most victims in residential fires were asleep at the time of their injury. The data also indicate that a high percentage of the victims were partially incapacitated by alcohol, drugs, or infirmity associated with illness or old age. Smoldering cigarette ignition was the most frequent source of fires in bedding and upholstered furniture.

In 1972, the Secretary of Commerce issued a flammability standard (FF4-72) for mattresses and mattress pads to protect the public from death and serious burn injuries associated with ignition of mattresses and mattress pads by smoldering cigarettes. The standard prescribes a test for mattresses and mattress pads which requires placement of lighted cigarettes at specified locations on the surface of the mattress or mattress pad. An individual mattress or mattress pad prototype passes the test in the standard if no cigarette test location produces char length more than 50 mm in any direction.

In 1972, the Department of Commerce issued a notice regarding the need to develop a standard for upholstered furniture. This notice summarized the available accident data and solicited comments on the risks as well as the type of test method that would be appropriate. Assessing the ignition resistance of upholstered furniture is much more complex than mattresses due to the more complex geometry (both geometry of construction and geometry of exposure to a cigarette), more varied materials of construction, fabric coatings, back-coatings, liners, and the like.

In 1973, authority to issue flammability standards under provisions of the FFA was transferred from the Department of Commerce to the new Consumer Product Safety Commission (CPSC) by the Consumer Product Safety Act. Several key scientists transferred from NBS to CPSC to help provide continuity in the work on flammable fabrics.

In 1974, the Commission issued a flammability standard (FF5-74) for children's sleepwear in sizes 7 through 14. The safety requirements of the two children's sleepwear standards are nearly identical.

In 1976, CPSC contracted with the National Bureau of Standards to draft a standard for upholstered furniture's resistance to ignition from lit cigarettes, and a standard (PFF6-76) was proposed. By 1978, CPSC had made improvements to the proposed standard, and it was prepared for formal issuance. Industry opposition to the mandatory standard resulted in a compromise in which the mandatory standard was not promulgated, and the furniture industry moved aggressively in 1979 into a voluntary alternative program run by their Upholstered Furniture Action Council (UFAC). UFAC promoted industry use of cigarette resistant upholstery fabric and furniture design, testing protocols, and a hang-tag program. Those refinements have been incorporated into NFPA and ASTM voluntary standards based on PFF6-76. Most manufacturers of upholstered furniture follow this program and have changed furniture design, construction and materials so that resistance to cigarette ignition has improved greatly.

Today, using either government or industry data, it is widely acknowledged that deaths and injuries from cigarette ignition of upholstered furniture have declined dramatically. CPSC and industry data indicate that over 80 percent of currently manufactured furniture can be expected to resist cigarette ignition.

The issue of cigarette ignition has been, until recently, the main focus of CPSC's flammability investigations. CPSC data show that fire deaths due to cigarette ignition of upholstered furniture dropped from 1,150 in 1980 to 470 in 1994. Deaths from "small open flames" however, have remained consistent at about 100 per year during the same period, most of those deaths resulting from children playing with matches and lighters.

In 1998, CPSC issued a draft regulation which would require that a piece of upholstered furniture resist burning when exposed to a small flame for a period of 20 seconds. "Small open flame" is understood as meaning candles, matches, or cigarette lighters. It is further understood that in most cases, such fires are begun when children under the age of five play with matches, lighters or other sources of flame. The problem of small flame ignition continues to be studied.

It is noteworthy that strategies other than fabric flammability standards have been used with success in helping to reduce deaths, injuries and property loss due to fire. CPSC has issued a safety standard for matchbooks requiring the product to meet several design requirements, including locating the friction surface on the outside back cover near the bottom of the matchbook. CPSC has also issued a safety standard for cigarette lighters to ensure the child resistance of these devices. In addition, smoke detectors have come into widespread use in residences, and sprinkler systems are used increasingly, especially in multi-family residences.

The Department of Commerce recognized James Winger's contribution to this work with its award of the Silver Medal in 1978.

In all, the efforts have contributed to a very substantial reduction in deaths, injuries and property loss due to flammable fabrics. Accident data from all sources indicate reductions ranging from 50 percent to 90 percent in deaths and injuries involving children's sleepwear, mattresses and upholstered furniture.

11.2 FIRE SCENARIOS

The thrust of *America Burning* [1] was to solve the Nation's "fire problem," and the report set a goal of reducing U.S. fire losses by half in the next generation. In practice the Federal emphasis, at least as far as NBS was concerned, was to be on improving life safety rather than property protection. Ensuring life safety is primarily a regulatory exercise, and so from there it was an easy step to articulating CFR's own long-term objective: to provide the technical basis, particularly for the requisite codes and standards, necessary to cut fire deaths in half in 25 years.

Impressive as this objective may sound, however, it is useless as a managerial metric. For one thing, NBS had no control over its technology once in the hands of the actual regulator, whose mode of implementation and enforcement was crucial to reducing losses. Moreover, the time scale for reliably detecting any real change in fire statistics is of the order of several years, far too long to be of help in directing a research program day-to-day. Instead, the real utility of the loss reduction objective was in shaping the content of a research program. The formalism which was used to connect the two, loss reduction and program content, was the fire scenario.

A fire scenario is essentially just that: an abbreviated story or script of a fire. From CFR's point of view, it was the "who, what, where, when, how, and why" of the incident that was of most interest, because the physical aspects were the clues to where technology might have an effect. Although it was recognized that every fire would be different if described in enough detail, it was also suspected that, for fatal fires at least, there would be common elements in many scenarios which would point to ways of breaking the chain of events leading to the fatal outcome. This suggested a plan: devise a set of "intervention strategies" designed to address the most common fire death scenarios and fashion a research program based on those strategies.

First, however, it was necessary to determine just what the most common scenarios were. Fire departments were not required to keep statistics and, even if they did, there was no requirement that they be reported in any systematic fashion. Therefore, the first attempt at identifying the most common fire death scenarios was not databased at all but was the result of a Delphi exercise carried out by the CFR senior staff. Scenarios were described by occupancy, time of day, ignition source, item-first-ignited, agents of spread (both smoke and flame) and cause of death (heat or smoke). The Delphi-based scenario ranking was the basis for the Center first long range plan, completed in early 1975 [2].

There were those, however, who thought that a quantitative scenario ranking was not only preferable but possible. Clayton Huggett, then Chief of the Chemistry Section and later Deputy Director of CFR, was particularly insistent that it was worth trying. He persuaded Frederic Clarke, who was in charge of the CFR planning effort, to visit the National Fire Protection Association (NFPA), dig through the NFPA data files and see what could be accomplished.

NFPA had two distinct fire databases, both of which depend upon the voluntary cooperation of fire departments across the country. One, which was the forerunner of the National Fire Data System now operated by the Federal government, was based on a standardized reporting system and used for NFPA's annual estimate of U.S. fire losses. Fires and fire deaths were counted by occupancy, by time-of-day, etc., but there was no way at the time to relate the various categories, so the scenario approach wouldn't work.

THE TOP FIRE DEATH SCENARIOS

Rank	Occupancy	Item First Ignited	Ignition Source	% of Fire Deaths
1	Residential	Upholstered furniture /mattresses	Smoking materials	27
2	Residential	Upholstered furniture	Open flame	5
3	a. Transportation	Flammable fluids	Several	4
	b. Residential	Apparel	Heating and Cooking equipment	4
	c. Residential	Furnishings	Heating and Cooking equipment	4
6	a. Several	Apparel/flammable fluids	Several	3
	b. Residential	Flammable fluids	Open flame	3
	c. Several	Apparel	Open flame	3
9	a. Residential	Interior finish	Heating and Cooking equipment	2
	b. Residential	Interior finish	Electrical equipment	2
	c. Several	Apparel	Smoking materials	2
	d. Residential	Structural member	Electrical equipment	2
	All others, each less than 2 percent of total			34
				100

Also, it was recognized that fire departments under-reported deaths in certain categories, notably those from apparel fires, because the fire in question was often too small to generate an alarm. They also tended to miss deaths which occurred after the victim was transported from the fire scene.

NFPA's other database, the Fire Incident Data Organization, or FIDO, was strictly anecdotal. For an incident to be included in FIDO, it had to involve death, serious injury or large property loss. FIDO was subject to some of the same fire-department-derived biases as the regular NFPA data system but it had two important features: it was large, containing data on approximately 11,000 fatalities and there was a coded description of each fire incident, so it was possible to learn something of the circumstances of the death.

Clarke and John Ottoson, of NFPA, were able to cross-correlate the FIDO database and mortality data from the Bureau of Vital Statistics of the US Department of Health, Education and Welfare, both of which contained incomplete - but overlapping - profiles of US fire deaths, to produce the first self-consistent and completely inclusive estimate of where they occur. With this information in hand, the in-depth information from FIDO was used to produce a list of 14 abbreviated scenarios which together accounted for an estimated two thirds of US fire deaths [3].

Fire data collection has improved a great deal in the past quarter-century but these early estimates have proven to be surprisingly good. Comparison with the rankings produced by the Delphi exercise showed that the intuition of the CFR staff was reasonably accurate with one exception: the importance of children's sleepwear fires was overstated. Since the mid-70s were the height of Federal interest and involvement in this issue, such a finding should not be surprising.

The principal utility of fire scenarios, of course, is that they highlight where efforts need to be applied. That the ignition of soft furnishings by smoking materials, primarily dropped cigarettes, was an important scenario came as no surprise, but the sheer size of the problem was somewhat unexpected. It provided much of the impetus for the Center's work on upholstered furniture and mattress ignition standards; studies of room fire buildup and flashover; and the first systematic investigations of combustion product toxicology. In 1979, Benjamin Buchbinder received the Department of Commerce Bronze Medal Award for his work on decision analysis for fire safety.

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11.3 FIRE RESEARCH INFORMATION SERVICES (FRIS)

The Apollo I spacecraft fire in 1968 killing three astronauts was the first fatal accident of the United States space program [1]. This accident was

Nora Jason, leader, Fire Research Information Services

so tragic that the National Aeronautical and Space Administration/Aerospace Safety Research and Data Institute (NASA/ASRDI) developed a plan to have better access to information applicable to the program. Twelve areas of knowledge were identified. One of the areas was fire safety and the NBS, well known for its fire research and safety program and the reputations of Alexander Robertson and John Rockett, was selected for the project. The tasks were to create input for a bibliographic database and write several state-of-the-art reports.

The bibliographic database was designed to meet specific NASA needs and it was futuristic for its time, that is in the early 1970s. Each record had the complete bibliographic reference, and in-depth narrative abstracts, major and minor keywords, in addition to report number, corporate source, contract sponsor(s), contract number(s). It is now incorporated into the NASA bibliographic database.

No fire safety thesaurus existed in the United States or elsewhere so a vocabulary list (later serving as the nucleus of the FIREDOC Vocabulary List [2]) was developed to ensure quality control of the information to assist the user.

The state-of-the-art research reports discussed topics such as fires in oxygen-enriched atmospheres, fire detection, and toxicity. In addition, a list of experts in the fire field [3] was developed to be a additional source of information.

There was no fire research library in the United States and NBS recognized that the NASA work could be a model for a fire literature collection. The decision to develop and maintain a fire research literature collection was recommended by the National Academy of Sciences [4]. Dick Katz was the selected as the first project leader of the Fire Research Information Services. Shortly thereafter he was transferred to the newly formed U.S. Fire Administration library and Nora Jason became the project leader.

The first NBS product was the annual compilation of fire research reports [5]. Over time this product continued to incorporate the technological changes and the organizational changes [6]. Nora Jason's work in establishing FRIS was recognized by the Department of Commerce Bronze Medal Award in 1976.

The first CD-ROM containing fire research publications [7] by the staff and grantees was created in 1993; by the following year the CD-ROM [8] included building staff contributions. S. Regina Burgess's scanning ability and Glenn Forney's computer skills have enhanced the product. The BFRL yearly bibliography in paper format ceased in 1996 and only the CD-ROM version was available. In 1997 the digital version of all BFRL publications became available on the NIST web site http://www.bfrl.nist.gov and listed in the section entitled BFRL Publications Online.

In 1986 FIREDOC, an online bibliographic fire research database [9], was first announced at the Society of Fire Protection Engineers' Annual Conference in Atlanta, Georgia. By 2000 Kathleen Whisner has devoted approximately 13 staff-years inputting 60,000 bibliographic records into the database. Initially it was accessed over telephone lines and telnet. In 1996 FIREDOC became available over the World Wide Web and today that is the sole source of entry; the URL is: http://fris.nist.gov. The effectiveness of FRIS' Fire on the Web was recognized in 1999 by the Bronze Medal Award of the Department of Commerce for Nora Jason and Glenn Forney.

The original NASA tasks set a precedent for additional work with NASA and other organizations in creating bibliographies and organizing conferences and editing conference proceedings [10]. Other agencies/organizations with projects that involved the FRIS staff included the Minerals Management Services, National Fire Protection Association Research

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11.4 FIRE INVESTIGATIONS AT NIST

11.4.1 INTRODUCTION

Serious fire by its natural is a large-scale event, and difficult to reproduce in laboratories, even in large laboratories. The study of real world fires provides the opportunity to test, evaluate and demonstrate the engineering tools developed by NIST and its colleagues around the world and to determine the efficacy of the various standard approaches included in building codes and other engineering regulatory and guide documents.

Ever since fire research became a NIST program in 1914, NIST has been interested in fires and have made investigations and evaluations of incidents. A formalized approach to investigation, however, did not get underway until the mid 1970s, and then at a relatively slow pace. Fire investigation is one of the responsibilities contained in the Fire Prevention and Control Act of 1974 [1]. NIST's initial response to this obligation was to award a grant to the National Fire Protection Association underwriting increased activity in their established fire investigation activates. The NFPA investigations, while important, concentrated on the construction, fire department activities and conformance with established codes and standards. They did not undertake engineering calculations or try to quantitatively analyze the fire phenomena. The situation is understandable when it is recognized that until the late 1980s there were few publicly available instruments for making such evaluations. One of the best of that era was the Fire Investigation Handbook [2] published in 1980. It however faded into virtual nonuse once the models and other analytical tools became available. For its time the Handbook was great but late and soon passed-over by fire technology advances. During the 1990s the Fire Safety Engineering Division was involved in the investigation and analysis of several large fire disasters around the world.

11.4.2 NURSING HOME FIRES

In 1975 NIST was charged by the Department of Health and Human Welfare formerly the Department of Health Education of Welfare (HEW) to improve the firesafety knowledge base in nursing homes. There had been a series of serious nursing home fires and Congress had passed an act mandating that nursing homes conform with the Life Safety Code published by NFPA. The desire of HEW was to go beyond this and develop a better understanding of the life safety problems in nursing homes and develop better means of responding to them. One of the initial NIST efforts was a study undertaken through a grant to the University of California at Berkley, with Professor Lars Larup as the principal investigator. Professor Lerup studied the available data. His primary source was NFPA reports of serious fires in nursing homes.

Working closely with the NIST staff he made parallel plots of the development of the fire and resulting fire hazard in comparison with the activities of the staff and patients. He presented these in graphic/realistic cartoon fashion [3]. Lerup's work brought out a number of observations important to safety to life that had not been previously detected. Of single most importance was the fact that nursing staffs did not understand the phenomena of flashover and the danger of allowing a flashover fire to vent itself inside the building. Both HEW and NIST agreed that it was important that nursing staffs be informed of flashover, its dangers, and safeguarding actions they could undertake. As a result NIST produced the training film Flashover, Point of No Return [4]. Flashover, Point of No Return demonstrated the risk of flashover, the impact of the phenomena, and the ability a nursing staff had to confine the fire using the traditional hospital patient room door. Flashover was first published in the late 1970s and is still actively used as a training tool. Hundreds of thousands of nursing staff have viewed it and indications are that it has resulted in incidents where the nursing staff followed its guidance and protected the residence of nursing homes from a potentially lethal insult. Both Lerup's analysis and Flashover received national recognition in the form of awards.

11.4.3 FIRE INVESTIGATION HANDBOOK

The Fire Investigation Handbook [2] was unique for CFR in that it was not based on original research at CFR. Instead, CFR performed an editorial and implementing function to prepare a handbook for fire investigators. Its separate sections were written by practicing experts under editorial guidance from Francis Brannigan, an eminent practitioner, and Richard Bright and Nora Jason of CFR. The whole handbook was reviewed by other experts and the U.S. Fire Administration. All of the contributors donated their contributions.

The sections are: Fire Ground Procedures, Post-Fire Interviews, the Building and its Makeup, Ignition Sources, the Chemistry and Physics of Fire, and Sources of Information. In addition there are appendices on how to organize an arson task force, how to be an effective expert witness, a list of independent testing laboratories, and a bibliography. The handbook was published by the U.S. Government Printing Office on paper that would survive moisture and rough handling in field use. It was reprinted at least twice.

11.4.4 ADVENT OF MATHEMATICAL POST FIRE ANALYSIS

At the time Lerup produced his graphic displays there were no available mathematical compartment fire models available to describe the fire. Lerup's work was primarily based on fire reports and the qualitative understanding of fire provided by the staff of the Center for Fire Research. Mathematical models, however, at that time were beginning to emerge from several sources, sponsored by NIST. This includes grant work by Edward Zukoski at California Institute of Technology, the work of Howard Emmons and his colleagues at Harvard and the Factory Mutual Research Corporation, and the work of Thomas Waterman and Ronald Pape at Illinois Institute of Technology. All of these came to fruition at about the same time. Each was different in its detail while following the same general concept of entrainment of gases (air, smoke, etc,) into the flame and fire plume, heat balance, radiation, and fluid (smoke) flow. Also about the same time the concept of oxygen depletion calorimetry also was developed. This development was primarily through the efforts of William Parker and Clayton Huggett at NIST. Their work resulted in a breakthrough in the determination of mass burning rates and rates of heat release of both individual materials and full size furniture assemblies.

With the availability of these new tools and the associated knowledge, it became feasible to make scientifically based quantitative analysis of the fire phenomena and to reconstruct the course of the fire and the reasons that a fire behaved as it did. The first efforts focused on specific occurrences during the fire, latter the scope was expanded to a more universal appraisal. Improvements in both scope and quality of scientifically based fire investigation continue to this day.

NIST has been involved in a large number of fire investigations. A selected series of investigations are listed to demonstrate the progression in increased sophistication with time.

11.4.4.1 Beverly Hills Supper Club, 165 Fatalities, May 18, 1977

One of the first application of the new analytical knowledge to fire investigations occurred in the litigation resulting from the Beverly Hills Supper Club Fire on May 18, 1977. One hundred and sixty-five persons died in this fire. The Beverly Hills Supper Club was a large complex with several different activities. These included a traditional dining room restaurant, a cabaret, and a separate bar. The fire started in the bar and, at a point early in the fire, spread with great speed to the cabaret room where the majority of the deaths occurred. It was initially held that fire spread on the surface of combustible material through a corridor linking the bar to the cabaret space. Howard Emmons, a close colleague and grantee of NIST at Harvard University analyzed the fire phenomena involved, Emmons used the phenomenology developed as part of the work he and his team at Harvard and Factory Mutual Research Corporation were undertaking as part of a NIST grant covering the development of fire models. Emmons demonstrated that the fire spread as fast as it did not because of a progressive ignition on a combustible surface, but rather as a fluid mechanics movement of a flame front containing yet unburned pyrolized products. The flame and fuel moved as a fluid transported down the corridor from the bar to the cabaret.

11.4.4.2 MGM Grand Hotel and Casino, Las Vegas, Nevada, 84 Dead, November 21, 1980

In the MGM Grand Hotel Fire John Klote acting as the advisor for NIST, used his work on smoke travel to identify the paths of smoke movement from the fire source at ground level to the various upper levels of the building. The enclosures around the earthquake joints and the elevators were found to be the prime source of smoke and toxic gas movement. Also, post-fire evaluation of the chemical content of victims blood, by Merit Berky, lead to a conclusion that the carbon monoxide (carboxyhemoglobin) was not sufficient to be the sole source of fatality and there was strong suspicion of hydrogen cyanide presence in the smoke distributed throughout the building.

During the litigation following the fire, Emmons was again retained as an expert witness and used the Harvard V model, recently developed, to demonstrate which of the materials in the kitchen and dining room area, where the fire started, contributed to the development of flashover and which did not.

11.4.4.3 Hospice of Southern Michigan, 6 Dead, December 1985 [5]

This analysis was the first attempt by the NIST staff to use fire modeling to reconstruct a fire incident. The actual field investigation was conducted by the NFPA fire investigators. The subsequent analysis by NIST. The fire models used in the analysis were ASSETB [6] and DETAC T[7]. In this incident, a fire occurred in a bedroom off a corridor. The bedroom door was open. The window broke as the room went through flashover, and smoke progressed down the corridor invading other rooms. The initial appraisal of the carbon monoxide content in the atmosphere flowing into the exposed rooms down the corridor appeared to be marginal in its lethality. However, all of the exposed patients died. Since this was a hospice it was first felt that the terminal conditions of the patients made them extraordinarily susceptible. Autopsies however, indicated that almost all of the victims had high carboxyhemoglobin concentrations in their bloodstream, indicating that their personal health condition was not a factor. As a result of this inconsistency, Nelson conducted an experiment in the NIST burn test corridor where the arrangement of spaces was reconfigured to imitate the situation at the hospice. In the fire air was drawn in through the broken window of the room of fire involvement. This sustained a flashed over high-energy fire. The fire vented smoke laden with carbon monoxide and devoid of oxygen into the corridor which spread into the sleeping rooms. The result of this test demonstrated a massive switch in the chemical balance between carbon monoxide and carbon dioxide, producing conditions 30 times to 100 times more lethal than free and open burning with adequate air. Further testing at NIST continues to this day and has demonstrated the appropriateness of this conclusion.

11.4.4.4 Dupont Plaza Hotel, Puerto Rico, 90 Dead, December 31, 1988

This is the first incident in which NIST used its emerging analytical techniques and models to describe the course of events in fire. James Quintiere and. Nelson joined the Federal investigation team working at the site. Their prime purpose was to both assist the Alcohol, Tobacco and Firearms team and to demonstrate and test the ability of the computational instruments then arriving on the scene.

Nelson used the collection known as FIREFORM [8]. FIREFORM included various closed form equations related to fire and Nelson's partially completed compartment fire model (then called ROOMFIRE, but later entitled FIRE SIMULATOR). With these the NIST team was able to demonstrate the speed of development of the fire as well as its production of excess pyrolstate (unburned fuel) mixing with the flames. The transfer of this flaming mixture of burning yet unburned combustible material from the ballroom, where the fire occurred, into the large foyer and from there traversing the casino, where the majority of the deaths occurred was determined by Quintiere and Nelson. The reconstruction developed by the NIST team was found to be in very close proximity with the findings made by ATF and FBI through interviews and matched very closely with photographs taken during the fire. It's felt this investigation was a breakthrough investigation in terms of advancing the concepts of fire reconstruction with physical and mathematical models. Jack Snell was awarded the Gold Medal of the Department of Commerce in 1987 for overall leadership of the investigation and for subsequent efforts to modernize Puerto Rican regulations for the fire safety of buildings.

The engineering tools used in this evaluation have been refined and brought together in the collection FPETOOL [9]. The FPETOOL collection and other models are now heavily used throughout the entire fire safety community in both risk appraisal and fire incident reconstruction. Prime examples of the advances being made are the use of Computational Fluid Dynamics (CFD) fire and smoke models in the reconstruction of events in the Cherry Road Fire and the work currently underway in understanding the events resulting in the collapse of the World Trade Center attack on September 11, 2001.

Also, as a result of the demonstration of the value of engineering analysis and fire science to fire investigation, the ATF has undertaken a serious effort to train its fire investigators in the rudiments of fire science, added fire protection engineers to their staff and is in the process of the construction of a major new fire test and investigation laboratory.

11.4.4.5 First Interstate Bank Building, 1 Dead, May 4, 1988 [10]

One person died in this fire. This fire initiated in the trading room on the twelfth floor of a 60 story building. While sprinkler protection was in the process of being installed, it was not in service at the time of the fire, so the building responded as a non-sprinklered building. The fire traveled from floor to floor, presumably through the space between the exterior wall and the floor slab, eventually covering four floors. Problems with the water supply hampered the fire department and the fire burned unattacked for almost two hours. The fire propagated around the entire building on each of these floors and was fully involved for the entire floor areas for most of its duration. The probable point of origin was mathematically determined by the sequence of response of the smoke detectors and the characteristic burns of the living contents. The models in FPETOOL were used and proved capable of analyzing the fire development and spread on any floor. The spread from floor to floor was, however, estimated on the physical evidence of the flame and empirical understanding of the construction of the joints between floor slabs and curtain walls. The building survived with complete

First Instate Bank Building. BFRL develops improved methods to evaluate fire performance of new materials and structures.

burnout of the involved floors, but no structural damage or failure of a load-supporting member.

11.4.4.6 Hillhaven Nursing Home Fire, 13 Dead, October 5, 1989 [11]

In this fire 13 persons died. The fire was reminiscent of the conditions previously described for the hospice of Southern Michigan. A flashed over fire occurred in a bedroom, the patients from that room were removed to a place of safety, but the doors on the other patient's rooms failed to close properly and the carbon monoxide loaded gas propagated through the corridor, entering these rooms and killing patients in their beds. The importance of this investigation has been an impact on the fire investigation field. The report lays out step-by-step the engineering analysis of the incident starting with the ignition of the initial fuel and proceeding to the final end result. The report is used in numerous fire investigation courses as an example of a methodology to be emulated.

11.4.4.7 Happy Land Disco, Bronx, New York, 87 Fatalities, March 25, 1990 [12]

In this fire an arsonist splashed gasoline over the entrance to the building. It was estimated about 3.8 L of gasoline was used. The fire was then ignited, it flashed over the foyer, followed by flashover of the adjacent barroom and then raced up stairs, pushing toxic fumes ahead of it, until it filled the upstairs main room with toxic fumes. Relatively small amounts of flame actually reached the upstairs. The fire scene was investigated by Richard Bukowski and Harold Nelson and the model FAST [13], then in its final pre-release stage of development at NIST, was used to reconstruct the process and progress of the fire. The model demonstrated the manner in which oxygen was depleted in the original space of involvement, resulting in the production of high carbon monoxide, which rapidly anesthetized and then killed the occupants of the second floor.

11.4.4.8 Oil Fields of Kuwait

As a result of the Iraqi invasion of Kuwait and the subsequent conflict, 749 oil wells were systematically damaged with explosives in February 1991 resulting in uncontrolled gas and oil well blowout fires on 610 of the wells. As part of the international scientific response to the environmental and health emergency, NIST in coordination with the United Nations Environment Programme (UNEP), the World Meteorological Organization (WMO), the U.S. Army Corp of Engineers, and U.S. Gulf Environmental Technical Assistance Task Force, performed exploratory

Daniel Madrzykowski, fire engineer, is performing heat flux measurements. The flame height is about 65 m high with a heat release rate of 1.7 GW.

measurements to demonstrate the feasibility of determining the heat release rate of burning wells as an essential part of the characterization of the fires for use in modeling of the smoke plume[14].

Dave Evans, Dan Madrzykowski, and George Mulholland traveled to Kuwait in May 1991. Flame height and heat flux measurements were made on a number of burning oil wells in the Al Mawqá and Al Ahmadi oil fields [15]. Smoke samples were also collected. Gerald Haynes provided NIST with an aerial flame height survey of burning wells in the Al Minagish oil field. A radar altimeter was used from a helicopter to perform this measurement. The heat release rate of the fires measured ranged from 90 MW to 2,000 MW that corresponded to 1,500 barrels to 30,000 barrels of oil per well per day.

11.4.4.9 Oakland Hills

On Sunday, October 20, 1991, Oakland California experienced one of the worst single fire losses events in recent U.S. history. Twenty-five persons were killed and 2,889 dwellings were destroyed. The conflagration, which covered 7.2 km2, was a classic example of a wind driven, wildland/urban interface fire [16]. Kenneth Steckler, David Evans and Jack Snell comprised the NIST team who worked with fire experts from Japan, the U. S. Department of Agriculture, and UC Berkeley. The objective of the investigation was to determine the role that wood framed structures played in the fire spread. The investigation found that the high wind speed, proximity of flammable vegetation to structures and the flammability of exterior construction materials were factors in the spread of the fire. The use of wood framing members did not significantly influence the rate of spread or the extent of the fire [16].

An Oakland Hills neighborhood that was in the fire's path and completely destroyed. Note the burned automobiles in the foreground.

11.4.4.10 Post-Tsunami Fires, Hokkaido, Japan

On July 12, 1993, an earthquake registering 7.8 on the Richter scale struck in the Japanese Sea off the coast of Hokkaido. The earthquake generated a tsunami that devastated the small island of Okushiri. The tidal wave destroyed buildings, overturned fuel tanks and spread debris making it difficult for the fire department to respond to the fires that followed the tsunami. The disaster resulted in more than 200 people dead and more than $60 million dollars in damages. By the time the fires were extinguished almost 300 homes had been destroyed. Through the effective bilateral collaborative US-Japan Program on Natural Resources (UJNR), which includes a Panel on Wind and Seismic Effects and a Panel on Fire Research and Safety, Noel Raufaste of NIST and Kazuhiko Kawashima of the Japan Public Works Research Institute (PWRI) quickly organized teams to investigate the damages and what might be done to mitigate future disasters of this type. Richard Bukowski, of NIST, and Charles Scawthorn, of EQE International, headed the fire portion of the investigation [17]. The study found that the combustible construction of the buildings, combustible debris between the buildings and the unanchored kerosene and propane tanks all contributed to the fire spread. Comparisons were made between the events of these post-tsunami fires to the post-earthquake fires that occurred in the 1980s after the Coalinga, Loma Prieta and San Francisco earthquakes.

11.4.4.11 Post-Earthquake Fires, Northridge, CA

A magnitude 6.8 earthquake struck the San Fernando Valley at 4:31 AM on January 17, 1994. Fifty-eight people died and thousands of injuries resulted

A collapsed carport shields a house from the adjacent structure that burned down completely.

from the earthquake. Building damage was wide spread with approximately 80,000 people to 125,000 people displaced from their homes. In the most severe cases, buildings and elevated highways collapsed. The earthquake also resulted in 30 to 50 significant fires throughout the valley and an increased number of fires in the days following the earthquake due to restoration of power and gas to damaged buildings. A multi-agency team, organized under the auspices of the Interagency Committee on Seismic Safety in Construction and headed by the NIST, was assembled and within days of the incident were working at the disaster locations [18].

Doug Walton led the fire portion of the investigation for NIST. His focus was to identify the factors that contributed to the cause, spread of and loss from the fires. The finding of the study indicate that a significant number of the post earthquake fires involved natural gas leaks due to damaged lines or equipment. Due to light winds, high moisture content in natural fuel, building construction and spacing, and the intervention of the fire department most of the fire were limited to the building of origin. However building-to-building fire spread did occur in three manufactured housing developments. In these developments, close spacing and combustible construction lead to multiple unit fires. In some instances, the collapse of carports between units helped to form a firebreak. In addition to documenting what happened, the poster disaster report states that given the favorable weather conditions and the time of the occurrence, the fire losses were small relative to the loss potential under windy, hot and dry conditions [18].

11.4.4.12 Post-Earthquake Fires, Kobe, Japan

A year to the day, after the Northridge, CA earthquake, an earthquake of similar magnitude struck Kobe, Japan and its surrounding areas. The earthquake resulted in more than 6,000 deaths and over 30,000 injuries. The multi agency investigation was conducted under the auspices of the UJNR Panel on Wind and Seismic Effects. The objectives were to document important lessons from this earthquake that might be used to mitigate the impact of future earthquake disasters [19].

From the U.S., the fire team was composed of Dan Madrzykowski from NIST and Ed Comeau from the National Fire Protection Association. They were in Japan from February 12 through 18, 1995. One hundred forty eight fires occurred during the three days following the earthquake. The fires damaged or destroyed approximately 6,900 buildings and burned the equivalent of 70 city blocks. The source of many fires were broken gas lines and damaged kerosene heaters. Many of the ignitions occurred as electric power restoration was attempted. Collapsed buildings intermingled with crushed automobiles assisted the fires in spreading from block to block. The damage in Kobe to the water supply,

An example of the many collapsed buildings that blocked entire streets making it difficult for emergency response on in some cases, escapes. If this building had caught fire, it would have easily spread the fire to both sides of the street and exacerbating the fire conditions considerably.

the emergency water cisterns, and to the transportation systems (highways, train trestles, etc) significantly limited the fire department response. Lessons learned for the U.S. covered a broad range. Beginning with large scale governmental issues, such as city planning and design to develop fire breaks and alternative water supplies and ending with information and training for residents so that they can be prepared to help themselves in times of widespread disasters that overwhelm public service resources.

11.4.4.13 Cherry Road Fire, Washington, D.C, 2 Firefighter Fatalities, May 30, 1999, [20]

NIST was asked to help on the Cherry Road Fire Investigation by the District of Columbia Fire & Emergency Medical Services Department Reconstruction Committee. The reconstruction committee could not explain several things about the fire incident.

1. Three firefighters received severe burn injuries that seemed to be inconsistent with the limited thermal damage in the room they were in.
2. The severe burn injuries to the three firefighters were inconsistent with the minor injuries to other firefighters that were in close proximity.
3. The two nozzle men, both fatalities, were well trained and adequately equipped. Why didn't they flow water from their charged (pressurized) hose lines to protect themselves?

Two NIST models, the Fire Dynamics Simulator [21] and Smokeview [22], were used to simulate and visualize a townhouse fire that claimed the lives of two Washington D.C. firefighters. A model following the Standard Operating Procedures (SOPs) of the fire department for comparison purposes was also developed.

The Fire Dynamic Simulator simulations and the Smokeview visualizations helped the department understand the incident. It also demonstrated the value of the departments SOP relative to venting. The CD-ROM format allowed research results and fire modeling technology to be used directly by the fire service (i.e. a training officer can take the CD and use it to demonstrate the benefits of proper ventilation, the speed with which a fire environment can drastically and tragically change).

The results are being made available to a wide audience to educate firefighters in an effort to prevent a similar incident from occurring. NIST engineers developed a CD-ROM demonstrating the application of the models to this case [23]. The Smokeview visualizations have been incorporated into a number of fire fighter training curriculums, including IAFC's Command School, the National Fire Academy. As discussed below these models are cornerstone elements in the ongoing analysis of the fire development in the World Trade Center attack of September 11, 2001.

NIST staff engineers, Daniel Madrzykowski, Robert Vettori, Doug Walton, Glenn Forney, and Kevin McGrattan, formed the team that enhanced the existing models, applied then to the problem and presented the results in a manner meeting the needs of the investigation.

11.4.4.14 Summary

The sophistication, quality, and impact of NIST fire investigations have massively increased over the last decades. Investigations have become an important test of and technology transfer instrument for dissemination of NIST products.

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11.5 SMOKE AND FIRE DETECTORS

A summary of early work at NBS was prepared by Dan Gross for the third IAFSS Conference in 1991 [1]. The earliest studies at NBS of the performance of detectors were conducted in the 1920s and 30s. In the 1950s pioneering work was conducted by McCamy on flame detectors for aircraft engine nacelles [2] in which he published data on both ultraviolet (UV) and infrared (IR) signatures and proposed coupling IR sensors with flame flicker circuits to discriminate hot objects from actual flame.

11.5.1 OPERATION BREAKTHROUGH

In the late 1960s the US Department of Housing and Urban Development (HUD) instituted a major, innovative housing demonstration project called "Operation Breakthrough" [3]. Intended to facilitate the development of novel approaches to design, materials, and construction techniques for improving low-income housing, the program included the submission of concepts and the actual construction of demonstration homes by the winning submitters. Because traditional, prescriptive building codes could not deal effectively with innovative methods and materials, HUD engaged NBS to develop performance-based guide criteria to assure safety, functionality and durability of the innovative systems. The guide criteria were a prototype for the performance standards now being promulgated globally. HUD obtained waivers of local prescriptive building codes to allow construction and occupancy of the demonstration homes.

At the time of Breakthrough, fire alarm systems in homes were rare, and where installed used commercial detectors and panels designed by the rules applied to commercial properties. Heat detectors usually were used in occupied spaces. In commercial installations, relatively expensive smoke detectors usually were used only to protect high value items, so they were rare in home systems. A then typical residential system cost as much, in 1968 dollars, as residential sprinkler systems cost in 2000 dollars. The (single-station) smoke alarm had been developed in 1965 but sales were low and availability poor for the few models being marketed.

One of NBS's fire protection engineers, Richard (Dick) Bright, had been impressed with an article published by Canada's National Research Council in 1962. John McGuire and Brian Ruscoe [4] studied 342 residential fire deaths in Ontario from 1956-1960 and judged the life saving potential of a heat detector in every room or a single, smoke detector outside the bedrooms and at the head of the basement stairs (if the home had a basement). Their judgment was that the heat detectors would have reduced the fatalities by 8 percent and the smoke detectors by 41 percent.

NIST included in its Breakthrough criteria [5] a requirement for smoke detectors located in accordance with the McGuire and Ruscoe guidelines. Since few of these homes were built, no substantial fire experience was gained with these detectors.

11.5.2 HURRICANE AGNES

In 1971, heavy rains from Hurricane Agnes flooded many homes in central Pennsylvania and lower New York. HUD mounted a federal disaster relief effort (this was before FEMA was created) including the provision of temporary housing for many poor residents of the region. HUD purchased 17,000 mobile homes (later called manufactured homes) and asked NIST to apply some of the lessons of Breakthrough to the purchase specification. NIST included a requirement for a single-station smoke detector (typically battery operated) outside the bedrooms of each unit. The order for 17,000 smoke detectors had to be split among five manufacturers because at the time no single company had the production capacity to fill the order. Today, one manufacturer could do so with two days' production.

The 17,000 homes were delivered to several sites and were used by families until they could rebuild or find alternative accommodations. Most lived in the homes for a year but some were still occupied three years later. The fire safety statistics were surprising. While the statistically expected number of fires did occur, there were no fire deaths and few injuries. The smoke detectors were credited with getting occupants out before they became trapped - just as McGuire and Ruscoe had surmised.

This was the first, large installation of residential smoke detectors and the results convinced the manufactured housing industry to adopt the first smoke detector "ordinance." In 1975 it became the policy of the Mobile Home Manufacturing Association (the predecessor of today's Manufactured Housing Institute) that one smoke detector located outside the bedrooms be provided in every manufactured home produced by a member company.

11.5.3 UL STANDARD

The large procurement of smoke detectors for the hurricane Agnes homes piqued Dick Bright's curiosity about just how well these devices performed in detecting fires. He modified a spare prototype of the NBS Smoke Chamber (that later became ASTM D648) to generate smoke from a small source and circulate it with a small bar heater. When he hung production smoke detectors in the box he was appalled to see the "power on" light on many disappear in the smoke without a sound from the detector.

Further tests revealed a problem with smoke entry into the outer housing at low convective flow rates. The smoke box test used by Underwriters Laboratories (UL) at the time had two large fans pointed directly at the detector forcing the smoke in - a not so realistic condition. This experience led Bright and his supervisor Irwin Benjamin to conclude that the potential of residential smoke detectors would not be realized unless there were effective product approval standards that assured their proper performance and reliability.

Bright and Benjamin approached UL about participation in a cooperative project under NBS' Industry Research Associate program where UL would assign an employee to work at NBS for a year to develop the basis for such a standard that UL would then promulgate. Richard Bukowski was selected by UL for the one-year assignment, beginning in the fall of 1973.

One of the unique aspects of this project was that it was conducted in close cooperation with the residential smoke detector industry, who themselves were working with an immature technology. Companies provided samples of current product and were very grateful for constructive criticism. Company engineers began to visit with prototypes of models under development that were jointly evaluated and improved. This cooperative environment led to rapid improvements in the performance of detectors that benefited the public and the industry.

The work that year uncovered a number of issues identified as problems (or potential problems) that were corrected by the industry and incorporated in the suggested standard that was presented to UL and formed the basis for the first edition of their Safety Standard for Single- and Multiple-Station Smoke Detectors, UL217. These included:

- Identification and quantification of low velocity smoke entry problems into detector housings or sensor assemblies and the associated Variable Velocity and Directionality tests in the new Standard.
- Design of a new smoke box for sensitivity testing with improvements to the flow characteristics and instrumentation that is now used for all smoke Detectors.
- Effects of the condensation of moisture on sensor or circuit boards that could cause false alarms or non-operation and the Humidity Plunge test placed in the Standard to address this issue.
- Development of an electrical transients test to improve reliability by reducing the susceptibility of detectors to damage from transients.
- The application of the "full-scale fire tests" to all smoke detectors where they had previously been used only for ionization type.
- Agreement on the policies of minimum one-year battery life, including the battery with the detector at purchase, the use of commonly available batteries, functional testing features, and others.

11.5.4 NFPA STANDARD

In the fall of 1974, Bukowski returned to UL and completed the development and adoption of UL217. Bright had been appointed Chair of the National Fire Protection Association (NFPA) Committee on Household Fire Warning Equipment that developed the NFPA 74 Standard on the Installation, Maintenance, and Use of Household Fire Warning equipment. First published in 1967 as a guide for homeowners this document reflected the philosophy of the times that homes should be protected in the same way as commercial businesses - with a heat detector in every room wired to a fire alarm panel and alarm bells. The cost of such a residential fire alarm system for an average home was about $1500 so they were rare.

Since the installation of residential fire alarm equipment was voluntary (and no one thought that requiring fire safety equipment in homes would ever happen), Bright felt that homeowners should be given the opportunity to choose a minimum system that provided some protection at low cost, like that suggested by McGuire and Ruscoe. The committee proposed a system of four "Levels of Protection" in the 1974 edition of NFPA 74. These were:

Levels of Protection

- Level 4 was a smoke detector outside the bedrooms and at the head of any basement stairs from McGuire and Ruscoe.
- Level 3 added heat or smoke detectors in living or family rooms that had the highest statistical likelihood of residential fire initiation.
- Level 2 added heat or smoke detectors in the bedrooms that were next on the list of fire initiation.
- Level 1 was the full system of a heat or smoke detector in every room.

This unique concept was presented to the NFPA Membership for adoption at the May 1974 meeting in Miami Beach and it was strongly opposed by the fire services (the Fire Marshals and Fire Chiefs). Their concern was that they saw no evidence that anything less than "complete protection" (Level 1) was adequate. They were correct - the levels were solely based on the judgment of the committee and that of McGuire and Ruscoe.

11.5.5 INDIANA DUNES TESTS

While the Levels of Protection concept was adopted at that meeting the concern expressed by the fire service were not taken lightly. Bright proposed that NBS fund a research project, which came to be known as the Indiana Dunes Tests, [6] to assess the effectiveness of the Levels of Protection. This contract was awarded to IIT Research Institute and UL. The Principal Investigators were Tom Waterman of IITRI, and William Christian and Bukowski from UL.

Detectors currently available on the market were installed in actual, unoccupied homes that were scheduled for demolition and available for fire tests. Fires involved actual residential contents and instruments monitored conditions within the homes to judge when unassisted escape using doors (but not jumping out windows) would no longer be practical.

The research involved 76 experiments conducted in three homes over two years. The data showed that the optimum performance was obtained with a smoke detector on every floor level of the home, mostly because smoke flow up stairs could be impeded by flows induced by HVAC systems, especially air conditioning. A closed door at the top of the basement stairs could create a dead air space that delayed response. The home was better protected from fires starting in the basement by a smoke detector on the basement ceiling near the stairway.

The report presented results in a unique way, in terms of the escape time (time between detector alarm and reaching one of the tenability limits defined by the study) provided by the detectors. These escape times were used to produce a probability plot of the percent of experiments in which a given amount of escape time was provided. Thus the reader could select a time needed and determine the percent of cases in which that (or more) time was available.

In an independent analysis of the first year results, a fire safety panel, advising the governor of Massachusetts on a statewide detector law, applied an arbitrary three-minute escape time requirement. The data showed that a smoke detector on every level would provide the required three-minutes in 89 percent of the cases, while a smoke detector in every room would increase meeting the requirement only to 93 percent.

In 1978 the US Department of Housing and Urban Development (HUD) commissioned a study similar to the Indiana Dunes Tests to be conducted in a manufactured home [7]. HUD was preparing to promulgate their federal Manufactured Home Construction and Safety Standards (49CFR3280) and this work provided the basis for the smoke detector requirements therein.

11.5.6 REGULATORY ACTIONS

The Indiana Dunes tests had a strong and immediate impact and soon various jurisdictions began to adopt laws requiring the provision of smoke detectors in every level of new residential housing. More surprising to many was the adoption by some of regulations requiring the installation of smoke alarms in existing residences. This ran counter to the U.S. tradition of "a man's home is his castle;" most opposition was not to the smoke detectors, but to the challenge to this tradition. Montgomery County Maryland was one of the first to adopt such an ordinance in 1975, effective in 1978. Even more startling was the immediate impact of the law. As implementation began the residential fire death rate, which had been steady for some years at around 32 per year, began to drop significantly. After the law became effective fatalities became zero in compliant homes and stayed there for several years; this convinced other jurisdictions to adopt similar laws.

Successes like that of Montgomery County led to the rapid adoption of mandatory smoke detectors in most state or provincial building codes in the U.S. and Canada. Codes at the city or county level often went further by requiring the installation of smoke detectors in existing residential properties. Coupled with effective marketing campaigns by major appliance manufacturers such as GE and Gillette, and retailers like Sears, compliance with these regulations was unusually high - typically above 90 percent. The result was a decline in U.S. fire deaths by 50 percent between 1975 and 1998 that has been attributed largely to the smoke detector.

11.5.7 FURTHER STUDIES

The "Indiana Dunes Tests" and other similar studies conducted in the 1970s and 80s clearly demonstrated that the occupants of most homes with smoke detectors at every level could expect 3 minute to 5 minutes of escape time for most fires. However there were several human factors questions such as how effective smoke detectors were at awakening sleeping people and how much time was needed for a family, especially with young children, to escape.

To address these issues NBS awarded a grant to Professor E. Harris Nober at the University of Massachusetts at Amherst to conduct a study. Nober had a sleep laboratory on campus and experience in this field, although like most sleep researchers he had focused on insomnia as opposed to awakening. Nober's work [8] began in the laboratory but soon moved into homes to provide more realism and to address the behavior of whole families. He developed a protocol to install in a test home a smoke detector that could be activated with a radio transmitter from the street. After waiting several weeks to avoid biasing the trial, the researchers activated the alarm in the middle of the night. The family had been instructed to turn on a bedroom light immediately on awakening (this gave a measure of awakening time), to place a call to the Amherst Fire Department (which participated in the study and provided a time for the call), and to evacuate outside to a prearranged meeting place in front of the house. These experiments it determined that three minutes, as judged almost a decade prior, was a typical evacuation for families.

In the early 1980s NBS decided that the residential smoke detector issues had largely been addressed and the technology matured. Product approval standards (UL217) and installation standards (NFPA74) were in place and the combination of regulatory and voluntary installations were at a pace that soon nearly every home would be equipped. Thus, NBS decided to apply its limited resources in other areas.

The result was limited studies mostly aimed at improving detector performance in special applications. The applications addressed included health care facilities [9, 10] (especially reducing the incidence of nuisance alarms that were affecting system credibility), fire protection for atria [11] (these had become a common architectural feature), and even spacecraft [12]. NASA had begun advanced planning for their 21st Century projects, including a space station, and wanted to explore innovative techniques for fire detection.

In the 1990s NIST (formerly NBS) pioneered the use of computational experiments to study the performance of, and to develop guidelines for the installation of, smoke detectors. In a project funded through a public/private consortium through the (National) Fire Protection Research Foundation, NIST researchers evaluated the effects of both geometry and physical barriers, and the interaction with mechanical ventilation systems on smoke and heat detector activation times. While others have used computational techniques to design specific installations, this was the first time anyone performed parametric calculations designed like a series of experiments to provide systematic information on a hypothesis.

The results of the study were revealing; confirming some common practice and indicating that some assumptions may be wrong. The results had a direct and significant effect on the code requirements [13, 14, 15, 16].

NIST is still involved in detector research. One project involves the development of an apparatus for evaluating the performance of multi-sensor devices. Called the Fire Emulator/Detector Evaluator (or FE/DE), the apparatus shows real promise for international standardization [17]. With links to the Indiana Dunes Tests, NIST is conducting a new evaluation of residential smoke detectors (now commonly referred to as smoke alarms). This work intends to re-examine the installation and siting rules, the efficacy of current sensor technologies, examine nuisance alarm sources, and develop data with which alarm algorithms might be developed for multi-sensor devices.

Finally, NIST is using its experience in computational fire models to develop a "sensor-driven" or "inverse" model [18]. Where traditional fire models start with the heat release rate of the fire and predict the fire's impact on the building this model takes the analog signal from fire sensors and predicts the heat release rate of the fire most likely to be producing those signals. This model holds promise in allowing fire alarm systems to produce real time data of significant use to the fire service in making tactical decisions, as well as evaluating detector signals for consistency with fire chemistry and physics and determining the level of threat to people and property.

Fire detectors and the systems to which they connect play a significant role in the reduction of fire losses. Thus the NIST fire program will continue to conduct research on detection as a means to achieve its goals of reducing the burden of fire.

The Department of Commerce recognized Richard Bright's work on smoke detectors with its award of the Silver Medal in 1976.

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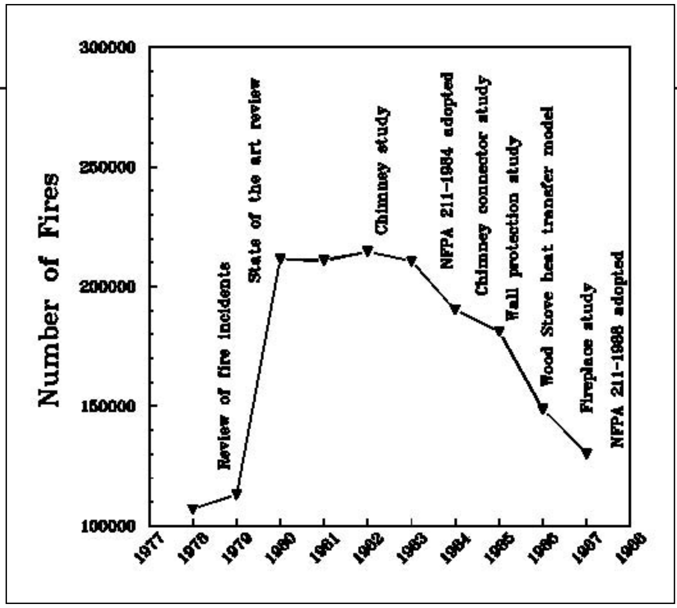
11.6 WOOD HEATING SAFETY RESEARCH



The energy crisis in the late 1970s led to a large increase in the use of wood as an alternate heating source. Along with this increase came a dramatic increase in the number of unwanted fires. The marked increase in the late 1970s and early 1980s is attributed to a growing number of installations and expanded use of wood burning stoves in homes throughout the United States and the fact that most homes are made of combustible construction. Standards for the safe installation and use of the appliances were based on information more than 40 years old and rarely applicable to modern appliances.

BFRL led concentrated research efforts to provide new and updated information to develop appropriate codes and standards for the modern appliances. Programs have been targeted to raise consumer awareness through education and to improve the standards and codes governing the construction, installation, and testing of appliances. Much of the supporting technical information for the standard and code changes and for consumer education has come from BFRL research. The point has finally been reached when much of the 40-year-old data and folklore originally used to develop the codes, standards, and public educational materials is being replaced by solid technical information.
Wood heating safety research at BFRL concentrated on several key aspects of the fire problem: clearances needed between wood burning appliances and combustible construction materials, creosote buildup and burnout, protective barriers to allow reduced clearances of appliances to combustible walls, safe methods of joining a chimney connector to a masonry chimney through a combustible wall, and theoretical prediction of appliance/wall heat transfer with arbitrary wall protection. As the research results became available in NIST reports and journal articles, BFRL staff worked closely with building and fire code committees to develop a new generation of code requirements for wood heating appliances. Most of the current codes related to wood heating are based on BFRL research.

Positive actions by BFRL and others have improved the safety of these appliances and, thus, reversed an increasing fire incidence rate. After several years of extensive research and activity in this area, new and up-to-date technical information and standards on fire safe installation and use of solid fuel heating appliances have contributed to reversing a dramatically increasing fire problem. A review of related publications are listed [1-6].

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11.7 FIRE SAFETY EVALUATION SYSTEMS

The Fire Safety Evaluation System (FSES) was conceived of by Harold (Bud) Nelson and Irwin Benjamin to provide a series of separate systems each designed to measure the level of fire safety of an existing or proposed structure housing a given type of occupancy. These have provided means of meeting or exceeding the level of safety prescribed by the applicable code while providing the designer with a wide range of cost saving and functional options. The FSES for Health Care Facilities [1] was the first of a series of documents covering a variety of types of occupancies including apartment buildings [2], prisons and jails [3], office and laboratory buildings [4], overnight accommodations in National Parks [5], and board and care facilities [6].

The FSES for Health Care Facilities was part of a broad fire safety effort sponsored by the Department of Health and Human Service in response to an important need to develop a means of meeting the fire safety objectives of prescribed codes without necessarily being in explicit compliance with the code. In the 1960s with the birth of the Medicare and Medicaid programs Congress prescribed conformance with the requirements of the Life Safety Code, National Fire Protection Association Standard 101, in all nursing homes and hospitals receiving funds under the program. A nation-wide inspection and enforcement program was established to assure compliance. Most if not all inspected facilities were found to be in some degree of non-compliance with the specific requirements of the Life Safety Code. A significant number were closed as a result. Others undertook correction programs. Many, including some of the Nation's largest and most prestigious hospitals, were declared to fail this safety standard.

The FSES for Health Care Facilities was developed to discover alternate solutions, delivering at least an equivalent level of safety as compared to that produced by exact compliance with the detailed prescriptions of the Life Safety Code. In the case of one large hospital complex, the use of the FSES

Harold Nelson, innovative fire protection engineer.

reduced the cost of compliance from an estimated $30 million to $60 million to less than $2 million. Equally important, the development of alternative approaches allowed the improvements to be made without interruptions of hospital services.

The FSES is a grading system designed to determine the overall level of fire safety of an existing or proposed facility in comparison with a hypothetical facility that exactly matched each requirement of the Life Safety Code. The system is based on common building factors that determine fire safety, such as type of construction, partitioning and finishes, hazardous activities, fire detection and fire suppression and fire alarm systems. For practical considerations, however, factors relating to building utilities, furniture, and emergency procedures are handled elsewhere in the FSES. An informative discussion of the relevance of the approach to validity is available in Nelson's paper An Approach to Enhancing the Value of Profession Judgment in the Derivation of Performance Criteria [7].

The FSES for Health Care Facilities was adopted by the National Fire Protection Association as part of the 1981 edition of the Life Safety Code and a recognized means of developing alternative approaches to determine compliance with the code in that and later editions of the Life Safety Code. The FSES's have been adopted into building codes and similar regulations and have been institutionalized by the establishment of a special technical committee of the National Fire Protection Association (NFPA) charged with the responsibility for Alternative Methods for Life Safety in Buildings. This committee maintains NFPA Standard 101A [8] in support of the FSES's, thereby assuring that each FSES remains current and an appropriate reflection of the changing safety levels prescribed by building codes and regulations.

Subsequently, the Life Safety Code adopted FSES's developed by NBS/NIST covering Detention and Correctional Occupancies (i.e. prisons and jails), Board and Care Occupancies, and Office Occupancies. In 1995 the National Fire Protection Association created a new document NFPA 101A, Guide on Alternative Approaches to Life Safety [8] to gather and contain the FSES's in a single publication and place them in the care of a single technical committee. Nelson was the initial chair of this committee, and upon his retirement the chair was given to David Stroup, also of NIST.

The FSES for Board and Care Occupancies includes an innovative method for appraising the emergency evacuation capability of the occupants and staff of a board and care home housing persons of varying individual capacity and varying staffing. The system, developed under the leadership of Bernard Levin, measured the amount of assistance needed by each housed individual as compared to the capabilities of the staff to provide the needed help. The result was a break through in understanding the life safety needs of group homes housing persons of diminished capabilities.

The FSES's have stood the test of time and are now a regular part of life safety design in many buildings. They have both improved safety and reduced costs. In the NIST study Benefits and Costs of Research: A Case Study of the Fire Safety Evaluation System by Chapman and Weber [9], an estimate savings of almost $1 billion up to 1995 was credited to the FSES for Health Care Facilities. Unmeasured but significant savings have also been achieved by the other FSES's.

In the early 1980s Chapman and his colleagues [10] extended the work of Nelson's team by the development of a cost optimizer computer program enabling the user to determine the best cost acceptable alternatives to achieving equivalent safety with the Life Safety Code requirements for Health Care Facilities. In 1994 this work was used to develop the computer program ALARM 1.0, Decision Support Software for Cost-Effective Compliance with Fire Safety Codes [11].

In the long term, the principal importance of the fire safety evaluation systems lies not only in the specific objectives of delivering safety with lower cost and greater design flexibility, but in the demonstration that a total performance approach to fire safety was feasible. Nelson's contributions to FSES and other fire safety technologies have been recognized by Silver and Gold Medal Awards from the U.S. Department of Commerce, in 1982 and 1989 respectively, the Special Award for Technology Transfer of the Federal Research Laboratory Consortium, the first Harold E. Nelson Professional Service Award from the Society of Fire Protection Engineers, the Standards Medal of the National Fire Protection Association, and the Kawaoe Medal of the International Association for Fire Safety Science.   In addition, Irwin Benjamin received the Department of Commerce Silver Medal in 1979 for his contributions to FSES

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11.8 SMOKE MANAGEMENT

Smoke management provides protection from smoke exposure by one or more of the following mechanisms: compartmentation, dilution, pressurization, airflow and buoyancy. From the early 1970s to the 1990s the objective of the NIST smoke management effort was to aid the advancement of this technology as it became an established part of building fire protection. This went beyond development of models to include concept studies, field tests, and large scale fire experiments. Thomas Lee received the Bronze Medal Award of the Department of Commerce in 1979 for development of the Smoke Chamber test method.

The 1983 book by ASHRAE, Design of Smoke Control Systems for Buildings [1], was primarily written at NIST and for the first time provided designers with methods of analysis for smoke control systems. John Klote and Harold Nelson of NIST were major contributors to the 1988 NFPA publication, Recommended Practice for Smoke Control Systems [2] that incorporated the approaches of the 1983 book. These approaches were based on engineering principles, and they were experimentally verified by large scale fires at the Plaza Hotel in Washington, DC [3].

Smoke protection of large spaces such as atria are a unique challenge, and John Klote and Harold Nelson were major participants in the development of 1991 NFPA standard, Guide for Smoke Management Systems in Malls, Atria, and Large Areas [4]. This topic was included in a more exhaustive book, Design of Smoke Management Systems [5] that was jointly published by ASHRAE and SFPE. Even before publication, John Klote won the 1991 BFRL Communication Award for his work on this book. Four ASHRAE best paper awards won by John Klote [3, 6, 7, 8] are an indication of the quality of NIST work in this area.

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11.9 SOFTWARE FOR FIRE HAZARD ASSESSMENT

NIST Handbook 146, HAZARD I - Fire Hazard Assessment Method [1], represents the culmination of a long-term program aimed at placing the prediction of fire outcomes on a more objective and scientific basis. In the 1970s NBS provided a grant to Harvard University to develop numerical models that could predict, from the basic equations of heat transfer and fluid flow, the temperature in a room containing a fire. These early models were difficult to use and interpret; required large, mainframe computers that were only available in academic institutions; and were plagued with long execution times often interrupted by software crashes. Major pieces of fire physics and most fire chemistry were not well enough understood to be included in the models, so that predictive accuracy was disappointing. As a result, these early models were little more than academic playthings, which were seldom put to practical use.

In 1983 CFR established a goal to develop a tool that could evaluate the role of the fire performance of an individual material or product in the outcome of a specific fire in a specific compartment or group of compartments. The first year of the effort was involved with determining what capabilities would be needed to accomplish this, and the result was somewhat daunting. Not only would it be necessary to predict the fire environment in the space resulting from the material or product burning, but it would also require understanding the movement and behavior of occupants and the physiological and psychological effects of exposure to this fire.

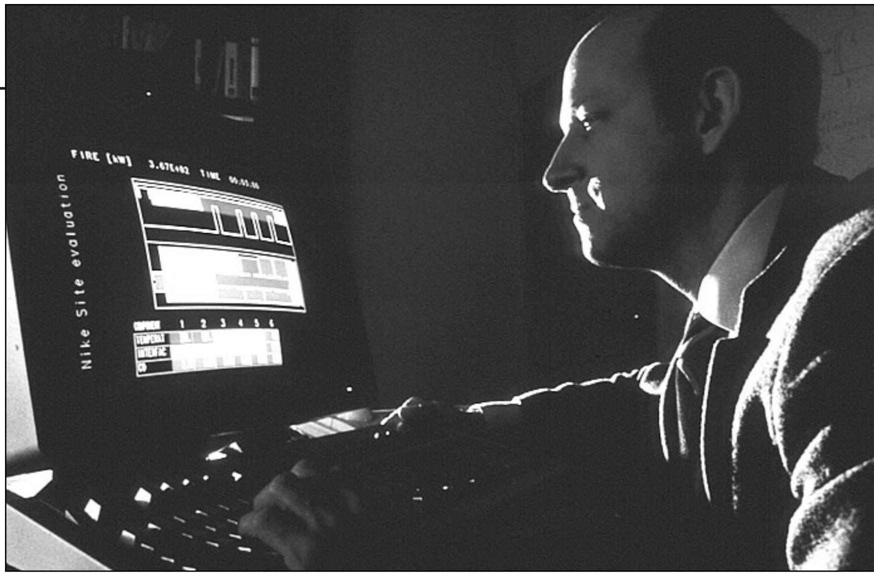
Since the project started before the personal computer revolution, the initial plan was to develop the software to run on NBS's mainframe and to equip a "fire simulation laboratory" at NBS with terminals and graphics equipment so that scientists and engineers could learn how to use the software to address practical problems. Once the usefulness of these models were appreciated, the larger engineering firms were expected to invest in the hardware needed to exploit the technology. Somewhere by the end of the century these firms would have the computers to run the software in their own offices.

By 1986 the CFR multi-compartment model, FAST (Fire and Smoke Transport) [2] had been enhanced so that its predictions were credible when applied within specific bounds. CFR's pioneering development of oxygen consumption calorimetry provided a means to measure the rate at which mass and energy were released from a burning item. By expressing a material's fire performance in terms of conserved quantities, it was possible to describe burning behavior for a predictive model. An CBT psychologist was developing a unique evacuation model with embedded behavioral rules derived from interviews with fire victims. Finally, the CFR combustion toxicology program was producing data that showed toxicological effects were primarily from a small number of toxic species.

Also at this time, the personal computer revolution was well underway. It became clear that a computer on every desktop would soon be a reality, so the CFR software was now targeted at that audience. Efforts were expended on an improved user interface that would both simplify data entry at the front end and provide graphical output support to make the results more understandable and useful at the back end.

In 1989 the first version of the HAZARD I software and documentation [1] was released. The software was designed to provide material and product manufacturers with a tool to assess the fire hazards of their products and a means to justify higher costs associated with better performing products. However, the manufacturers were underwhelmed because the methods required some skill to apply and were unproved.

Several pressures came together to begin to change perceptions of the potential of HAZARD I. First, there was political pressure to regulate combustion toxicity, with one state actually promulgating a regulation. NIST produced a fire hazard analysis that showed burning rate was much more important as an indicator of fire hazard than toxicity. Second, a well respected fire protection engineer became inter-



The Hazard I computer model was developed for engineers, architects, building owners, and others to predict the spread of smoke, toxic gases, and heat from a fire in a room to other parts of a building without having to burn a room or building. This photo shows one of the developers, Walter Jones, physicist, running the fire model from this software suite.

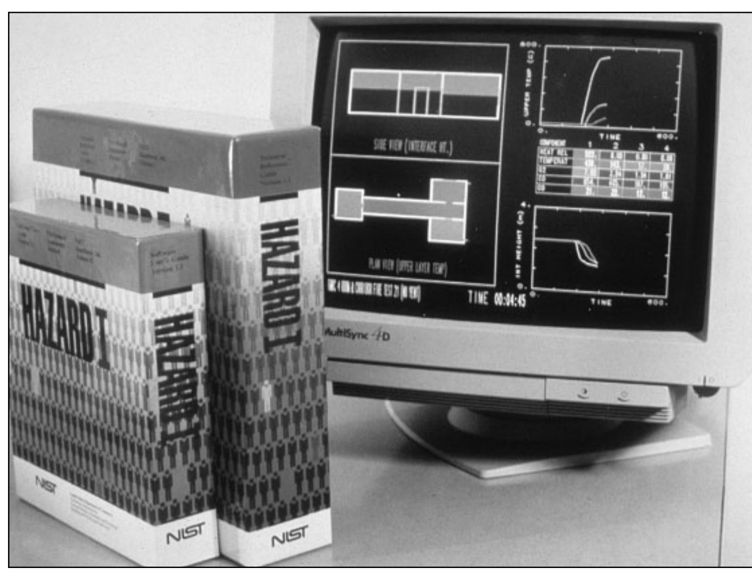
ested in learning these new techniques and successfully applied HAZARD I to absolve clients of liability in civil litigation involving a fire. This led to additional uses in both civil and criminal litigation and represented the first significant application of modern fire models.

The publication of NIST Handbook 146 represented a watershed for NIST in several ways. While NIST had developed and distributed other software products (such as DATAPLOT, a scientific graphing package), HAZARD I was an engineering analysis tool that could be used to make (literally) life and death decisions. It contained a broad range of engineering and scientific methodology that needed to be appropriately documented. Documentation consisted of a Technical Reference Guide, which underpinned the equations and assumptions and explained how they are coded, a set of worked examples, and a Users' Guide to the software. The product was packaged as a commercial product with printed binders for the manuals, shrink wrapped disks with the software and installation program, and even a printed function key template. This Handbook received special scrutiny on technical, policy, and legal fronts and was the model for most NIST software to follow.

The HAZARD I product was distributed under a formal agreement with the National Fire Protection Association (NFPA), a not-for-profit standards organization. They offered for purchase an initial package, upgrades when issued by NIST, and discounts for their members. Over a decade they sold several thousand copies.

One interesting aspect of this development involved the exclusion of government-developed software from copyright. Since the software is in the public domain, users are legally unencumbered by the cautions in the documentation. A solution was found in including a users' registration card that is to be signed, dated, and returned to qualify for technical support. The signature on the card was below a statement that the signer read and agreed to the limitations in the documentation - thus creating a contractual agreement. Later, a Government Accounting Office study of the copyright policy applied to government software cited two specific examples of critical government software that should have

HAZARD I software and documentation package. In 1989, the first version of the HAZARD I software and documentation (NIST Handbook 146) was released. HAZARD I includes several technological advances that were crucial to its acceptance in practice: the CFAST fire model, the EXITT evacuation model and the TENAB toxicology model. This is the only existing software suite to provide a complete hazard analysis for unwanted fires.



copyright protection - Grateful Med from the National Library of Medicine and HAZARD I. Several legislative proposals on this issue were considered but never adopted.

By 1990 successes in litigation led the fire protection engineering community to begin to use HAZARD I in building design. While building codes prescribed the minimum required fire safety features of buildings, they also contained a provision recognizing alternate approaches that can be shown to provide equivalent protection. Demonstrating this equivalence to regulatory authorities was always the difficult part. Now HAZARD I could be used to show equivalence in safety to occupants rather than having to prove that an alternative approach performed the same function.

The acceptance of HAZARD I in demonstrating code equivalence led to a global revolution in building codes. It became possible for codes to specify only the desired outcomes in terms of life safety and property protection and to allow any solutions that provided that level of performance. Such performance-based codes had long been discussed but were impractical until means were available to measure fire safety performance quantitatively. The U.S. building regulatory community began work in 1996 on a performance code, which was published in 2000. As similar codes are being developed and adopted in other countries these are eliminating non-tariff barriers to trade that result from unique, local or country-specific, test methods. These are being replaced by nearly uniform performance objectives. HAZARD I and its sub models are specifically cited in most of these codes and supporting guidelines documents as an acceptable means of demonstrating compliance with the codes.

HAZARD I included several technological advances that were crucial to its acceptance in practice. First, the fire model, FAST, was more robust and easier to use because of a significant investment in the user interface software. There were embedded databases of material properties, and additional references to data were cited. One of the criteria used by the development team was to require as inputs only data that were available and to cite sources for everything. Many other models at the time used engineering estimates that required coefficients to be entered by the user based solely on judgment rather than properties for which measurement methods and handbook values existed.

The equation solver used was carefully selected to work efficiently and seldom failed to converge. The software could be run interactively (with real-time graphics) for exploratory purposes or in batch mode to generate case files or for sensitivity analysis in engineering applications.

The FAST model predictions were compared to a range of full-scale experimental data and these comparisons were published to form a body of verification literature. Further, a suite of test cases was developed that stressed the model in different ways to see if it would fail. This test suite was run each time the model was modified. Computer Aided Software Engineering (CASE) tools were used to document changes to the model and to allow changes to be reversed if necessary. Each revision of the software was backward compatible so that users would not have to work excessively to re-run older cases, and the effect of changes was documented. Each of these aspects followed good (commercial) software development practice.

The EXITT (for Exit Time) [3] evacuation model differed from most of its contemporaries in the inclusion of a behavioral sub model. Other evacuation models of the day had everyone making the correct decisions and, while some allowed for user-selected decision delays, people marched quickly toward the exits. In HAZARD I people investigated the fire until seeing smoke or flame, assisted other family members, or even (children) hid or waited for instructions from an adult. The result was an amazingly realistic sequence of actions and an evacuation process that convinced users and authorities of its applicability.

The toxicology module TENAB (for Tenability) [1] was the only 20th century attempt to model physiological effects of the inhalation of a mixture of toxic gases. Based on correlations to data from animal exposures, but with an implementation that mimics important physiological interactions, the model produced results that aligned well to actual fire experience. In one case, HAZARD I successfully predicted the development of the fire, including a prediction of which occupants successfully escaped and which died, including the location of the bodies and the autopsy results on each. This particular case involved NIST using HAZARD I to support a Justice Department attorney to defend the federal government in a wrongful death suit from a fire on a military base. The final analysis indicated no fault by the government, and the day following the deposition of the NIST staff the plaintiff's council offered to settle this $26.5 million suit for $180 thousand.

NIST's pioneering work to develop engineering tools to predict fire performance in buildings, and especially the HAZARD I methodology, represented the enabling technology for the move to performance-based building and fire codes which are being adopted globally. The methods and models included in HAZARD I are routinely cited in these performance-based codes and in their associated codes of practice, worldwide. These performance methods are reducing the costs of fire safety in the built environment and are eliminating non-tariff barriers to trade for U.S. companies. Emil Braun, Richard Bukowski, Lynn Forney, Walter Jones, and Richard Peacock received the Silver Medal Award of the Department of Commerce in 1990 for the development of HAZARD I.

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11.10 LARGE EDDY SIMULATIONS OF FIRES

11.10.1 INTRODUCTION

The idea that the dynamics of a fire might be studied using digital computers probably dates back to the beginnings of the computer age. The concept that a fire requires the mixing of a combustible gas with enough air at elevated temperatures is well known to anyone involved with fire. Graduate students enrolled in courses in fluid mechanics, heat transfer, and combustion have been taught the equations that need to be solved for at least as long as computers have been around. What is the problem? The difficulties revolve about three issues: First, there are an enormous number of possible fire scenarios to consider. Second, there is neither the physical insight nor the computing power to perform all the necessary calculations for most fire scenarios. Finally, since the "fuel" in most fires was never intended as such, the data needed to characterize both the fuel and the fire environment may not be available.

Howard Baum of CFR and Ronald Rehm, then of the Center for Applied Mathematics, tackled the problem in one of NBS Director Ambler's first "competence" projects. The results show the wisdom of his decision to invest in fundamental, path-breaking research to place NBS in a lead position in the most important areas of science and technology.
In order to make progress, they greatly simplified the problem. Instead of seeking a methodology that can be applied to all fire problems, they began by looking at a few scenarios that were most amenable to analysis. They used idealized descriptions of fires, based on the kind of incomplete knowledge of fire scenarios that is characteristic of real fires, and approximate solutions to the idealized equations. However, the methods were capable of systematic improvement as physical insight and computing power grew more powerful.

The "Large Eddy Simulation" (LES) technique, developed at NIST over a nearly two decade period, refers to the description of turbulent mixing of the gaseous fuel and combustion products with the local atmosphere surrounding the fire. This process, which determines the burning rate in most fires and controls the spread of smoke and hot gases, is extremely difficult to predict accurate-

Howard Baum pioneer of the new generation of fire models.

ly. This is true not only in fire research but in almost all phenomena involving turbulent fluid motion. The basic idea behind the use of the LES technique is that the eddies that account for most of the mixing are large enough to be calculated with reasonable accuracy from the equations of fluid mechanics. The hope (which ultimately was justified by appeal to experiments) was that small-scale eddy motion can either be crudely accounted for or ignored.

Ronald Rehm, co-developer of large eddy simulations of fire phenomena.

The equations describing the transport of mass, momentum, and energy by the fire induced flows were simplified so that they could be solved efficiently for the fire scenarios of actual interest. The general equations of fluid mechanics describe a rich variety of physical processes, many of which have nothing to do with fires. Retaining this generality would lead to an enormously complex computational task that would shed very little additional insight on fire dynamics. The simplified equations, developed by Rehm and Baum [1], have been widely adopted by the larger combustion research community, where they are referred to as the "low Mach number" combustion equations. They describe the low speed motion of a gas driven by chemical heat release and buoyancy forces.

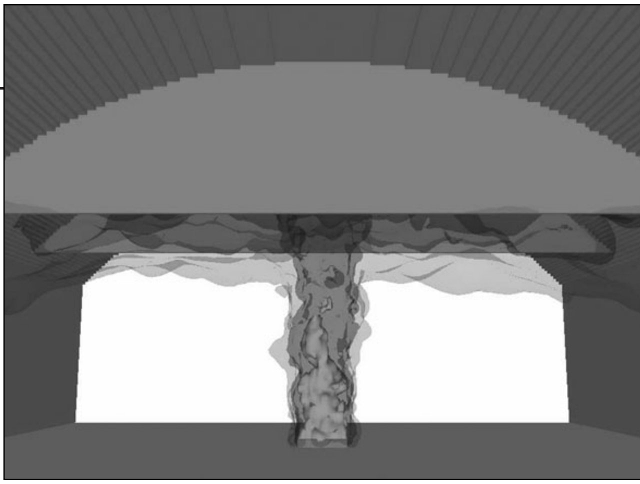
The low Mach number equations are solved on the computer by dividing the physical space where the fire is to be simulated into a large number of rectangular cells. In each cell the "state of motion," i.e. the gas velocity, temperature, etc. are assumed to be uniform; changing only with time. The computer then computes a large number of snapshots of the state of motion as it changes with time. The figure shows one such snapshot of a hangar fire simulation. Clearly, the accuracy with which the fire dynamics can be simulated depends on the number of cells that can be incorporated into the simulation. This number is ultimately limited by the computing power available to the user. Present day computers limit the number of such cells to at most a few million. This means that the ratio of largest to smallest eddy length scales that can be resolved by the computation (the "dynamic range" of the simulation) is roughly 100 to 200.

Unfortunately, the range of length scales that need to be accounted for if all relevant fire processes are to be simulated is roughly ten to one hundred thousand. Much of the discrepancy is due to the fact that the combustion processes that release the energy take place at length scales of 1 mm or less.

11.10.2 Fire Plumes

The idea that different physical phenomena occur at different length and time scales is central to an understanding of fire phenomena, and to the compromises that must be made in attempting to simulate them. The most important example is an isolated fire plume in a large well ventilated enclosure.

Simulations of scenarios of this kind are reported in [2, 3]. The fire plume is the "pump" which entrains fresh air and mixes it with the gasified fuel emerging from the burning object. It then propels the combustion products through the rest of the enclosure. The eddies that dominate the mixing have diameters that are roughly comparable to the local diameter of the fire plume. Thus, in the above simulation, the cells have to be so small that many (a 12 x 12 array in this case) are used to



Simulation of a fire in a hanger.

describe the state of motion across the surface of the fuel bed. Since the simulation also needs to include the remainder of the hangar as well, even the 3 million cell simulation shown above cannot cope with the combustion processes without additional modeling effort.

Physical processes like combustion that occur on scales much smaller than the individual cell size are often called "sub-grid scale" phenomena. The most important of these for our purposes are the release of energy into the gas, the emission of thermal radiation, and the generation of soot together with other combustion products. These phenomena are represented by introducing the concept of a "thermal element" [4]. This can be thought of a small parcel of gasified fuel interacting with its environment.

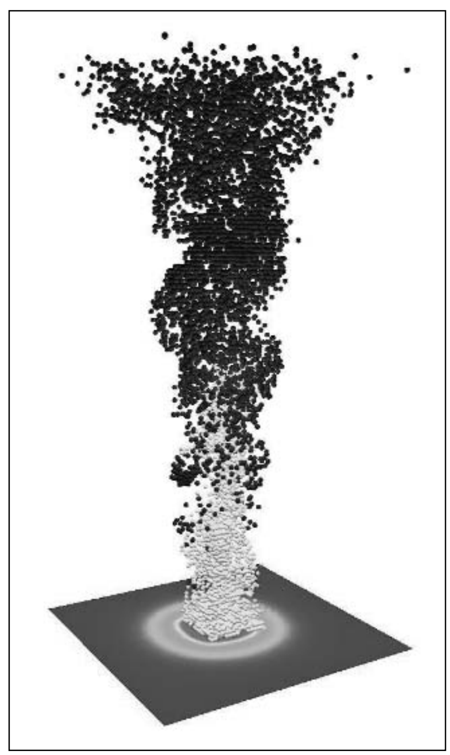
Each element is carried along by the large scale flow calculated as outlined above. As long as the fire is well ventilated, it burns at a rate determined by the amount of fuel represented by the parcel and a lifetime determined by the overall size of the fire. The lifetime of the burning element is determined from experimental correlations of flame height developed by McCaffrey [5]. A prescribed fraction of the fuel is converted to soot as it burns. Each element also emits a prescribed fraction of the chemical energy released by combustion as thermal radiation. This fraction is typically about 35 percent of the total. The soot generated by the fire can act as an absorber of the radiant energy. Thus, if the fire generates large amounts of soot, the transport of radiant energy through the gas must be calculated in detail [6]. Even in the absence of significant absorption of radiant energy by the products of combustion, the radiant heat transfer to boundaries is an important component of the total heat transfer to any solid surface.

11.10.3 OUTDOOR FIRES

Large outdoor fires can be conveniently divided into two categories based on the fuel source. Wildland fires are characterized by a relatively low heat release rate per unit area of ground covered by fuel, but a very large area over which the fire can spread. Indeed, the description of the fire spread process is an essential part of any successful simulation of such an event. Industrial fires, in contrast, are usually much more highly localized but intense emitters of heat, smoke, and other combustion products. This is particularly true if the fuel is a petroleum based substance, with a high energy density and sooting potential. This latter type of fire is the object of study here.

The hazards associated with such fires occur on two widely separated length scales. Near the fire, over distances comparable to the flame length, the radiant energy flux can be sufficiently high to threaten both the structural integrity of neighboring buildings, and the physical safety of firefighters and plant personnel. At much greater distances, typically several times the plume stabilization height in the atmosphere, the smoke and gaseous

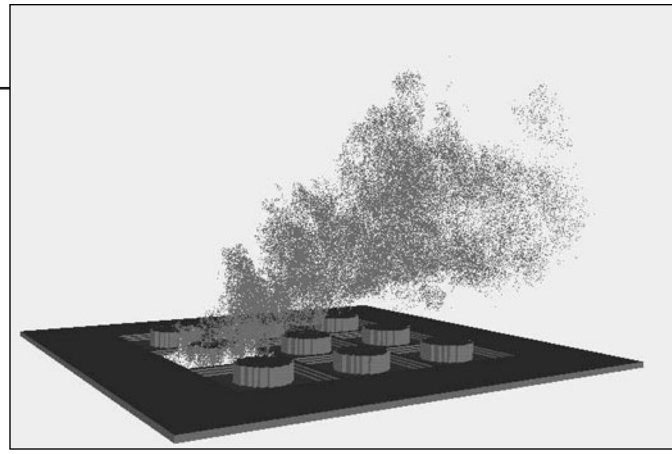
Thermal elements in a fire plume simulation of hot and burned out thermal elements; net reflective flux on the floor.



products generated by the fire can reach the ground in concentrations that may be unacceptable for environmental reasons. This latter, far field, hazard has been studied extensively by NIST researchers [7, 8]. This work has led to the development of a computer code ALOFT [9] and its generalizations to complex terrain.

A distinct approach is needed to model the near field hazard associated with the flame radiation. An example scenario is a fire surrounding an oil storage tank adjacent to several neighboring tanks. The heat release generated by a fire on this scale can reach several gigawatts if the entire pool surface is exposed and burning. Such fires interact strongly with the local topography (both natural and man made), and the vertical distribution of wind and temperature in the atmosphere. Moreover, the phenomena are inherently time dependent and involve a wide temperature range. Thus, the simplifications employed in ALOFT and its generalizations can not be used, and the "low Mach number" combustion equations need to be modified to account for the stratification of the atmosphere.

The photograph shows a simulation of a fire resulting from an oil spill trapped in the containment trench surrounding one of a number of oil tanks [10]. The diameter of each tank is 84 m, the height 27 m. A wind profile that increased from 6 m/s near the tank top to 12 m/s at 768 m that is representative of the atmospheric mean wind profile near the ground was chosen. The ambient temperature was taken to be constant. This is a very stable atmosphere, typical of winter conditions in northern climates. The spilled oil in the trench was assumed to burn with a heat release rate of 1,000 kW per square meter, for a total heat release rate of 12.1 GW. Each element was assumed to emit 35 percent of its energy as thermal radiation, and 12 percent of the fuel was converted to soot.



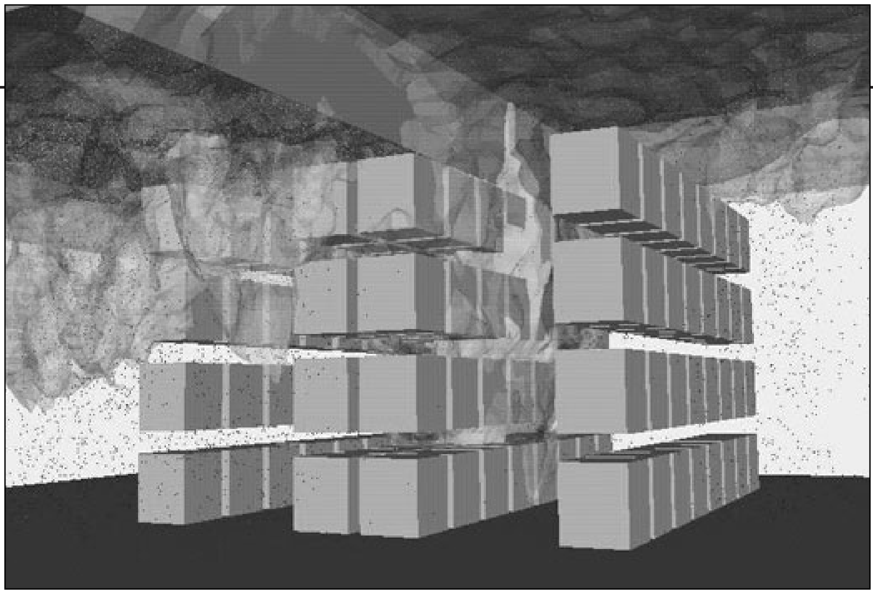
Large Eddy Simulation of a fire in containment trench surrounding an oil storage tank.

The bright colored elements in fig. (oilplume) are burning, releasing energy into the gas and the radiation field. Thus, the composite burning elements represent the instantaneous flame structure at the resolution limit of the simulation. The dark colored elements are burnt out. They represent the smoke and gaseous combustion products that absorb the radiant energy from the flames. It is important to understand how much of the emitted radiant energy is re-absorbed by the surrounding smoke. The model showed that of the original 35 percent of the energy released as thermal radiation, 29 percent was reabsorbed, in agreement with earlier measurements by Koseki [11].

11.10.4 INDUSTRIAL FIRE CONTROL

Recently, the LES techniques have begun to be used to study the effects of human intervention to control the damage caused by fires. The International Fire Sprinkler, Smoke and Heat Vent, Draft Curtain Fire Test Project organized by the National Fire Protection Research Foundation brought together a group of industrial sponsors to support and plan a series of large scale tests to study the interaction of sprinklers, roof vents and draft curtains of the type found in large warehouses, manufacturing facilities, and warehouse-like retail stores. The tests were designed to address relatively large, open-area buildings with flat ceilings, sprinkler systems, and roof venting, with and without draft curtains. The most elaborate tests involved a series of five high rack storage commodity burns.

In parallel with the large scale tests, a program was conducted at NIST to develop a computer model based on the LES methodology, the Industrial Fire Simulator (IFS) that incorporated the physical phenomena needed to describe the experiments. A series of bench scale experiments was conducted at NIST to develop necessary input data for the model. These experiments generated data describing the burning rate and flame spread behavior of the



Computer simulation of a rack storage cartooned plastic commodity fire test using the NIST Large Eddy Simulated Fire Model.

cartoned plastic commodity, thermal response parameters and spray pattern of the sprinkler, and the effect of the water spray on the commodity selected for the tests.

Simulations were first compared with heptane spray burner tests, where they were shown to be in good quantitative agreement with measured sprinkler activation times and near-ceiling gas temperature rise. The sprinkler activation times were predicted to within 15 percent of the experimental values for the first ring of sprinklers surrounding the fire, and 25 percent for the second. The gas temperatures near the ceiling were predicted to within 15 percent. Next, simulations were performed and compared with the unsprinklered calorimetry burns of the cartoned plastic commodity. The heat release rates were predicted to within about 20 percent. Simulations of the five cartoned plastic commodity fire tests were then performed see photograph.

The goal of these simulations was to be able to differentiate between those experiments that activated a large number of sprinklers and those that did not. This goal has been met. The model was also used to provide valuable insight into what occurred in the experiments, and what would have occurred for various changes of test parameters. Further information about this work can be found in [12,13].

There are plans to continue the development of the IFS model in the future. Much more work is needed to verify the additional models used to account for the flame spread, the interaction of the spray with fuel surfaces, and the various heat transfer mechanisms. However, the results obtained to date are certainly encouraging. The simulations yield information that is difficult if not impossible to obtain any other way. Moreover, it is possible to test the various assumptions and models individually against experiments designed to yield much more precise information than can be obtained from large scale tests. Thus, the knowledge gained from a limited number of large scale tests could be systematically extended by coupling this information to the results of computer simulations.

11.10.5 ACKNOWLEDGMENTS

The work described here is the contribution of many people at NIST. Howard Baum and Ronald Rehm collaborated over many years to develop these fire modeling capabilities. Kevin McGrattan has been the architect and creator of the computer programs that convert the simplified physical and mathematical models into practically useful predictive tools. William Mell and William Walton contributed their expertise to the modeling and experimental confirmations. Finally, the work was guided and encouraged over the years by the Late Professor Howard W. Emmons, who was the father of modern fire science. This section is based on a paper by Baum [14].

The Department of Commerce recognized fire modeling advances with a number of its medal awards.

- James Quintiere received the Bronze Medal in 1976 for studies of room fire growth.
- John Rockett received the Silver Medal in 1977 for early work in fire modeling.
- James Quintiere received the Silver Medal in 1982 for fire growth modeling.
- Bernard McCaffrey received the Bronze Medal in 1983 for large plume experiments and theory.
- Howard Baum and Ronald Rehm received the Gold Medal in 1985

for development of the large eddy simulation technique.

- Daniel Madrzykowski received the Bronze Medal in 2001 for large scale field fire tests.
- Kevin McGrattan and Glenn Forney received the Silver Medal in 2001 for advanced fire dynamics simulations.

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11.11 FIRE FIGHTER EQUIPMENT

11.11.1 FIRE DEPARTMENT GROUND LADDERS

During the decade of the 1960s several serious fire service accidents occurred when using ground ladders. The ladders failed during normal fire fighting operations. Some of the failures related to load carrying capabilities, and others failed as a result of loads and heating from the fire. The objective of this effort was to review existing standards to identify issues related to ladder failure, study key performance requirements for the use of fire service ground ladders, and recommend improvements for NFPA and American National Standards Institute (ANSI) ground ladder standards [1].

NBS' Fire Service Section of the Fire Technology Division teamed with the Prince Georges County, Maryland and Bowie, Maryland fire departments; and the Fire Service Extension Department of the University of Maryland to identify performance issues associated with the use of fire department ground ladders. Field studies of ground ladder applications were carried out. Metallurgical studies were conducted on three ladders that failed in service. Ladders were also tested for deflection response to load, failure in horizontal bending, and resistance to impact. Human factor issues related to sizing and design were studied. Information gained from these studies was presented to

ANSI and NFPA to assist in improving ground ladders standards.

Results from this study were presented to NFPA and ANSI. NFPA 193, Standard on Fire Department Ladders and ANSI A14.2 Standard for Portable Metal Ladders were both modified to reflect many of the recommendations made by NBS.

Participants in this project from NBS included H. P. Utech, T. Robert Shavers, Donald C. Robinson, Donald B. Novotny, Henry C. Warfield, and Joseph M. McDonagh. William E. Clark of the Prince Georges County, Maryland Department of Fire Protection also assisted with this study.

11.11.2 FIRE FIGHTERS' TURNOUT COATS

The purpose of this research was to improve the protection afforded fire fighters by their turnout coats and to insure the durability of the coats. It developed standard specifications for the selection and purchase of for fire fighters' turnout coats, and turnout coat specifications for development of a standard for fire fighters' protective clothing.

NBS conducted a series of studies to determine what was needed by the Fire Service in the use of turnout coats, and investigated the most practical means for meeting those needs [2]. The studies concentrated on evaluating what was available in the marketplace. Based on these studies and the needs and desires of the Fire Department of Prince Georges County, Maryland, a purchase specification was developed which was used by that county to purchase a number of coats. A coat manufacturer produced the coats, and the Prince Georges County Fire Department evaluated the garments through field use. Comments were obtained from the fire department, each Director of State Fire Service Training, the International Association of Fire Fighters (IAFF), turnout coat and coat component manufacturers, and other interested parties. The comments were analyzed and a new draft specification was prepared. The proposed changes were discussed at a series of seminars arranged by the fire service groups. Additional drafts of the specifications were prepared based on comments received, and a final report [3] was prepared.

Findings from this work were shared with the NFPA Sectional Committee on Protective Equipment for Fire Fighters that was a part of the Committee on Fire Department Equipment. The final NBS report was published in October of 1975 and NFPA adopted much of the report recommendations at its fall meeting on November 18, 1975. This standard, NFPA 1971, became the first American national standard for fire fighters' protective clothing.

Other organizations assisting with this project: Prince Georges County Maryland Fire Department; International Association of Fire Chiefs; International Association of Fire Fighters; International Fire Service Training Association; National Fire Protection Association; University of Maryland Extension Service; and the Federal Fire Council. This work was sponsored by the U.S.

Turnout coat damaged from thermal exposure.

Department of Commerce, National Fire Prevention and Control Administration.

11.11.3 FIRE FIGHTERS' PROTECTIVE CLOTHING

The initial project compared conditions measured in room fires conducted over several years at NBS' CFR to protection levels provided by fire fighter turnout coats and pants conforming with NFPA 1971, Standard for Protective Clothing for Structural Fire Fighting.

Heat flux conditions measured in seven room fire tests [4, 5] were compared to heat flux values and the thermal protective performance (TPP) ratings of fire fighters protective clothing. NFPA 1971 required that fire fighters' protective clothing protect the wearer against second degree burns when a heat flux of 84 kW/m^2 is applied to its outside surface for a minimum of 17.5 seconds. Heat flux data representing the TPP test exposures were superimposed on heat flux plots from the room fires.

Comparisons of heat flux from room fires to heat flux exposures from the TPP test showed that room fire will often exceed test conditions provided by the TPP test. Data from this study suggested that turnout garments that meet requirements for the NFPA 1971 TPP test only allow a short time for escape. Estimates for escape time from this study indicate that a fire fighter has less than 10 seconds to escape a flashover fire instead of the 17.5 seconds suggested by the NFPA TPP test.

Example of modern fire fighter protective clothing under simulated thermal environment.

The paper by Krasny, Rockett, and Huang received the Fire Technology, National Fire Protection Research Foundation, Harry C. Bigglestone Award For Excellence in Written Communication.

Although significant advances had been made in the performance of fire fighters' protective clothing, by the mid 1990s the number of serious burn injuries had remained constant for more than a decade. Therefore research was resumed to develop measurement methods and computer based predictive methods that would provide a detailed understanding of thermal performance for fire fighters' protective clothing. These analytical tools were designed to assist manufacturers in product development, assist the standards writing organizations in development of technically sound standards for thermal protective clothing, and provide the fire service with information and tools for selecting thermal protective clothing, training fire service personnel in the proper use of the protective clothing, and for analyzing fire fighter thermal injury cases.

An initial study [6] was conducted to quantify what was known about the thermal environments of fire fighting and fire fighter burn injury and death statistics. NIST rejoined the NFPA and ASTM technical committees that maintain standards on fire fighters protective clothing. A workshop [7] was held to identify fire service and protective clothing industry concerns associated with protecting fire fighters from thermal exposures and to facilitate the exchange of ideas. NIST worked with numerous fire departments to better understand issues related to the performance of fire fighters protective clothing. This effort included the study of serious burn injury cases and fire fighter fatality cases that resulted from thermal exposure. Existing ASTM and NFPA thermal test methods for measuring the thermal performance of fire fighters' protective clothing were evaluated [8]. Knowledge learned from these studies was carried to the laboratory and resulted in the development of two new thermal test apparatus [9, 10] that could be used to better quantify the thermal performance of fire fighters' protective clothing. In addition, an effort was begun to translate what was being learned from these studies into a physics based computer program for predicting the thermal performance of fire fighters' protective clothing. A one dimensional heat transfer model [11] was developed that could be used to predict heat transfer through the multiple layers of fire fighters' protective clothing garments. In addition, NIST developed thermal properties data [12] for the fire fighters' protective clothing predictive heat transfer model and began developing data on thermal conductivity. Other studies are underway to quantify specific heat and the thermo-optical properties of protective clothing materials.

Five major manufacturers of components for fire fighters' protective clothing and protective clothing garment systems have developed proprietary research agreements with NIST and have used the protective clothing thermal measurement facilities to study their products. Data generated by these measurement apparatus have resulted in design modifications to fire fighters' protective clothing and components used to fabricate fire fighters' protective clothing. Primary areas where protective clothing has seen improvements are turnout coat sleeve cuff designs, knee pad and elbow pad designs and improvements in thermal performance of trim materials. Information on these measurement methods has been submitted to ASTM International Committee F23 on Protective Clothing and the National Fire Protection Association (NFPA) Committee on the Protective Ensemble for Structural Fire Fighting. Data from these measurement apparatus are being applied to performance evaluations of other test methods used for the analysis of thermal protective clothing.

Robert T. McCarthy, Chief, Fire Technical Programs Branch (USFA) worked with NIST in support of this effort. This project was supported by the U.S. Fire Administration (USFA) and the National Institute of Standards and Technology. Thomas Van Essen, Fire Commissioner, Chief Stephan J. King, Safety Chief, and Battalion Chief Hughie Hagan of the York City Fire Department (FDNY) supported development of the dynamic compression test apparatus, and Lt. Kevin S. Malley, Director of Human Performance (FDNY), became a NIST Guest Researcher to assist with development of the test apparatus and assisted with protective clothing testing and report preparation. Division Chief, Kirk Owen of the Plano, Texas Fire Department and Chairman of the NFPA Committee on the Protective Ensemble for Structural Fire Fighting provided technical council. The following fire departments participated in these efforts by cooperating with field studies and providing other forms of assistance: Austin Fire Department, TX; Cincinnati Fire Department, OH; Denver Fire Department, CO; Fairfax County Fire and Rescue Department, VA; Jacksonville Fire Department, FL; Lexington Fire and Emergency Services, KY; Louisville Fire Department, KY; Montgomery County Fire and Rescue, MD; York Beach Fire Department, ME. Manufacturers providing assistance and contributing materials for this research effort were: Alden Industries; Celanese Corporation, Dupont Advanced Fiber Systems; Globe Firefighter Suits; Lion Apparel Inc.; Minnesota Mining and Manufacturing Company (3M), Safety and Security Systems Division; Morning Pride Manufacturing, Inc.; Reflexite Corporation; Southern Mills Inc.; W. L. Gore and Associates. Other NIST staff participating in this effort were: Robert L. Vettori and Dan Madrzykowski.

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11.12 FIRE SPRINKLERS

11.12.1 INTRODUCTION

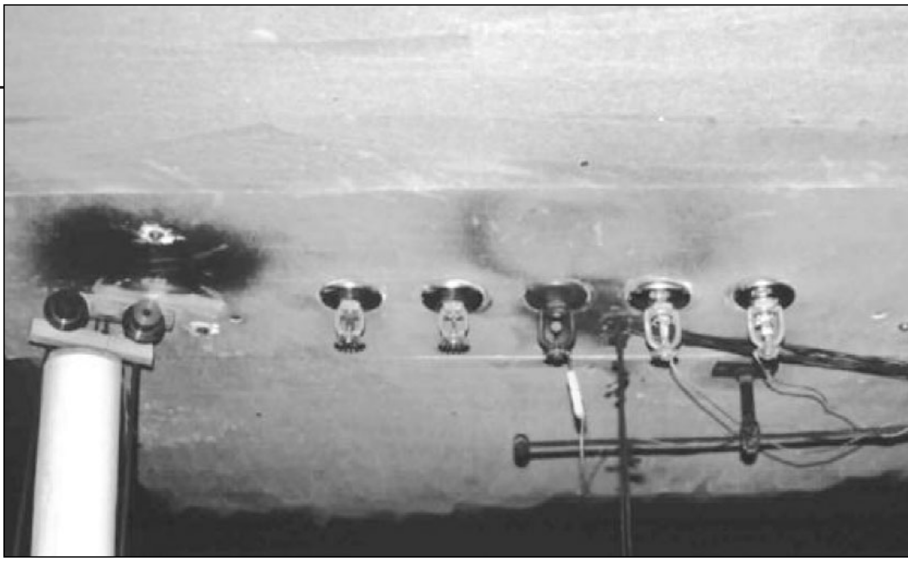
Automatic sprinkler systems have been successfully used to protect industrial and commercial buildings and their occupants for more than 100 years [1]. The Report of the National Commission on Fire Prevention and Control, America Burning, issued in 1973, changed the focus of sprinkler research, in both government and private sector labs, from protecting the building and its contents to protecting the occupants of the building [2]. The research efforts at NIST used measurements and analysis in order to develop methods of predicting automatic sprinkler response and fire suppression effectiveness. The impact of the research conducted during this period can be seen in a variety of engineering applications, standards development and as a foundation for much of the fire suppression research that is currently underway at NIST and other research laboratories around the world.

In its most basic form, an automatic fire sprinkler system consists of a water supply, piping to deliver the water from the supply to the sprinklers and thermally activated sprinklers. In most cases, each sprinkler has a temperature sensitive link. Hence water is only discharged in the area where the gases from the fire have gotten hot enough to activate the sprinkler. While the system seems simple enough, the process of accurately predicting multiple sprinkler activation and fire suppression from the water spray cannot be done a priori. As a result, the most reliable means of determining the effectiveness of fire sprinklers for a given set of conditions is full-scale testing.

11.12.2 FULL-SCALE FIRE SUPPRESSION EXPERIMENTS

By 1977, NBS had two major sprinkler research projects; 1) automatic sprinklers in health care facilities and 2) the use of sprinklers or water sprays for protection of open stairways [3]. These projects were being conducted by the Program for Fire Detection and Control in the Center for Fire Research (CFR).

New Sprinkler Technology for Health Care Occupancies– The objective of the first project, sponsored by the U.S. Department of Health, Education, and Welfare (HEW), was to determine the effectiveness of automatic sprinklers in terms of fire control and life safety. Over the course of this project, 1977 - 1982, O'Neill, Hayes and Zile conducted 21 full-scale fire experiments in a patient room, corridor and lobby arrangement that had been installed in a former NIKE missile base barracks building adjacent to the NIST Gaithersburg Campus [4, 5, 6]. The fires were set in mattresses with bedding or in wooden wardrobes filled



Instrumented "standard" and "quick" response sprinklers, installed in the Barracks Building at the NIST Annex (former Nike Site).

with clothing to demonstrate a "worst case" shielded fire. In later stages of the project, gas burners were used to replicate the thermal conditions of the burning furnishings [7].

The research was seminal in many ways, it demonstrated the life safety value of "fast response" (low thermal inertia) sprinkler activation technology. In addition, it provided a comparative database for temperatures, gas concentrations, and smoke obscuration based on the thermal response of the sprinkler, as well as the location of the sprinkler in the room i.e. pendent versus sidewall. Last but not least, the results of this research program were used to develop recommendations for the positioning of hospital privacy curtains with respect to the location of the sprinkler. Installation criteria based on the NBS recommendations were adopted in the National Fire Protection Association (NFPA) 13, Standard for the Installation of Sprinkler Systems, in 1983.

In 1993, the research on protecting patient rooms with sprinklers was augmented by Notarianni [8]. The research sponsored by the National Institutes of Health (NIH), focused on tenability conditions within the room of fire origin, with similar comparisons as the previous HEW sponsored studies, quick-response versus standard response sprinklers and pendent versus sidewall position. This work reaffirmed the utility of QR sprinklers for defend in place situations and provided further insight on the reduced level of obstruction created by privacy curtains with open mesh near the top.

Using Sprinklers to Limit the Spread of Fire and Smoke– O'Neill and Cooper studied the abilities of sprinkler and water spray nozzle systems to protect open stairways and other openings in fire-resistive walls and ceilings [9, 10]. The experiments, sponsored by the Occupational Safety and Health Administration (OSHA), were conducted in a three-story stairwell that was built in the opening of an underground bunker used for the storage of NIKE missiles. The stairwell was exposed to fire sizes up to 4 MW with and without the sprinklers. The results of the experiments demonstrated the effectiveness of sprinkler protection for openings and have provided data for use with NFPA 13.

Impact of Sprinklers on Office and Laboratory Fires– The next major series of full-scale sprinklered fire experiments began in the late eighties under the sponsorship of the General Services Administration (GSA). By now, NBS had developed oxygen consumption calorimetry methods, which had been implemented in the Large Fire Research Facility (Bldg 205). This enabled researchers to measure the impact of the sprinklers on suppressing the fire in terms of heat release rate. Walton conducted fire experiments examining the impact of sprinkler spray density on the burning fuels representing a "light hazard" [11]. The results demonstrated that 0.07 mm/s was the "reliable minimum" for rapidly reducing the heat release rate and suppressing the fire [11].

The GSA research was continued by Madrzykowski, with the objective of quantifying the sprinklered fire exposure on an exit corridor and spaces adjacent to that corridor [12]. The fire source in the burn room was a shielded wood crib, sized to maintain a 1 MW fire. Tenability was assessed using both temperature and gas toxicity criteria. The experiments showed that the sprinklers maintained tenable conditions in the corridor and in the adjacent room. Without the sprinkler protection, the corridor became untenable within 6 minutes.

GSA was funding this research as part of an effort to develop an engineering based approach to fire safety design [13]. Implementing this approach was constrained in part by a lack of relevant heat release rate data and the inability to determine the impact of an activated sprinkler. In response to this need, Madrzykowski and Vettori conducted a series of experiments burning a wide variety of office furnishings and measuring the heat release rate with and without sprinkler activation. The effect of a "light hazard" design density of 0.07 mm/s was documented and used as a basis for an empirical suppression model [14].

Under the sponsorship of GSA and NIH, Walton and Budnick conducted a set of fire sprinkler experiments in a lab building, which was slated for renovation, on the NIH campus [15, 16]. This test series is key for two reasons: first, it identified the life safety and design benefits of using quick response sprinklers in chemical laboratories and office areas and second, it was the first major fire research program conducted in a "field location." While the fire research program had conducted simple field experiments with simple instrumentation prior to NIH, this series of experiments included complex detection and suppression experiments and measurements. Several similar lab rooms were instrumented to record activation times of detection and suppression systems, temperature, and concentrations of oxygen, carbon dioxide and carbon monoxide. Videos of the fire room and hallway were made during the experiments. Walton would use this experience to optimize and enhance NIST's field measurement capabilities. In the decade that followed these capabilities would be used for a wide range of field experiments addressing mitigation of oil spills, fire suppression effectiveness of Class A foam, arson burn pattern studies and further studies on the impact of sprinklers in various occupancies.

11.12.3 SPRINKLER RESEARCH AREAS

Given the complexities of understanding sprinkler activation and suppression under actual fire conditions, the problem was de-coupled and studied in parts: activation, sprinkler spray characterization, cooling via water droplets, and suppression. Finally, several studies have been conducted looking at the potential impact of sprinkler systems.

Sprinkler Activation– The study of sprinkler activation at CFR was spearheaded by Evans [17, 18]. Beginning with the characterization of the thermal response of fusible links used to activate sprinklers, Evans' study of the thermal elements used in sprinklers and the characteristics of the hot gas environments generated by a variety of fires coupled with research conducted by Factory Mutual and others would soon lead to the development of a computerized means of predicting sprinkler activation [19-21]. In addition to laboratory-based experiments, many sprinkler activation experiments were conducted in "real world" environments including a mobile home, a hotel, and large aircraft hangers [22-27]. This data has been used to either evaluate a predictive sprinkler activation model or to develop new ones.

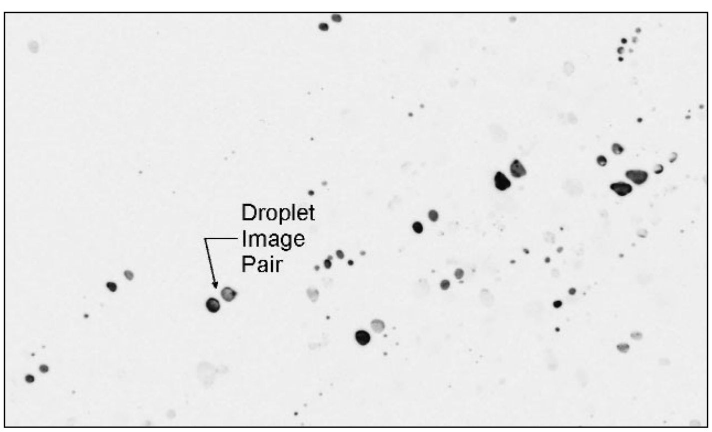
Sprinkler Spray Characterization– The measurement of sprinkler sprays has been addressed in a number of ways since 1985. The measurements have been limited by the measurement technology available at the time. Ideally a water droplet can be described in terms of size and velocity. This would enable the prediction of the trajectory of the droplet and the determination of the momentum of the droplet. Within the scope of a sprinkler spray, it is important to know the distribution of the droplet sizes and velocities in order to determine how this water spray may impact a fire.

Hayes conducted a literature survey of existing drop size data, means of measuring drop size and the significance of drop size in fire suppression [28]. His survey led to sprinkler spray measurements, sponsored by GSA and conducted by Lawson et al. using a computer controlled shadowgraph technique [29]. This device used a strobe light and light sensitive array to provide the measurements. Subsequently, spray measurements were conducted by Putorti et al. using an improved shadowgraph method incorporating a self contained laser beam and an optical diode array [30, 31]. In 2000, several researchers were developing water droplet measurements, Widmann using Phase Doppler Interferometry

Photographs (such as this) of sprinkler sprays were used to examine water sheet break-up and droplet formation in the 1980s.

(PDI) and Sheppard and Lueptow using Particle Image Velocimetry (PIV) [32]. While both methods permit accurate and non-intrusive measurements of sprinkler sprays, the PIV only measures mean drop velocity and does not provide drop size distribution, while PDI provides both drop size and velocity. Characterizing a sprinkler spray field is a tedious and difficult process given the small measurement volume used in both systems. As the new century dawns, Putorti and Atreya have begun the development of a unique measurement device, the large-scale planar laser, drop size and velocity measurement apparatus. After utilizing the best commercially available technology and falling short of the goal of fully characterizing the sprinkler spray it is hoped that this heuristic approach can provide the insight and the data required to enable a sprinkler spray based suppression predictive method.

Determination of water droplet size and velocity using the Particle Tracking Velocimetry and Imaging Technique (PTVI). Two images of each droplet are obtained by fluorescence with two laser sheets.



Photographs of water droplets fluoresced via a sheet of laser light. Computer analysis of this photo will provide droplet size and velocity data.

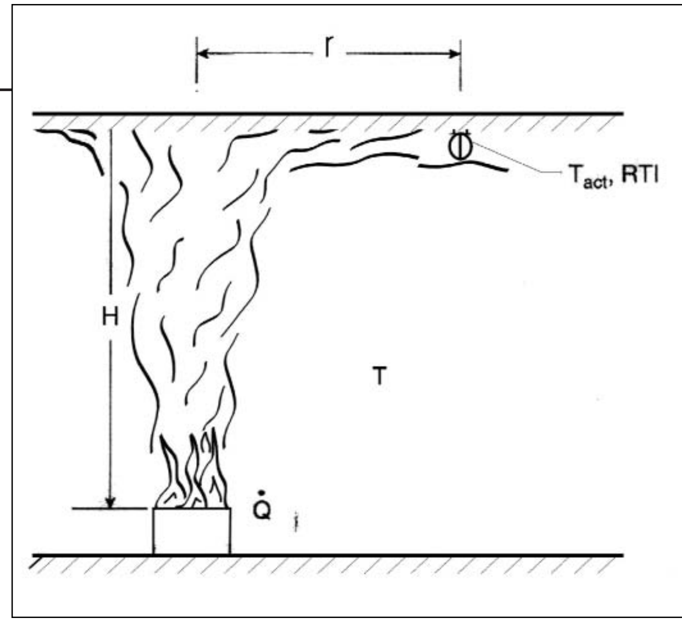
Sprinklered Fire Suppression - From 1986 through 1996, teams of University of Maryland students, led by diMarzo, with scientific oversight from Evans, have worked on measuring the cooling of a hot surface by droplet evaporation [33-38]. Based on the measurements, a coupled model was developed that can simultaneously yield the surface temperature and heat flux as well as the transient due to droplet evaporation. Coupled with the droplet measurements, the results from this research would provide a portion of the fuel-cooling piece of the fire suppression puzzle.

Given that the universal sprinkler suppression solution is still many years in the future, parallel research efforts were undertaken to provide a near term, although limited solution. The empirical suppression model by Madrzykowski and Vettori was incorporated in to FPETool [14, 39]. Based on these experimental results and those of Walton, Evans developed a generalized suppression model for light hazard occupancies that could account for a range of spray densities [40]. This model was incorporated into the HAZARD I model. As part of a National Fire Protection Research Foundation project on predicting the impact of sprinklers in high rack storage warehouses, Hamins and McGrattan embarked on a set of reduced scale experiments to develop a fire suppression model with a given fuel, (group A plastic commodity), in a given configuration, (rack storage), with a given water flux. Algorithms, compatible with a computational fluid dynamics model, describing the heat and mass transfer taking place during suppression were developed from the data [41].

Sprinklered Life Safety Analysis– In addition to studying the heat transfer and fluid dynamics aspects of sprinkler fire suppression, NIST has conducted studies focused on the life safety impact of installing sprinklers. In 1984, Budnick published a study estimating the improvement that state of the art detection and suppression technology could have on life safety in residential occupancies. It was estimated that residential sprinklers, in conjunction with a smoke detection/alarm system could reduce residential fire deaths by 73 percent [42]. Also in 1984, Ruegg and Fuller completed a cost benefit analysis on residential sprinkler systems [43]. In 1998, Notarianni and Fischbeck, developed a methodology to handle value judgments, such as the value of premature death avoided, by means of comparative analysis, parametric analyses, and switchover analysis. This methodology was applied to a model for determining the benefits and costs of residential fire sprinklers [44].

11.12.4 PREDICTIVE METHODS

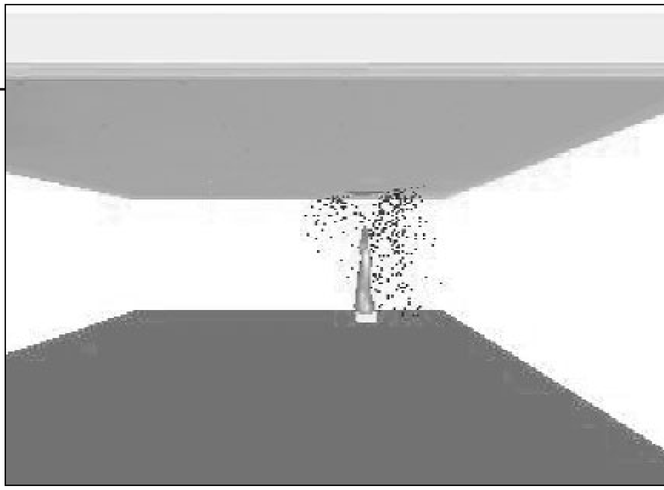
Stand Alone Sprinkler Activation Models– The predictive models of sprinkler activation and fire suppression are used by engineers around the world to address fire protection and investigation challenges. While these models are still under development, significant progress has been made by NIST fire research. In 1985, Evans and Stroup developed the first public domain computer model, DETACT-QS [45]. The model was designed for calculating the response time of heat detectors or sprinklers installed below large unobstructed ceilings. Stroup, Evans and Martin further developed another heat detector activation model, DETACT-T2, aimed at evaluating the response of existing systems with a range of fire growth rates [46, 47]. Given limited access to computers by the general engineering community, the models were published with a large number of cases pre-run and arranged in look-up tables. Two versions were published one in English units and one in metric units. Cooper, Stroup and Davis worked from 1986 through 1990 developing a different model for predicting sprinkler activation in a compartment [48-51]. The resulting model, LAVENT, considered the effects of a compartment, had the ability to accommodate vents in the ceiling and allowed the user to position the detector at different distances below the ceiling as opposed to DETACT which assumed that the detector was in the position of maximum temperature and velocity in the ceiling jet.



Schematic of DETACT-QS sprinkler activation model inputs.

Integrated Sprinkler Activation and Suppression Routines in Zone Models– As NIST continued to develop models that would consider fire development in the context of a room environment which could include heat loss to the walls and ceiling, doors or windows that could open and occupants, the basic DETACT sprinkler algorithm was incorporated [52-54]. Over the years refinements were added to the zone models' sprinkler capabilities, this included modifying the heat transfer algorithm to be more representative of actual compartment temperature conditions and adding limited empirical sprinkler suppression algorithms [39, 55]. However the zone models were still limited to the activation of the first sprinkler.

Multiple Sprinkler Activation with Suppression– Beginning in the mid 90s, McGrattan and Forney began examining the interaction of sprinkler sprays and fire gases using a computational fluid dynamics model (CFD) [56]. The CFD technology enabled the prediction of multiple sprinklers and how the water spray might inhibit the activation of additional sprinklers. At



Smokeview visualization of a heptane fire with two sprinklers activated.

this point, the model was known as the NIST Large Eddy Simulation (LES) fire model. NIST entered into an agreement with the National Fire Protection Research Foundation, where members of the foundation would fund full-scale fire experiments at UL's new state of the art test facility in Northbrook, IL. NIST would model the experiments and actually provide the model predictions before the experiments were conducted. McGrattan, Hamins and Stroup accepted the challenge of the International Sprinkler, Smoke and Heat Vent, Draft Curtain Fire Test Project for NIST [57. 58]. By the end of the project, 34 heptane spray burner experiments and 5 Group A plastic commodity high rack storage fires had been conducted. This did not include numerous reduced scale experiments to support model development. While the initial predictions for time to activation needed some improvement, the most challenging task of predicting the number of sprinklers to activate was met with great success. As other physical phenomena were incorporated into the model to improve the time to activation prediction, the model evolved and was renamed the Industrial Fire Simulator 2 (IFS2). McGrattan, Baum, Rehm, Hamins and Forney continued to improve the capabilities of the model and the first version of the NIST Fire Dynamics Simulator (FDS) was released in January of 2000 [59]. A sister model to FDS, Smokeview, was released in May [60]. This was a post processing scientific visualization tool, which allows the user to see the numerical results of FDS. Hence with Smokeview the user could watch the simulated fire develop in a room. Watch the sprinkler activate and suppress the fire, all on the screen of a computer monitor. This visualization model is one of the most dramatic improvements to the computer models because it enables a wider range of people, including: engineers, building owners, and other members of the fire protection community, to see and understand the results of an FDS model run.

11.12.5 SUMMARY

Since 1975, the fire research program at NIST has been leader in research aimed at developing and validating methods to predict the activation and suppression effectiveness of sprinklers. Results from this research have been incorporated into building codes and sprinkler standards. The sprinkler activation models are a critical piece of the infrastructure that supports performance based fire safety design around the world. Today the Fire Research Division at NIST continues to improve the body of knowledge regarding fire sprinklers with the mission of reducing loss of life and property due to fire.

David Evans received the Bronze Medal Award of the Department of Commerce in 1990 for his work on sprinkler response prediction.

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11.13 BURNING OIL SPILLS

One of the risks of oil drilling and transportation is that accidents can occur releasing natural crude oil or its refined products as oil spills. Oil contamination of land or water is an environmental hazard to life. Historically oil spill response has been limited to various mechanical means of recovering the spilled oil from land or water and then disposing or reprocessing the waste. Generally using mechanical recovery large amounts of oil contaminated materials need to be removed and treated. Mechanical recovery of oil in areas such as rocky shorelines, marshlands, and in ice laden waterways is impractical. In the 1980s burning oil in place - in-situ burning -- was explored as a primary technology for oil spill response.

The 1989 oil spill from the Exxon Valdez tanker onto the waters of Prince Williams Sound in Alaska focused national attention on oil spills. An estimated 42 million liters of oil were released from the ship into the water. Some of the oil, driven by winds and currents, was deposited on the shoreline of Prince Williams Sound. At the time of that spill, NIST and others were already engaged in the evaluation of burning as a response to oil spills. Industry was beginning to produce fire resistant booms that could be used to confine oil spilled on water to burn it in-place. It is a little known fact that using a fire resistant boom, approximately 57,000 liters of oil from the Exxon Valdez that had been in the water for nearly two days was confined and burned. The resulting fire lasting approximately 45 minutes consumed all but 1,100 liters of residue that remained in the boom [1].

Burning oil spills in-place normally produces a visible smoke plume containing soot and other combustion products produced in the burning. Lack of knowledge about the extent of the area affected by the smoke plume produced by burning crude oil spills and the possibility of undesirable combustion products carried in the plume have led to public concerns over the effects of intentional burning large crude oil spills. Unresolved questions about personnel and equipment safety from the heat and thermal radiation produced by large fires also has hampered application of burning to oil spills. In the decision process for approval of intentional burning of oil spills, local authorities need to have tools to quantify the likely benefits of the burning in terms of oil removal and the likely consequences in terms of the fire generated smoke plume. BFRL's in-situ oil spill research program was designed to develop quantitative information and software tools to aid authorities in making informed decisions. The lack of this information was an impediment to the acceptance and use of this emerging technology.

To understand and quantify the important features of in-situ burning it was necessary for BFRL to perform three scales of experiments. Laboratory tests furnished property data, experiments utilizing large-scale outdoor burn facilities provided mesoscale data and means to develop and evaluate instrumentation, and finally, actual burns of spilled oil at sea provided data on in situ burning at the anticipated scale of actual response operations [2]. In this research program, there has been continued interaction between findings from measurements on small fire experiments performed in the controlled laboratory environments of NIST and the National Research Institute of Fire and Disaster (NRIFD) in Mitaka, Tokyo, Japan, and large fire

Crude oil burn at the U.S. Coast Guard Safety and Fire Test Detachment mesoscale burn facility in Mobile, Alabama.

experiments at facilities like the USCG Fire Safety and Test Detachment in Mobile, Alabama where outdoor liquid fuel burns in large pans are possible.

Large scale burns of a confined oil layer up to 15.2 m x 15.2 m were used to determine a mean value for the burning rate per unit area of (0.052 +0.002) kg/s/m^2 and for the heat release rate per unit area is (2180 +100) kW/m^2 assuming a heat of combustion of 41.9 MJ/kg. The wind direction and speed in the outdoor burns contributed to the wide variation in fire extinction behavior observed although it did not appear to affect the average burning rate.

Crude oil released into a fire resistant containment boom and burned during the Newfoundland Offshore Burn Experiment conducted off the coast of St. John's Newfoundland on August 12, 1993.

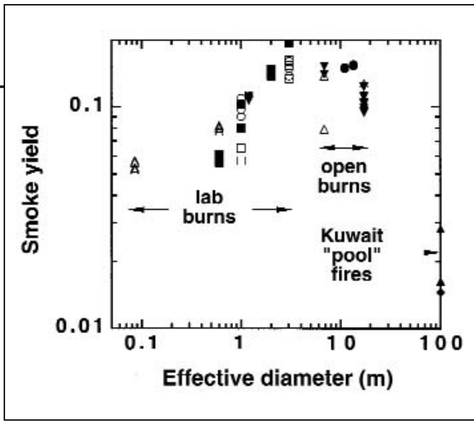
The amount of smoke particulate released from large oil fires is characterized by the smoke yield. Smoke yield is defined as the mass of smoke aerosol generated per mass of fuel consumed. The smoke aerosol collected during these experiments contained both solid material (graphitic carbon) and condensable hydrocarbons from the fire plume. Two methods for determining smoke yield were used in this study. The first was the flux method, which measured the smoke collected on a filter and the mass loss from the burning specimen [3, 4]. This type of measurement worked well in a laboratory test environment where all the products of combustion were collected and drawn through an exhaust stack.

The second method of determining the smoke yield is referred to the carbon balance method [4, 5]. This method required a determination of the ratio of the smoke mass in a given volume to the total mass of carbon in the form of gas or particulate in the same volume. This was accomplished by dividing the smoke mass collected on a filter to the sum of the smoke mass and the mass of carbon contained in the forms of CO and CO_2.

In the figure the smoke yield is plotted versus pool diameter. The effective diameter of the 2.7 m square pan was defined as the diameter of a circle (3.05 m) with area equal to the square pan. This figure includes other crude oil fires with "pan sizes" ranging from 0.085 m to 100 m [6 - 12]. The data from 2 m to 15 m based on five studies [6 - 10] with five types of crude oils (Murban, Arabian light, Louisiana crude, Murban-Arabian light mixture, and Newfoundland crude) appear to be independent of size; with one exception the data fall in the range 0.13 to 0.16. For the pan sizes larger than 3 m, the burns were performed outside where the ambient wind may affect the smoke yield. The results from two series of tests at 17.2 m are significantly lower than the results from 2 m to 15 m. The results from one series [6] range from 0.101 to 0.111 with a mean of 0.107 while the other was a single test with a value of 0.127 [10]. The cause for an apparent decrease is not known.

As an aid to effectively transfer the result of the BFRL research useful to authorities and emergency responders (decision makers about applying intentional burning of an oil spill) BFRL developed software to estimate the extent and concentrations of particulate in the smoke plume and at ground level.

The ALOFT (A Large Outdoor Fire plume Trajectory) model developed by



The effect of pool diameter on the smoke yield from burning different crude oils in laboratory and outdoor burns.

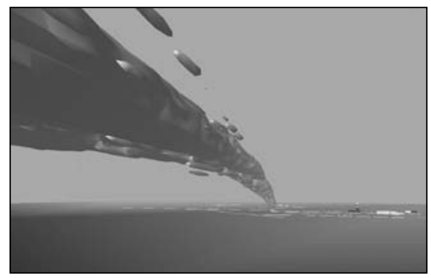
BFRL takes an approach similar to that of Ghoniem et al [13], but it uses finite-difference methods to determine the large scale mixing, combined with a Lagrangian description of the transport of the smoke and other pollutants. The ALOFT model differs from most of the atmospheric dispersion models in use today because it is a deterministic rather than an empirical model. The approach is to solve the equations governing the flow rather than to rely on empirical formulae that approximate the extent of the dispersion. Empirical models typically assume the pollutant is Gaussian-distributed in the plane perpendicular to the direction of the prevailing wind. The parameters defining the distribution are estimated from experiments. However, Gaussian models are inappropriate for two reasons: (1) the characteristics of the "source" are different from the smokestacks that are usually assumed by such models, and (2) the size of the source is well beyond those considered in industrial applications and thus outside of the experimental parameter range used to calibrate the models.

Aerial photograph taken of the second ACS burn, Prudhoe Bay, September 1994

During development ALOFT-FT predictions were compared with measurements taken at three field experiments. It should be pointed out that the experimental data were used to assess the accuracy of the model predictions. The data were not used to calibrate the model. This is an important distinction, and it points out the difference between a deterministic and an empirical model.

In early September 1994, Alaska Clean Seas (ACS) conducted at its Fire Training Ground in Prudhoe Bay, Alaska, three mesoscale burns to determine the feasibility of burning emulsified oil [14]. The photo shows an aerial view of the second burn. Twelve real-time aerosol monitors (RAMs), supplied by the US Environmental Protection Agency, the EPA's Emergency Response Team (EPA/ERT), were set out on meter high tripods, spread out in rows of three or four, at distances ranging from 1 km to 5 km downwind of the burn site to provide data on particulate concentrations at ground level. Model predictions showed good agreement with ground particulate concentration measurements. Simulations of the smoke plume from the burns showed good agreement with the observed plume trajectory (see photo).

To facilitate the approval of in situ burning as an oil spill response method, the Alaska Department of Environmental Conservation sought assistance from BFRL to use the newly developed ALOFT model for smoke plume trajectory to help develop guidelines for approval of intentional burning of spills. Two in situ burning scenarios were developed by NIST: one representing the burning of Cook Inlet crude oil in the Cook Inlet region and the other North Slope crude oil in the North Slope region.



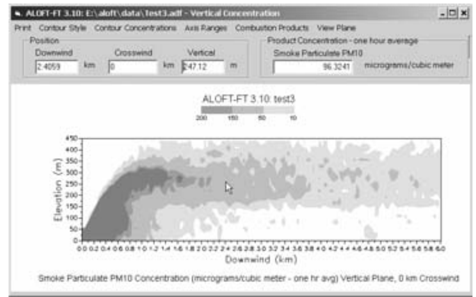
Downwind view of the simulated smoke plume from the second ACS emulsion burn, Prudhoe Bay, September 1994.

In 1994, the State of Alaska used the results of this BFRL research as a basis for revision to their guidelines for approval of in-situ burning [15]. In the state guidelines BFRL's research is cited as:

Based upon the finding of the NIST report, "SmokePlume Trajectory from In-Situ Burning of Crude Oil in Alaska," the ARRT [Alaska Regional Response Team] has set a worse case, conservative downwind distance of 10 kilometers or approximately 6 miles as the primary value for "a safe distance" to conduct burning operations away from the human population... This distance may be modified (decreased or increased) after evaluating spill specific data such as location of spill, type of oil, and stability class of current meteorological conditions. If the burn involves either Cook Inlet or North Slope Crude and is located on the North Slope or in South Central Alaska, i.e., Cook Inlet/Prince William Sound, values from Table 7 [Burn Scenarios] of the NIST report, which presents a summary of smoke trajectory runs, may be utilized with a safety factor of 2X. Table 7 is included as an attachment to this review checklist.

To put the capabilities of performing smoke trajectory calculations in the hands of responders for the purpose of assessing the acceptability of initiating in-situ burning considering specific conditions at a site, BFRL developed the ALOFT-FT smoke plume trajectory software for personal computers [16,17]. This software produces trajectory predictions and downwind particulate concentrations within the uncertainty of the computations performed with more powerful computers at BFRL, but is capable of being run on portable computers in the field. A user-friendly interface was developed to allow users to input available data from site measurements or simply observations so that the calculation could be as specific to the incident as possible. Responders found the graphic output (see figure) provided by the model useful in explaining the findings of the calculations to local authorities for approval for intentional burning. Results from the ALOFT-FT model were used by local officials in the decision to intentionally burn fuel onboard the freighter, New Carissa grounded in Coos Bay, Oregon in February 1999. Burning was the only response option feasible to reduce the potential for a disastrous oil spill from the imminent breakup of the ship. The ALOFT-FT model was cited by the on-scene scientific advisors as providing the timely and critical information about the impact of burning on air quality.

Equally important to the quality of the computations was the quality and clarity of the graphic presentation of the results. The ALOFT-FT software provided information on the smoke plume trajectory and downwind concentrations in a manner that could be easily understood by local officials and public interest groups involved with the incident. The combined visual presentation of technical results provided by ALOFT-FT, the long history of verification testing, and the reputation of NIST as a source of high quality measurement and prediction technology provided the confidence for approval of intentional burning. This incident is the first time that intentional burning received wide spread publicity in the United States as a spill mitigation technique. Removing oil from the ship by burning helped to prevent millions of dollars of shoreline clean-up costs that would have occurred as the grounded vessel, battered by waves ruptured and split into two pieces shortly after the burns.



Example output screen from the NIST ALOFT-FT personal computer software used to quantify down wind particulate concentrations from large fires.

NIST measurement and prediction efforts have played a major role in establishing in-situ burning as an oil spill response method for use in the United States to minimize the pollution from oil spills. The better understanding of oil spill burning and the consequences produced by the NIST research enabled guidelines to be established whereby in situ burning is now considered to be a primary oil spill response technology. Burning is no longer regarded as an oil spill response method of last resort. Important data has been generated to quantify the smoke particulate in large fire plumes. Methods have been developed to reliably predict the downwind concentrations of particulate transported by wind blown fire plumes. Tools have been developed to make this information accessible and usable by the fire and oil spill response communities.

William (Doug) Walton received the Bronze Medal Award of the Department of Commerce in 1993 for leadership of field tests of burning of oil spills. David Evans received the Silver Medal Award of the Department of Commerce in 1995 for his leadership of experimental and analytical studies of burning of oil spills and of implementation of the techniques with state and federal environmental regulatory agencies.

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11.14 ZONE FIRE MODELING

The origin of zone fire modeling using computers dates back to 1976 with the publications and talks given by Quintiere [1], Reeves and MacArthur [2], Mitler [3], and Pape and Waterman [4]. Of these early models, only Harvard 3 developed by Emmons, Mitler, and Trefethen [5] survives today as a substantially revised model, FIRST [6]. These early computer models ran on mainframe computers: an inconvenient format to distribute to the fire community. Other early models developed at NIST include: ASET by Cooper and Stroup [7], DETACT by Evans and Stroup, and later the multiroom models by Tanaka [8], Harvard VI by Emmons and Mitler [9], and FAST by Jones [10].

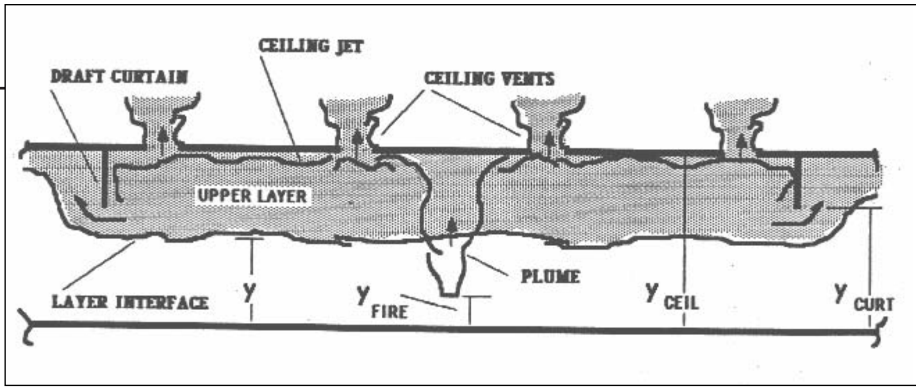
When the IBM PC was developed, Walton recognized that NIST's fire programs could be moved from the mainframe computers to the PC and made available to the fire protection engineering community. Walton simplified ASET and rewrote it to run on a PC. The new program, ASETB [11], became one of the most widely used fire programs ever released by NIST. DETACT was converted to DETACT-QS by Walton and Stroup [12] and DETACT-T2 [13] by Evans and Stroup. Both programs would run on a PC. These programs are used today and are part of NFPA 204, 2002.

Walton started a computer bulletin board for the NIST computer programs and modified most of the existing mainframe programs such that they could run on the PC. He provided documentation for each program and a description on how to use the program. This effort made available NIST's fire programs to the fire protection community. Stroup and Davis converted Harvard 5 to run on a PC. The new program was renamed FIRST. At the time, it was the most complete fire model from a fire physics standpoint and was the first zone model to provide a self-consistent model of the fire.

Gross and Davis used FIRST to model STARK, the USS Stark (FFG 31) 1987 shipboard fire caused by an Iraqi Exocet missile striking the frigate. FIRST was used because other NIST fire models did not have adequate fire physics to give realistic answers. During this project, Davis rebuilt the solvers in FIRST, developed addition fire physics, and released the second version of FIRST [14].

Fire modeling at NIST in the middle to late eighties continued development of the multiroom zone models HARVARD 6 by Rockett and Mitler [9] and FAST by Jones [10], the introduction of a new multiroom zone model CCFM by Forney and Cooper [15], and. the development of a single room fire model LAVENT (Link Activated Vent) by Davis [16] based mainly on a theory developed by Cooper [17]. LAVENT featured new physics that included the activation of fusible links by a ceiling jet that was modified by the presence of a hot layer. The impact of the position of the detector both below the ceiling and radially away from the fire could be predicted. This new algorithm represented an upgrade in sophistication from the program DETACT-QS. LAVENT could be used to estimate the impact of ceiling venting on the upper layer and on detector activation that represented a substantial advancement in zone modeling. Davis wrote a graphics display program, GRAPH, using a NIST developed, Fortran callable graphics package [18] to display the output of LAVENT. LAVENT is in use today and featured in NFPA 204, 2002.

With the increasing fiscal constraints of the early nineties, it was decided that only one multi-room zone model should be developed. Forney and Jones merged FAST [10] and CCFM [15], taking the best from each, to produce CFAST [19]. An upgrade occurred for CFAST as Forney, Peacock, and Reneke changed the model structure, solver and added new fire physics. Later, Forney added a sophisticated radiation package and a corridor algo-



An example of a fire scenario that demonstrates much of the fire physics included in LAVENT.

rithm. Today, CFAST is one of the leading multi-room zone models and is used worldwide.

FPETool was being developed in the early nineties by Nelson and Deal [20]. The model was based on the ASETB zone model and included a number of algebraic algorithms to provide a toolbox for the fire protection engineer. This model became one of the most widely used models of the nineties.

In the middle nineties, Gott of the Naval Facilities Engineering Command and Notarianni of NIST devised an experimental program to examine fire detection in military hangars [21]. Davis was brought into the program to model the experiments as preplanning for instrument placement and fire sizes. Davis used the computer models LAVENT and Harwell FLOW3D [22] to examine instrumentation and fire sizes for the two hangars that were located in Hawaii and Iceland. Gott and Notarianni, working with major industrial partners, allowed BFRL to test a number of different heat detectors, smoke detectors, UV/IR detectors and slow and fast actuating sprinkler links. Notarianni and Davis designed the experimental fires such that threshold effects for detector activation could be studied. These experiments were unique due to the variety of devices tested, the threshold effects for detectors demonstrated in the experiments, the extensive use of scientific monitoring devices to clarify the detector behavior, and the quality of the experiments that provided a basis for further model development.

In analyzing the Navy hangar experiments, it was evident that none of the zone fire models could perform an adequate job predicting the plume centerline temperatures or the ceiling jet temperatures reached by the largest fires. Davis developed a method to model these experiments using a substitute source theory for plume temperatures developed by Evans [23] and a variable radiation fraction as a function of fire size based on experiments by Yang et. al. [24]. The resulting algorithm represented a substantial step forward in modeling fire phenomena when a hot layer was present. Davis used the Navy data to develop a new

Fire test, in a Navy aircraft hanger, Keflavik, Iceland, to determine how the latest generation of fire detectors and sprinkler heads respond to increasing sizes of fires. Many of the team members shown in the photograph are from NIST, other organizations that made hangar experiments possible include: members from The Naval Facilities Engineering Command, The Naval Air Stations at Keflavik, Iceland and at Barbers Point, Hawaii, The U. S. Air Force, the U. S. Marine Corps, The U. S. Army Corps of engineers, Simplex Time Recorder Co., The Viking Corporation, Detector Electronics Corporation, Detection Systems, Inc., and Alison Control, Inc.

ceiling jet model and packaged the new fire physics in a zone model, JET [25] that used many of the older algorithms of LAVENT. JET was the first of the zone models to use Microsoft Visual Basic to build a user input module.

The Navy data also proved useful in demonstrating that CFAST was predicting too high of temperatures. The earlier data sets that were used for FAST and CFAST did not have the instrumentation to demonstrate this problem convincingly. Paul Reneke found and corrected the error.

The Navy hangar data has been used as an aid in the design of fire protection for high ceiling structures worldwide. Based on the information collected in the project, fire protection design was substantially changed in military hangars. It ranks high in NIST fire experiments that impacted fire protection engineering.

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12. FIRE SCIENCE

12.1 FIRE GRANTS

The CFR Grants Program was initiated in 1975 with funds from the plastics industry, and then in 1976 augmented by transfer of the fire program of the National Science Foundation's Research Applied to National Needs (RANN) project. This transfer was made with the understanding that the NSF funds would continue to be used for a grants program.

The NSF RANN program, developed and managed by Ralph Long, was focused around "Centers of Excellence." Primary among them were the Harvard University-Factory Mutual Insurance Corporation joint effort led by Professor Howard Emmons, Johns Hopkins Applied Physics Laboratory led by Professor Walter Berle, Princeton University led by Professor Irvin Glassman, University of California Berkeley led by Professor Patrick Pagni, and California Institute of Technology led by Professor Edward Zukoski. Each lead professor became an expert in the field of fire, and with his graduate students contributed major research papers, participated in the yearly CFR research conference, and in sessions and publications of other technical societies. The graduate students frequently went on to become experts in fire protection, professors at other institutions or new staff members at CFR.

There were individual grants as well on specific research projects. These varied such that in any typical year, 20 percent to 30 percent of the program was in new grants.

Initially, the CFR program was administered by Clayton Huggett with yearly proposals from the principal investigators reviewed by CFR staff members with frequent review, evaluation and use of the results by CFR staff engaged in related research. Subsequently the program was managed by Robert Levine. Administrative matters were handled by Sonya Cherry of CFR who worked with the financial officers of the grantee organizations and the procurement staff at NBS. When questions arose about financial or administrative matters, Sonya Cherry's records and CFR procedures proved to be faultless. For these efforts, she received the Bronze Medal Award of the Department of Commerce in 1981.

The technical results of the program were outstanding. The Harvard-Factory Mutual Program, for instance, produced the first U.S. zone models of fire growth within a compartment (Harvard Fire Code V) and within a series of compartments (Harvard Fire Code VI). These became the bases for the Hazard software for the engineering design of fire safety systems for various occupancies. A series of research tasks described parts of the fire process in algorithms suitable for use in fire models. For instance, the California Institute of Technology developed a mathematical description of the buoyant plume and of buoyancy-affected flow in corridors.

For much of its life, this program was deprecated by other parts of NBS as a distraction from research to program management. However, they did not distract CFR personnel from research but put them into collaborative research relationships addressing the CFR program with outstanding peers.

The grant program enlisted the support of the best brains in the country for fire research and trained a new generation of highly talented people for the fields of fire research and fire protection.

When the Federal Emergency Management Agency (FEMA) was formed, support of grants for fire fighting science and technology was transferred to FEMA, which divided the work at the Applied Physics Laboratory (APL) into two programs. Both programs died because APL management could not cope with the financial problems created by FEMA's late contracting. However before this, APL in cooperation with Johns Hopkin's Medical School and Maryland's Medical Examiner performed pioneering work on toxicology of fire gases through studies of fire victims. The results led to the use of breathing apparatus by fire fighters during operations and overhaul of fire scenes.

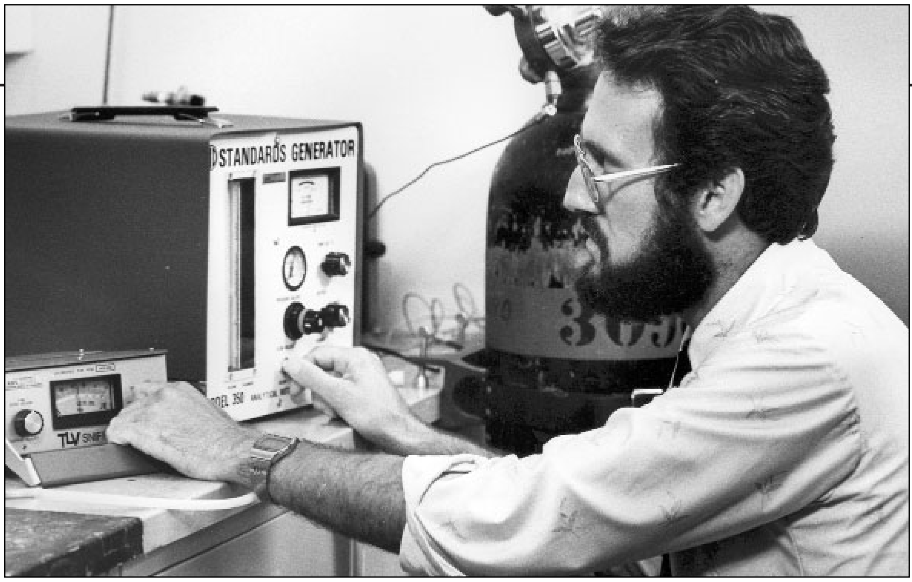
The nature and scope of the Fire Grants program changed as its funding was reduced in parallel with CFR funding during the budget crises of the 1980s. Funding declined from $2 million annually to $1.34 million annually, and the decrease was exacerbated by the effects of inflation on research costs. The Centers of Excellence disappeared as their principal investigators retired. The Grants Program continues as external projects developed in cooperation with BFRL group leaders to complement the BFRL fire research program.

12.2 MEASURING THE TOXICITY OF FIRE SMOKE

The creation of the NBS Center for Fire Research in 1975 made possible for the first time a technological assault on the United States fire loss record, which was the worst in the industrialized world. From the outset, the new Program sought to maximize its impact by focusing on the factors giving rise to the most prevalent fire loss scenarios.

Early analyses of the causes of fire deaths had indicated that most fire fatalities resulted from smoke inhalation rather than burns. Scientists at NIST [1], elsewhere in the U.S. and overseas then began to identify the chemicals produced during the pyrolysis and burning of the materials that make up interior finish and common household furnishings. They soon discovered that literally hundreds of chemicals were produced, some of which were known to cause harm when inhaled. Toxicologists quickly began a variety of experiments using laboratory animals to determine the potential of fire smoke to cause incapacitation and death.

Much of this work was sponsored in the early 1970s by the National Science Foundation under the Research Applied to National Needs (RANN) program. This research grants program was transferred to the NBS in 1976. One of their four centers of excellence was at the University of Utah under the leadership of Professor Irving Einhorn. The Utah team found that smoke from a particular burning material produced smoke so toxic that even a small amount caused debilitation and death in lab mice. They dubbed the harmful component from this type of material a supertoxicant.



Merritt Birky calibrating a combustible vapor detector.

Almost immediately, fire toxicology research became directed at identifying any materials that produced supertoxicants (just as many other fire tests were designed to identify materials with unusually high flame spread rates, etc.) so that regulations could ban their use. Nearly 30 research groups worldwide developed apparatus for combusting small samples of materials and exposing the smoke to laboratory animals.

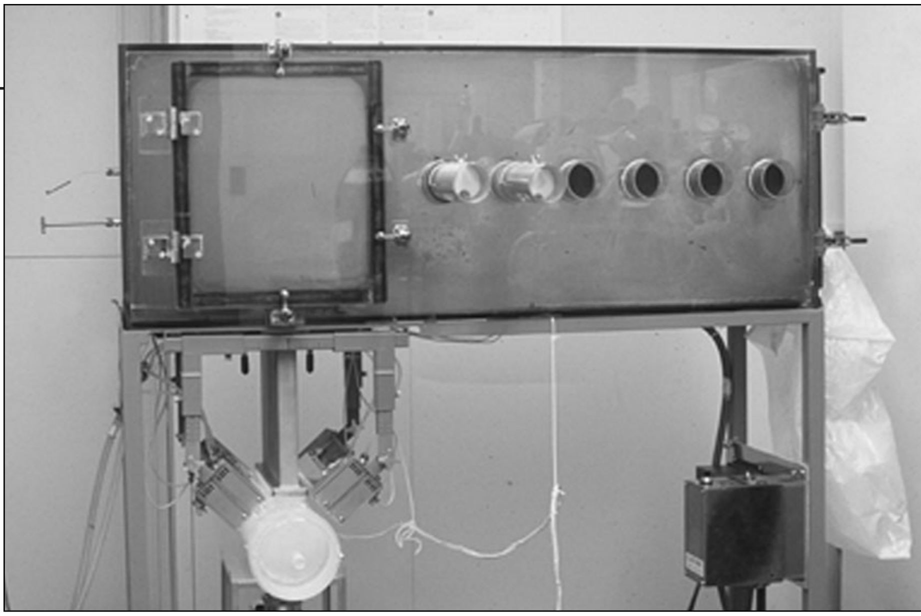
Barbara Levin, leader of smoke toxicity research.

Realizing that the toxic potency of smoke was only one input to the calculation of fire hazard, NBS began to develop a test method that could be used to provide that input and to screen for materials whose smoke toxic potency merited special attention. The work was led initially by Merritt Birky, and upon his departure from NBS was completed under the leadership of Barbara Levin. The NBS Toxicity Test Method (alternately known as the Cup Furnace Method), published in 1982 [2], exposed rats to the smoke from test specimens that were pyrolyzed or autoignited.

Concurrently, the CFR was sponsoring research into combustion toxicity in Professor Yves Alarie's group at the University of Pittsburgh. They developed a test method [3] in which mice were exposed to the evolved gases from a specimen combusted in a tube furnace. Listing of data using this method was required in 1986 by the State of New York as a condition for allowing building materials to be sold in the State; the requirement has since been dropped.

The field of fire hazard analysis was advancing rapidly in the late 1970s and into the 1980s. In 1989, NBS released the first version of HAZARD I, a methodology for predicting the threats to life in a building fire [4]. New findings enhanced the quality of the toxic hazard component of overall fire hazard. The Southwest Research Institute under the sponsorship of the Vinyl Institute, published data showing that hydrogen chloride could be lost to wall deposition as the smoke moved further from the fire source. Autopsy evidence accumulated, showing that carbon monoxide and hydrogen cyanide levels in the blood of fire victims were frequently at lethal levels [5]. Yoshio Tsuchiya of the National Research Council of Canada proposed that the toxicity of fire smoke could be estimated by the sum of the contributions of all the gases in the smoke.

At NBS, Barbara Levin began a series of animal (rat) experiments to quantify Tsuchiya's hypothesis. As her results began to emerge [6,7], Richard Gann of NBS suggested that one need not consider all the gases, but rather that a small number, N, of these might well account for almost all of the lethal effect and that an animal check test would reveal the validity of this concept. The use of an "N-gas model," with input data based on Levin's experiments soon became the preferred input for fire hazard estimations [8]. Barbara Levin's pioneering research into the combined effects of



NIST-developed apparatus for measuring the toxic potency of fire smoke. Now standardized as NFPA 269 and ASTM E1678, it is the only validated smoke toxicity test in the world.

smoke components was also a bellwether in the wider field of combined physiological effects of mixed gases.

During this same time period, fire science was emerging as a disciplinary field. Practitioners at NBS and elsewhere soon realized that (a) complex commercial products might not behave in a manner that could be constructed from their component materials and (b) the combustion conditions in the cup furnace and most of the other toxicity measurement devices did not closely resemble the conditions under which products were exposed in most fatal fires. Fire incidence data showed that most fatalities resulted from fires that had passed beyond flashover, the point at which multiple fuels were involved and their combustion was ventilation limited [9]. The thermal input to the fuels was largely radiative.

Thus, NBS developed a next-generation bench-scale toxic potency measurement method [10]. The combustor was radiant, based on a 1990 design of Arthur Grand of the Southwest Research Institute for the National Institute of Building Sciences. The rat exposure chamber was that of the cup furnace method. NBS staff under the leadership of Vytenis Babrauskas and Barbara Levin, developed a novel procedure for use of the apparatus.

Babrauskas next led development of a laboratory protocol to quantify the ability of bench-scale devices to reflect the potency of commercial products in real-scale fires. His team constructed five criteria for considering the accuracy of the bench-scale toxic potency data. They then showed that the radiant apparatus was superior to the Cone Calorimeter and the cup furnace in this respect, replicating the real-scale data within about a factor of three for the most conservative agreement criterion [11]. In 1997 under Gann's leadership, this method became the first (and still only) one adopted by U.S. national standards bodies as ASTM E1678 [12] and NFPA 269 [13]. Over twenty years after NBS began the enabling research, there was now a method of known accuracy for obtaining lethal toxic potency data for fire hazard and risk analyses.

There was concurrent activity on smoke toxicity in the international arena, mostly taking place in ISO Committee TC92, Subcommittee 3 on Fire Threat to People and the Environment. The contentious issue was the drafting of a document on smoke incapacitation data for use in estimating the time available for escape. An extremely restrictive version of the document had been voted down as an ISO Standard in 1999, largely because of poor resolution over what was and was not known about the sublethal effects of fire effluent. This shortcoming triggered a major project under the Fire Protection Research Foundation to provide technical resolution. Led by NIST, the project's first report was issued in 2001[14]. Under the leadership of Gordon Hartzell, retired Director of the SwRI Department of Fire Technology, and Gann, the ISO document was heavily revised to reflect these latest findings and new fire hazard analyses. It was approved in 2001 as an ISO Technical Specification [15] and will again be considered as an International Standard in 2004.

Today, fire smoke toxicity is routinely included in engineering estimations of fire hazard and risk. The drive to quantify and validate these data can largely be attributed to NBS/NIST metrology.

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12.3 MEASUREMENT OF HEAT RELEASE RATE

Intuitively, the rate of heat release from an unwanted fire is a major indication of the threat of the fire to life safety and property. This indeed is true, and a reliable measurement of a fire's heat release rate was a goal of fire researchers at NBS and other fire laboratories at least as early as the 1960s. Traditionally, heat release measurements of burning materials were based on the temperature rise of ambient air as it passed over the burning object. Because the fraction of radiant emission varies with the type of material being burned, and because that energy does not all contribute to temperature rise of the air, there were large errors in the measurements. Attempts to account for the heat that was not captured by the air required siting numerous thermal sensors about the fire to intercept and detect the additional heat. This approach proved to be tedious, expensive, and prone to large errors, particularly when the burning "object" was large, such as a full-sized room filled with flammable furnishings and surface finishes.

During the 1970s a novel alternative technique for determining heat release rate was developed at NBS. It had distinct advantages over the traditional approach, but its widespread acceptance was hampered by uneasiness in the fire science community concerning potential errors if the technique were used in less-than-ideal circumstances. In 1980, Clayton Huggett [1], fire scientist at NBS, published the seminal paper that convinced the fire science community that the new technique was scientifically sound and sufficiently accurate for fire research and testing. The technique now is used worldwide and forms the basis for several national and international standards.

The underlying principle of new heat release rate technique was "discovered" in the early 1970s. Faced with the challenge of measuring the heat release of combustible wall linings during full-scale room fire tests, William Parker, Huggett's colleague at NBS, investigated an alternative approach based on a simple fact of physics: In addition to the release of heat, the fire process consumes oxygen. As part of his work on the ASTM E 84 tunnel test, Parker [2] explored the possibility of using a measure of the reduction of oxygen in fire exhaust gases as an indicator of the amount of heat released by the burning test specimens. Indeed, for well-defined materials with known chemical composition, heat release as well as oxygen consumed can be calculated from thermodynamic data. The problem with applying this approach to fires is that in most cases the chemical compositions of modern materials/composites/mixes that are likely to be involved in real fires are not known. In the process of examining data for complete combustion (combustion under stoichiometric/excess air conditions) of the polymeric materials with which he was working, Parker found that although the heat released per unit mass of material consumed (i.e., the heat of combustion) varied greatly, the amount of heat released per unit volume of oxygen consumed was fairly constant, i.e., within ±15 percent of the value for methane, 16.4 MJ/m^3 oxygen consumed.

This fortunate circumstance—that the heat release rate per unit volume of oxygen consumed is approximately the same for a range of materials used to construct buildings and furnishings—meant that the heat release rate of materials commonly found in fires could be estimated by capturing all of the products of combustion in an exhaust hood and measuring the flow rate of oxygen in that exhaust flow. The technique was dubbed oxygen consumption calorimetry, notwithstanding the absence of any actual calorimetric (heat) measurements.

Later in the decade, Huggett performed a detailed analysis of the critical assumption of constant proportionality of oxygen consumption to heat release. Parker's assumption was based on enthalpy calculations for the complete combustion of chemical compounds to carbon dioxide, water, and other fully oxidized compounds. Indeed, a literature review by Huggett revealed that Parker's findings were actually a rediscovery and extension of Thornton's work [3], published in 1917, which found that the heat released per unit of oxygen consumed during the complete combustion of a large number of organic gases and liquids was fairly constant. Nevertheless, since in real fires and fire experiments the oxygen supply is sometimes limited, incomplete combustion and partially oxidized products can be produced. Huggett's paper examined in detail the assumption of constant heat release per unit of oxygen consumed under real fire conditions and assessed its effect on the accuracy of heat release rate determinations for fires.

Instead of expressing results on a per unit volume basis, as Parker did, Huggett expressed results in the more convenient and less ambiguous per unit mass of oxygen consumed. Huggett began by presenting values for the heat of combustion and heat of combustion per gram of oxygen consumed for typical organic liquid and gas fuels, assuming the products are CO_2, H_2O, HF, HCl, Br_2, SO_2, and N_2. Notwithstanding large variations in the heat of combustion (up to a factor of 4) for this group of fuels, the heats of combustion per unit mass of oxygen consumed fell within ± 3 percent of their average value of 12.72 kJ/g (O_2). Huggett explained that this near constancy was not surprising because the energetic processes are the result of breaking either carbon-carbon or carbon-hydrogen bonds, and these bonds have similar energetics.

An examination of the same data for typical synthetic polymers, some of which Parker did not consider, produced similar results; for this class of materials the heats of combustion per unit mass of oxygen consumed fell within ±4 percent of their average value of 13.03 kJ/g (O_2). Fuels of natural origin (e.g., cellulose, cotton, newsprint, corrugated box, wood, etc.), that are likely to be found in large quantities in building fires, have heats of combustion per unit of oxygen consumed that range within ± 5.3 percent of their average of 13.21 kJ/g (O_2).

The results presented so far assumed complete combustion. Huggett explored the effects of incomplete combustion on the assumption of constant heat release per unit of oxygen consumed. He did this by making several conservative but realistic assumptions concerning incompleteness of combustion for a range of materials likely to be found in a structural fire. For example, carbon monoxide often is present in a fire's combustion products, but usually at a very low level and rarely exceeds 10 percent of the carbon dioxide concentration produced by the fire. Huggett then calculated the heat of combustion per unit of oxygen consumed for the burning of cellulose in limited air, such that the carbon monoxide concentration was about 10 percent of the carbon dioxide concentration. The result was 13.37 kJ/g (O_2) compared with 13.59 kJ/g (O_2) for the excess air case. The difference was very small and, if necessary, could be corrected if the carbon monoxide concentration was measured.

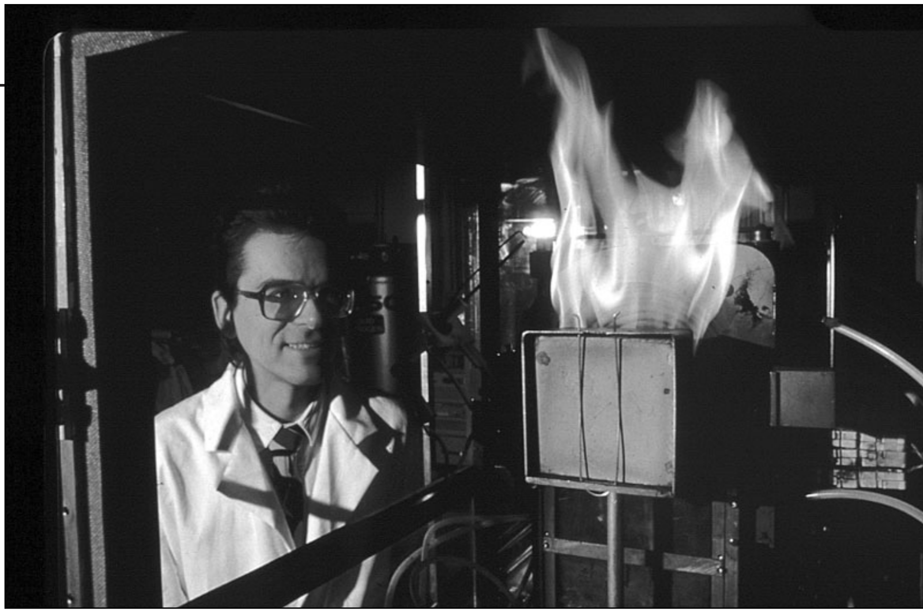
Another consideration was that cellulosic fuels tend to form a carbonaceous char that can affect heat release rate. By examining a hypothetical reaction that forces production of pure carbon, Huggett demonstrated that the effect was small; 13.91 kJ/g (O_2) when pure carbon was produced verses 13.59 kJ/g (O_2) when the reaction took place in excess air.

Other partial oxidation reactions can occur and affect the heat release rate. Huggett argued that although their details are unknown, their effects could be assessed via representative examples; noting that the actual material in the example was not important since only the chemical bonds that were rearranged by the reaction significantly affected the results. He considered partial oxidation of propylene, polyacrylonitrile (produces hydrogen cyanide under some combustion conditions), and polytetrafluoroethylene and argued that under worst-case conditions the heats of combustion per unit oxygen consumed range from 10.76 kJ/g (O_2) to 13.91 kJ/g (O_2) and if present in small quantities would not introduce a significant error in heat release based on oxygen consumption. All these scenarios were considered 'limiting cases'; the effect in real fires usually would be less than presupposed in the analyses. In situations where large quantities of incomplete combustion products were produced, corrections could be made if these products were measured.

Huggett concluded that the assumption of constant heat release rate per unit mass of oxygen consumed would be sufficiently accurate for most fire and fire-test applications. For fires burning conventional organic fuels, Huggett recommended the constant 13.1 kJ/g (O_2), which should produce heat release rate results accurate to ±5 percent or better. Ever since its publication, this value has been the accepted value for oxygen-consumption calorimetry when burning conventional materials.

Huggett examined other factors that influence the overall accuracy of oxygen consumption calorimetry. For example, dilution by products of combustion in the exhaust flow, where the oxygen concentration measurement is made, is a source of error because the number of moles of products is not the same as the number of moles of oxygen consumed. This 'dilution factor' is a function of the fuel's stoichiometry and can be taken into account if the stoichiometry is known. In general, however, this is not the case and the dilution factor must be estimated. Through analysis of 'limiting' cases, Huggett reasoned that if an appropriate dilution factor were not available, then assuming a value of 1.6 would lead to an error of less than six percent in the amount of oxygen consumed.

The paper by Huggett was published just as the rate of heat release was beginning to be recognized as the central property affecting fire growth [4]. The novel new technique was rapidly incorporated by Babrauskas and Twilley [5] in their invention of the



Vytenis Babrauskas, fire protection engineer and developer of the cone calorimeter, is collecting data critical to predicting the fire hazard of a product using a small sample of material. This test replaces time-consuming and expensive full-scale tests. ASTM and ISO adopted a voluntary fire hazard test method based on the instrument.

Cone Calorimeter, a bench-scale device now used worldwide for heat release rate measurements. It also became the technique used in fire calorimeters of larger (room) size at NIST and at most fire laboratories throughout the world. The oxygen-consumption technique forms the basis for several national (ASTM [6], NFPA [7]) and international (ISO [8]) standards.

Department of Commerce Medal Awardees received for this work include: the Bronze Medal to William Parker in 1976 for the concept of measurement of heat release rate; the Bronze Medal in 1984 to William Twilley for design and construction of the cone calorimeter; and the Bronze Medal in 1986 to Vytenis Babrauskas for the conception and standardization of the cone calorimeter. Babrauskas also received the NIST Rosa Award in 1992 for the contributions of heat release rate and the cone calorimeter to fire standards, worldwide.

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12.4 SMOLDERING COMBUSTION

Smoldering combustion has arisen as a fire safety issue in two principal contexts. The first is as a pathway for the initiation of destructive upholstered furniture and bed fires [1]. The threat here arises from the careless use of cigarettes whose own smoldering process can spread into soft furnishings with which they come into contact. The other context arose rather dramatically in the 1970s as a direct consequence of the increased use of thermal insulation materials in buildings to counter the rapidly rising cost of energy. Some of the most popular insulation materials were made from re-cycled newsprint that, if improperly formulated, could begin to smolder as a consequence of exposure to such heat sources as recessed light fixtures. In both of these areas, the life hazard was compounded by the possibility that the smoldering process would develop into a much more rapid flaming process. In both of the contexts, the goal of BFRL research has been to

Thomas Ohlemiller, chemical engineer, examines the results of an experiment to characterize the smoldering combustion of blown-in cellulosic insulation in attic spaces.

understand the basic mechanisms at work in this unique form of combustion so as to assure that test methods are soundly based.

The initial experimental and modeling studies were performed by grantees at MIT [2] and Princeton [3]. Simultaneous experiments at NIST established the fundamental role played by alkali metals as char oxidation catalysts in many practical materials. Thomas Ohlemiller moved to NIST and continued experimental and modeling studies of the variables, which influence smolder initiation [4], propagation rate and the transition from smoldering to flaming combustion [5]. This background was useful when NIST began to study the role that cigarette design parameters [6] have in the initiation of smoldering in soft furnishings; that study is described in more detail under its own heading.

The understanding of smoldering combustion phenomena expressed in the referenced publications and others has helped substantially in the development of appropriate test methods to assess this hazard in various applications. Ohlemiller received the Bronze Medal Award of the Department of Commerce in 1986 for his studies of smoldering combustion.

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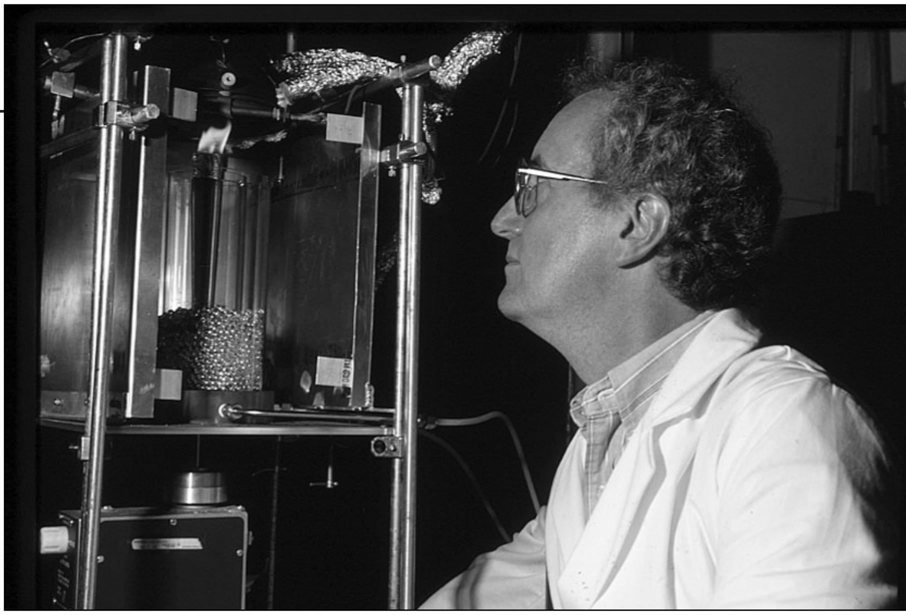
12.5 ADVANCED FIRE MEASUREMENTS

The need for fire metrology has been driven from the earliest days of NBS by building codes, product performance, and fire fighting activities. The objective of our research has been to develop measurement methods for the performance of products and fire control technologies that allow extrapolation of the behavior of these products and technologies to actual building fires. Measurement advances at laboratory-, mid-, and full-scale all have been targeted since accurate predictions only can be achieved by a higher level of understanding of the dynamics of fire and more certain measurement methods.

Predicting how an object will respond in a real fire, how a fire will grow beyond the room of origin, or how well a suppression system will extinguish the flames hinges on the measurement of key properties in and around the fire under carefully controlled conditions. Because the dynamics of fire are strongly non-linear, different measurement methods have



William Grosshandler, mechanical engineer, is using new test methods to quantify the impact of an electrically heated surface on the amount of a gaseous agent necessary to extinguish a burning plastic specimen.

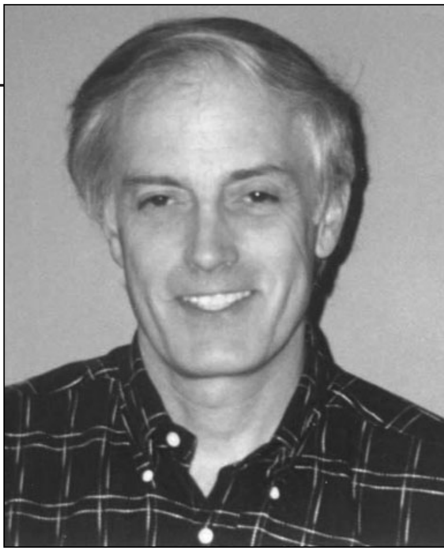
been developed to probe the multiple temporal and spatial scales that reveal the chemical and physical principles guiding fire behavior. Pioneering work was done by Ingberg [1] in the first quarter of the last century, with his measurement methods defining the concept of fire loading and endurance standards used in building codes throughout the world. The single most important characteristic of a fire is the rate of heat release. Huggett [2] developed a practical means to measure this parameter for fires at real scale, based upon the consumption of oxygen in the exhaust products. Oxygen calorimetry is now carried out routinely for fires of all materials, systems, and sizes as large as 10 MW.

Great attention has been paid to the design and scale of fire experiments. An important example is a multi-story house built within the large fire facility to duplicate a multi-fatality fire [3]. Measurements of CO in rooms remote from the fire revealed high levels, consistent with the cause of death but inconsistent with numerical predictions. These measurements led to a new research program focused on explaining this discrepancy.

Measurements of the transformations that occur in solid and liquid fuels prior to and during combustion, such as in the recent work by Nyden [4], promise to reveal mechanisms that can be exploited to increase the fire resistance of materials. The quantity and type of smoke generated by these and other burning materials is the third characteristic (along with the rate of heat release and CO) of great importance. Optical and extractive methods have been developed to measure smoke levels, and these depend upon the precise measurements by Mulholland of the soot morphology and optical properties [5]. The smoke and CO levels are sensitive to the equivalence ratio (symbolized by the Greek letter phi). A unique instrument was developed by Babrauskas et al. [6] to directly measure phi for the first time. Our understanding of the kinetics of soot formation have been greatly enhanced by the detailed spectroscopic species profiles measured by Smyth [7] in a laminar methane flame.

The turbulence associated with jet flames and fire plumes of greater size controls the local mixing process and time available for chemical reactions. Small and large scale turbulent structures have been measured using Rayleigh scattering to explain lift-off and stabilization of hydrocarbon jet flames [8]. As fires get larger and buoyancy dominates, and as fuels become more complex, detailed species, temperature, and flow data become difficult to measure with certainty. Turbulent pool fires are an example of this class, which has been much studied. Hamins et al [9] describe their measurement methods and the data gathered in liquid pool fires of a variety of fuels and sizes. A fire within an enclosure is another class that presents a measurement challenge, especially as the fire becomes underventilated, when the flow through the doorway controls the fire. Steckler and Quintere [10] quantified this flow in a full-scale room fire for the first time. While thermocouple measurements are straightforward to take, proper interpretation of the results and assessment of the measurement uncertainties are complicated in room fires. Blevins and Pitts [11] examined this problem and bracketed the magnitude of the uncertainty in temperature measurements for this situation.

Knowledge of the products of an incipient fire are key to early and certain fire detection. Traditional measurement methods have been used by



Kermit Smyth, leading researcher of chemical structure of flames.

Grosshandler et al [12] to characterize the content of the weak plumes that rise above small, growing fires. During the act of suppressing a fire, measurement of the details of the process are particularly challenging. In response to this challenge and with the desire to find suitable replacements for halon (halogenated hydrocarbon) 1301, several new measurement methods were developed that enabled the Department of Defense to select the best options for protecting military aircraft from in-flight fires [13].

Awards of the Department of Commerce for this work include: Bronze Medal to George Mulholland in 1985 for smoke particle generation and growth mechanisms; Bronze Medal to William Pitts in 1991 for turbulent combustion measurements; Silver Medal to Kermit Smyth in 1992 for measurements of the chemical structure of flames. Smyth also received the NBS Condon Award in 1987 for his seminal paper on the chemistry of molecular growth in flames.

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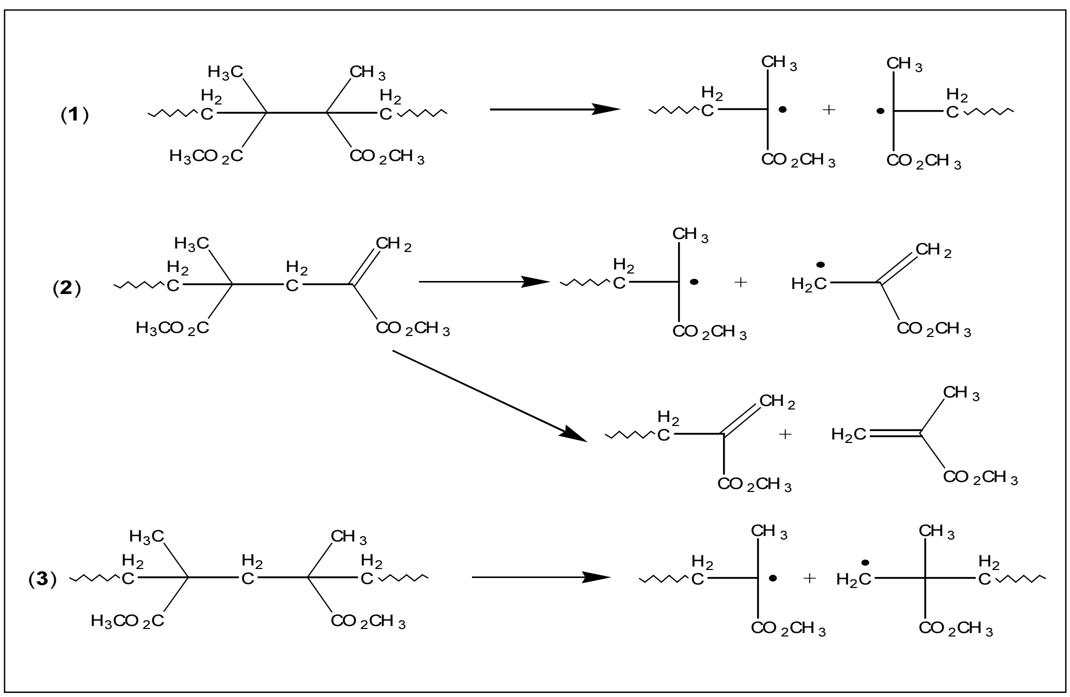
12.6 FIRE SAFE MATERIALS

In recent decades synthetic polymeric materials, because of their unique physical properties, have rapidly replaced more traditional materials such as steel and nonferrous metals as well as natural polymeric materials such as wood, cotton, and natural rubber. However, one weak aspect of synthetic polymeric materials compared with steel and other metals is that these materials are combustible under certain conditions. Thus the majority of polymer-containing end products (for example, cables, TV sets, electric appliances, carpets, furniture) must pass some type of regulatory test to help assure public safety from fire. However, these traditional pass/fail tests have not provided any information regarding the relationship between flammability properties and the physical and chemical characteristics of polymeric materials. Such information is needed to develop more fire-safe materials, a need which has accelerated because of European environmental concerns about the use of halogenated flame retardants (because of potential formation of dioxins in the incineration of spent end products). The paper, Effects of Weak Linkages on the Thermal and Oxidative Degradation of Poly(methyl methacrylate) [1] is one of a series published on this topic by the members of the Materials Fire Research Group at NBS/NIST from 1985 to 1994 [2-11]. These papers represent a new approach that studies the effects of molecular-level structure of polymers on their thermal stability and flammability properties instead of a traditional global thermal-balance approach. This series of studies is built upon the pioneering work on thermal degradation of polymers conducted at NBS from the late 1940s to early 1970s [12].

Providing the technical basis for industrial clients to design less flammable materials requires unfolding the structural features that determine thermal stability. This paper [1] reports a study of the thermal and oxidative degradation mechanisms of an acrylic polymer in atmospheres of nitrogen and air by measuring the change in the sample mass while various specially polymerized samples were heated from 80 °C to 480 °C. Thermal degradation of the acrylic polymer, which was polymerized using a free-radical method, proceeds in three steps of mass loss: the first and easiest (see figure below) is initiated by scissions of head-to-head linkages at about 160 °C (representing one type of defect at the polymer backbone); the second (scheme 2) by scissions at the chain-end initiation from vinylidene ends at around 270 °C; and the last (scheme 3) by random scission within the polymer chain (at the weakest bonds).

The first two mass loss steps were not observed with ionically polymerized samples, which indicates that the first two steps are caused by the defects in the polymer. Although the existence of head-to-head linkages could not be demonstrated, the vinylidene ends in the polymer were detected by the HNMR spectrum. No significant differences were seen in the thermal or oxidative degradation of the acrylic

Three proposed thermal degradation steps of PMMA.



polymer when it was polymerized with the free-radical method using two common initiators. It was found that gas-phase oxygen traps polymer radicals resulting from chain scissions at head-to-head linkages, and no mass loss was observed from this step in air. Similarly, oxygen traps radicals generated by end initiation, but mass loss is only delayed to slightly higher temperatures, presumably because of a slight gain in the thermal stability of the oxygen-trapped polymers compared with end initiation.

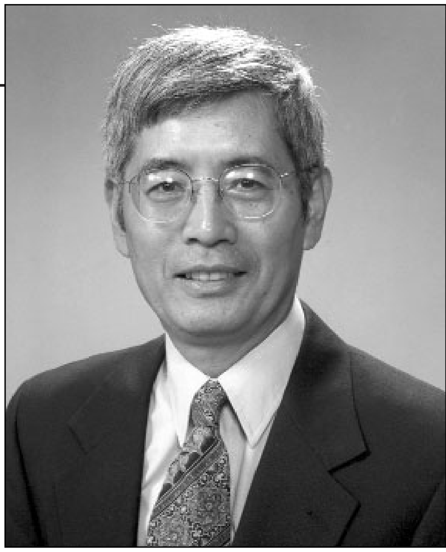
This series of studies involved not only experimental observations but also theoretical calculations in which kinetics equations were solved for each polymer chain. Detailed thermal degradation models were developed based on random initiation, depropagation of free radicals, and termination of free radicals; calculations were made with the assumption of steady-state free radical concentration [4] and without that assumption [5]. The kinetic rate constants for each reaction were derived by comparing experimentally measured molecular weights of polymer samples collected at various temperatures and exposure times with the theoretically calculated results [6]. The final paper of the series on thermal degradation investigated the behavior of primary radicals generated from random scissions by measuring evolved degradation products with a mass spectrometer [9].

Fire Materials Research Group, 1994

The influence on thermal stability by the above-discussed defects in the polymer have been studied and published [7,8,10]. The results show that a higher thermal stability increases piloted-ignition delay time and gasification rate of the polymer, but initial molecular weight does not affect ignition delay time. On the other hand, initial molecular weight of the polymer has significant effect on flame spread rate because low molecular weight materials will flow more readily when heated. The physical and chemical roles of the condensed phase in the burning process of polymeric materials were published as a summary of this series of studies [11].

The molecular-level study of the thermal degradation and flammability properties of polymers described above was pursued further by Marc Nyden and coworkers at NIST. They used molecular dynamic simulations of thermal degradation of polyethylene to identify factors that might be effective in reducing polymer flammability by promoting the formation of residual char [13]. The results predicted that the formation of cross-linking, for example by exposure of polyethylene to ionizing radiation, enhanced further cross-linking when the polymer is burned. An increase in ignition delay time was observed for irradiated polyethylene samples compared to unexposed samples. A similar approach has been pursued by Charles Wilkie at Marquette University, Richard Lyon at the FAA Technical Center, and James McGrath at Virginia Polytechnic Institute and State University.

Because of the increasing demand for non-halogenated flame retardant additives for polymeric end products, this molecular-level study has been extended to include flame retardant mechanisms of polymers containing small quantities of inorganic flame retardant additives. As a result of advancements in nanoscale science and technology, molecular-level studies of the effects of trace additives in clay-polymer nanocomposites are demonstrating enhanced physical properties with simultaneous improvements in the



Takashi Kashiwagi pioneered research in ignition and flame spread in microgravity and contributed significantly to understanding the combustion of polymeric materials and the mechanisms of flame retardants.

flammability properties of polymers. This contrasts with the traditional approach that improves the flammability but often degrades mechanical properties.

The study described in this paper involved the synthesis of specific polymers, analytical characterization of the synthesized polymers, and careful thermogravimetric analysis. Two different groups, the Materials Fire Research Group at NIST and Department of Chemistry at Osaka University, contributed their own expertise to this highly collaborative undertaking. The group at Osaka University synthesized and characterized all polymer samples used in the study, while the group at NIST performed the thermogravimetric analyses.

Takashi Kashiwagi joined NBS in 1971 after he received his Ph.D. from Princeton University. He was a group leader from 1988 to 1998 in the Fire Science Division. He is currently a materials research engineer working on improved fire-safe materials, as well as studying ignition and flame spread in a microgravity environment. He was a principal investigator of the ignition and flame spread experiment conducted on Space Shuttle flight STS-75. Atsushi Inaba received his Ph.D. in chemical engineering from Tokyo University in 1981 and was a guest scientist at NBS from May 1984 to March 1986. He is currently Director of the Research Planning Office of the National Institute for Resources and Environment in Japan. James E. Brown joined the Polymer Division of NBS in 1956 as a research chemist, moved to Fire Science Division in 1975, and retired in 1996. Koichi Hatada, a professor in the Department of Chemistry at Osaka University, was known internationally for his work on stereoregular and living polymerization and copolymerization. He retired from Osaka University in 1998 after serving as vice president of the University. Tatsuki Kitayama is a professor in the Chemistry Department of Osaka University. Eiji Masuda was a student under Professor Hatada and is currently a senior research scientist at Polyplastics Company in Japan.

Alexander Robertson received the NBS Rosa Award in 1978 for career contributions to standards for materials flammability test methods. Clayton Huggett received the Department of Commerce Silver Medal Award in 1978 for studies of flame inhibition, and William Bailey received the Bronze Medal Award for laboratory support of these and other fire studies. Takashi Kashiwagi received the Department of Commerce Bronze Medal Award in 1982 for studies of radiant ignition, the Silver Medal Award in 1991 for characterization of flame spread, and the Gold Medal Award in 2000 for flame retardants principles and models. James Raines received the Bronze Medal in 1982 for laboratory automation support of these and other fire studies. Kashiwagi also received the NIST Applied Research Award in 1991 for studies of the thermal degradation of plastics. Marc Nyden received the Bronze Medal Award in 1993 for his studies of computational molecular dynamics. Jeffrey Gilman received the Bronze Medal Award in 1999 for his studies of nanocomposites.

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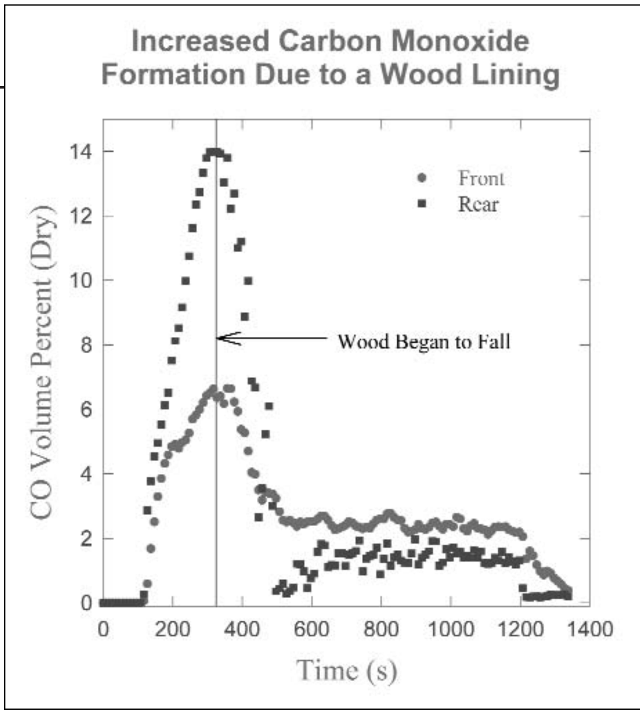
12.7 CARBON MONOXIDE FORMATION IN FIRES

Fire safety research has been ongoing at NIST since its founding one hundred years ago. This research has traditionally been focused on understanding fire behavior and developing tests to improve fire safety. By the early 1970s the understanding of fire behavior had advanced sufficiently that the development of engineering models capable of predicting the behavior of fires in buildings could begin. By the late 1990s modeling capabilities had been developed to a point where governing bodies were willing to consider performance based codes, which require engineering estimates of fire safety, in lieu of existing prescriptive codes.

Major components of fire safety engineering are human behavior and safety. Even though fire was a serious problem claiming thousands of lives each year, the causes of fire deaths were not well characterized during the first half of the last century. By the 1970s studies were indicating that most fire deaths were the result of smoke inhalation and not burns. The vast majority of victims of smoke inhalation were found to have carbon monoxide (a molecular species known to induce hypoxia) levels in their blood streams sufficient to cause incapacitation and/or death. Even though these studies suggested that the formation of carbon monoxide was responsible for a significant fraction of fire deaths, very little was known concerning the amounts formed or the physical mechanisms responsible for its generation. As a result, it was nearly impossible to model the effects of a fire on potential victims.

Recognizing the importance of carbon monoxide formation in fires, CFR initiated a long-term project aimed at identifying the mechanisms of carbon monoxide formation in fires and developing methodologies for predicting the levels generated [1, 2]. The principal investigator was William M. Pitts who worked with a number of BFRL staff including Nelson Bryner, Erik Johnsson, George Mulholland, and William Davis.

The starting point for the project was seminal research carried out at Harvard University and the California Institute of Technology under Center for Fire Research sponsorship. By using hoods to capture the products of combustion generated by fires burning in open laboratories, these researchers demonstrated that high levels of carbon monoxide were formed when the amount of air entrained by a fire plume located beneath a layer of combustion gases was insufficient to consume all of the fuel present. Such burning is referred to as being underventilated. Even more significant was the observation that concentrations of the major species of combustion (including carbon monoxide) in the hoods were strongly correlated with the ratio of the masses of products derived from fuel and air present in



The plot shows the dramatic increases in carbon monoxide levels due to the presence of wood in the upper layer of an underventilated enclosure fire. When the wood weakens and falls to the floor of the enclosure, the carbon monoxide levels return to those typical of fires without wood present.

the hood normalized by the fuel-to-air ratio required to fully convert the fuel to water and carbon dioxide. This normalized ratio is known as the global equivalence ratio (GER), and the existence of the correlations is referred to as the GER concept. Interestingly, when the yields of carbon monoxide were expressed on a mass generated per mass of fuel consumed basis, the results were found be nearly fuel independent. An initial survey of real-scale fire tests results carried out as part of the Building and Fire Research Laboratory project showed that observed yields of carbon monoxide in underventilated fires were roughly in line with those found during the hood experiments.

The NIST research program was designed to confirm the applicability of the GER concept for the production of carbon monoxide formation during enclosure fires as well as to identify other mechanisms capable of generating carbon monoxide in enclosure fires. A concurrent research program at the Virginia Polytechnic Institute and State University funded by the Building and Fire Research Laboratory had similar goals.

One of the first steps in the BFRL project was to perform fundamental thermodynamic and kinetic investigations in order to better understand the chemical nature of the upper layers formed during fires in enclosures. These studies indicated that the upper-layer combustion products formed during underventilated burning are predominately determined by kinetics and are far from thermodynamic equilibrium. The gases only start to approach thermodynamic equilibrium for temperatures in excess of 1100 °C. The calculated reaction behaviors were also consistent with the experimental observation that the composition in the hood experiments varied somewhat with the temperature of the gases.

The experiments that identified the GER concept are highly idealized models for enclosure fires. In order to verify that that the GER concept was appropriate for more realistic enclosure fires, a series of natural gas fueled fires were carried out in both a 40 percent-scale and a full-scale model of an enclosure widely used in fire testing. The full-scale room had dimensions of 2.4 m wide, 2.4 m high, 3.7 m long and contained a single doorway centered in one of the short walls.

Measurements made in the 40 percent-scale model revealed that the composition of combustion gases and temperatures in the upper layer of the fire varied somewhat with location, but that the composition was still strongly correlated with a global equivalence ratio based on the fuel release rate and the amount of air entering the doorway. This finding confirmed that the mechanism for carbon monoxide formation identified in the hood experiments was also important in enclosure fires. However, the experimental results, along with field modeling of the flows in the enclosure, also showed that a fraction of the air passing through the doorway could enter the upper layer of the room directly without being entrained into the fire plume. For a fuel rich upper layer the detailed chemical kinetic modeling indicated that this air would react with fuel to generate primarily carbon monoxide. Thus direct entrainment of air into a rich, high temperature upper layer provides an additional mechanism for carbon monoxide formation in enclosure fires.

Somewhat surprisingly, much higher levels of carbon monoxide were observed during burns in the full-scale enclosure than in the reduced-scale enclosure. Analysis showed that these higher levels were due to the higher temperatures present in the upper layer of the full-scale facility. These temperatures were sufficiently high for the underventilated fire gases to begin to react and approach thermodynamic equilibrium. This leads to increases in carbon monoxide since this species is thermodynamically favored at high temperatures. The upper-layer temperatures for which increased carbon monoxide formation was observed were consistent with the predictions of the detailed chemical kinetic modeling.

Comparison with a number of real-scale tests carried out at the Center for Fire Research indicated that the three mechanisms discussed above were sufficient to explain the formation of carbon monoxide for many fires. However, it was recognized that for several large fires in which wood was burned the levels of carbon monoxide were considerably higher than predicted based on these mechanisms alone. Since wood contains a significant fraction of oxygen and is known to generate carbon monoxide when heated to high temperatures in anaerobic environments, it was postulated that high concentrations of carbon monoxide in fires can be generated when wood is located in high temperature fire environments where oxygen is unavailable. In order to test this hypothesis, underventilated natural gas fires were burned in both enclosures in which the upper walls and ceilings were lined with plywood. Observed upper-layer concentrations of carbon monoxide were as much as six times higher than when wood was absent, thus confirming the hypothesis and providing a fourth mechanism for generating carbon monoxide in enclosure fire environments.

A scale model experiment used to investigate carbon monoxide formation during underventilated burning within an enclosure.

Based upon the understanding developed during the research program, an algorithm was developed that allows fire safety engineers to determine whether carbon monoxide is likely to be formed during an enclosure fire and to estimate the amounts generated. The four formation mechanisms identified during the investigation are incorporated: 1) quenching of a turbulent fire plume upon entering a rich upper layer, 2) mixing of oxygen directly into a rich, high-temperature upper layer with subsequent reaction, 3) pyrolysis of wood in high-temperature, vitiated environments, and 4) approach to full-equilibrium combustion product concentrations in a rich, high-temperature upper layer.

The results of this research not only provided an understanding and predictive method for the generation of carbon monoxide in enclosure fires, but also had an impact on the study of fire toxicity in general. Prior to this work it had been common for fire researchers to assess the potential of a particular fuel to generate toxic products by burning or pyrolyzing small samples and either identifying the products generated or monitoring the response of animals, such as rats, to the products. However, the results of this research showed that the amount of carbon monoxide, which is often the dominant toxic species present, generated is determined primarily by the ventilation and flow conditions under which real-scale burning is occurring and is much less dependent on fuel-to-fuel variations. This topic remains as active area of research, but many researchers have concluded that small-scale testing is only appropriate when it is suspected that unusually toxic species may be generated by a particular fuel.

The significance of this research was recognized in 1996 when Pitts was awarded the Department of Commerce's Silver Medal "for ground breaking research in predicting the yields of carbon monoxide from fire and propelling a new era in real-scale fire research."

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12.8 LESS FIRE-PRONE CIGARETTES

On September 30, 1984 the landmark Cigarette Safety Act of 1984 (P.L. 98-567) was signed into law. It had long been known that cigarette-initiated fires were the largest single cause of fire deaths in the United States: 1570 in 1984, along with 7000 serious injuries, 390 million of destroyed property, and a total cost of about $4 billion. Patents for less fire-prone cigarettes dated back to the turn of the century, but legislation to control the ignition strength of cigarettes had been thwarted by a powerful industry lobby. Rather, a mandatory standard for the cigarette resistance of mattresses and voluntary standards for upholstered furniture had become effective in the 1970s. Much of the developmental work for these standards was done in the Center for Fire Research by John Krasny and Joseph Loftus under the leadership of James Winger. They acquired detailed knowledge of cigarettes and furnishings. Now, this would be put to use in examining the cigarette.

The 1984 Act established a Technical Study Group on Cigarette and Little Cigar Fire Safety (TSG), which was directed to determine the technical and commercial feasibility, economic impact, and other consequences of developing cigarettes and little cigars that will have a minimum propensity to ignite upholstered furniture or mattresses. Such activities were to include identification of the different physical characteristics of cigarettes and little cigars which have an impact on the ignition of upholstered furniture and mattresses, an analysis of the feasibility of altering any pertinent characteristics to reduce ignition propensity, and an analysis of the possible costs and benefits, both to the industry and the public, associated with any such product modification. The TSG was composed of five representatives of Federal agencies, four representatives of the cigarette manufacturing industry, two members from the furniture manufacturing industry, two members from public health organizations, and two members from fire safety organizations. Richard Gann of the NBS Center for Fire Research was chosen to chair the TSG.

Over the next three years, most of the research was performed at NBS in the Center for Fire Research and the Center for Building Technology under the overall leadership of Gann: [1-7]. A team led by Robert Levine showed that it is possible to use laboratory-scale tests to produce cigarette ignition propensity data that correlated well with full-scale chairs of the same materials.

- Thomas Ohlemiller, Richard Harris, and co-workers identified certain properties of cigarettes that can be varied to reduce the likelihood of igniting a fire.
- Rosalie Ruegg's team of Steven Weber, Barbara Lippiatt, and Sieglinde Fuller, all from the Center for Building Technology showed that the cost of modifying cigarettes to lower ignition propensity is modest and is far outweighed by the societal benefits of fewer fires, injuries, and deaths.

Other projects were performed by the Consumer Product Safety Commission and the National Fire Protection Association.

As a result of this work, The TSG concluded that it was technically feasible to develop cigarettes with a significantly reduced propensity to ignite upholstered furniture and mattresses and to do so with minimal economic impact, presuming the modified cigarettes were commercially feasible. The TSG also identified five additional pieces of technical work needed to support a safety standard for less fire-prone cigarettes.

The Congress responded with a second piece of legislation, the Fire Safe Cigarette Act of 1990 (P.L. 101-352). It created a Technical Advisory Group (TAG) with the same composition as the TSG. Again, Gann was chosen as the Chair. This Act specifically charged the NIST Center for Fire Research to develop a standard test method for cigarette ignition propensity, compile performance data for cigarettes using this method, and conduct research to develop predictive capability. The Consumer Product Safety Commission and the Department of Health and Human Services were also assigned tasks.

The NIST research was again successful, generating the products directed by the Act:

- A team of Kay Villa, Emil Braun, Richard Harris, Randy Lawson and Richard Gann, led by Thomas Ohlemiller and supported by Keith Eberhardt of the NIST Statistical Engineering Division, developed two methods for measuring the ignition propensity of a cigarette type: [8,9]
  - The Mock-up Ignition Method measures whether a cigarette causes ignition by transferring enough heat to a fabric/foam simulation of a piece of furniture (substrate). A lit cigarette is placed on one of three different mock-ups. Ignition (failure) is defined as the char propagating 10 mm away from the tobacco column. The procedure is repeated a set number of times and the percent of failures is calculated.
  - The Cigarette Extinction Method measures whether a cigarette, when placed on a heat-absorbing substrate, burns long and strong enough to cause ignition had it been dropped on a piece of furniture. A lit cigarette is placed on one of three substrates consisting of a fixed number of pieces of common filter paper. Failure is defined as the cigarette burning its full length. The procedure is repeated a set number of times and the percent failures is calculated. [While the metric in this test is the cessation of burning, it is not a test for "self-extinguishing" cigarettes. Some cigarette designs that pass this procedure have also performed well in the Mock-up Test, burning their full length without causing an ignition.]

  The two methods produce similar results. Both were subjected to an interlaboratory evaluation to measure their reproducibility.
- Test data on 20 commercial cigarettes and 5 experimental cigarettes using the two methods. These data indicated that the best selling cigarettes were potent igniters of fur-

nishing and that a few specialty cigarettes had somewhat improved performance, while far better performance was technically possible. The data also provided a reference assessment of the 1993 marketplace for future use [8].
- Henri Mitler and George Walton created computer models of a multi-layer cushion subjected to a stationary heat source, a model of a burning cigarette lying on such a cushion and a protocol for using the two together [10].

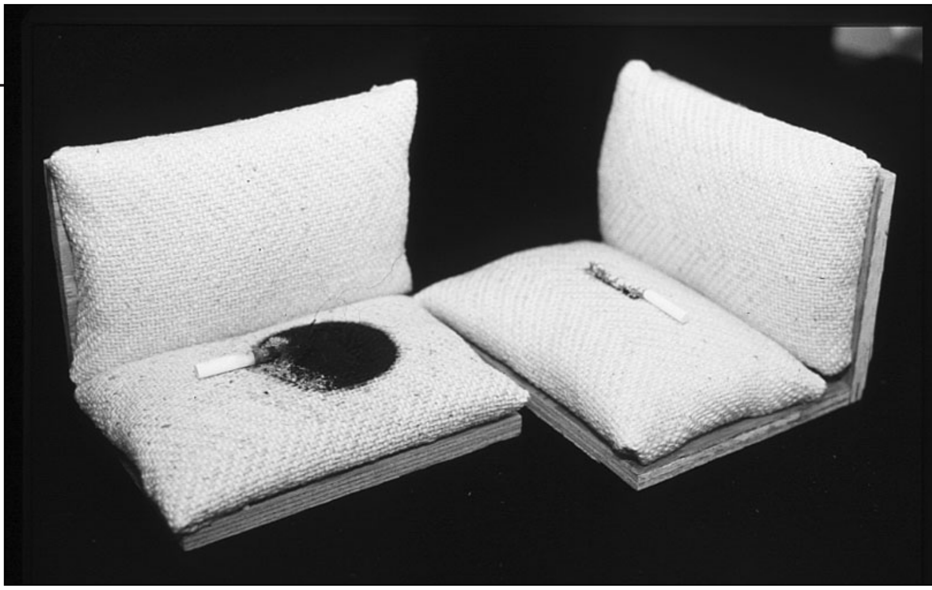
In March 1994, the crew of the CBS News Magazine, 60 Minutes, visited NIST. While there was concern among NIST management that the institution would be harmed by the team of reporter Mike Wallace and producer Lowell Bergman, this turned out not to be the case. Michael Smith, the BFRL technician who had done the lion's share of the testing of the commercial cigarettes, was filmed for the show and Dick Gann was interviewed about the NIST research. The segment "Up in Smoke" aired on March 27, 1994, marking the first time NIST had been featured on the show.

During the course of the filming, Mike Wallace (who generally struck fear in the subjects of his interviews) asked Michael Smith about the difficulties of giving up smoking. Smith suggested that Mike Wallace should keep the discussions to technical topics, and Wallace apologized for the intrusion.

Michael Smith, physical science technician (back to camera), demonstrates the NIST test for measuring the ignition strength of cigarettes (later ASTM E2187) for Richard Gann, chief, Fire Science Division and Mike Wallace of 60 Minutes.

For his leadership in response to both of these Acts, Gann was awarded the Department of Commerce Silver Medal. Both test methods are currently being processed by ASTM Committee E5 on Fire Standards. Based on these results, legislation to develop a National standard for less fire-prone cigarettes has been introduced in the Congress, but a law has not yet emerged. Meanwhile, there has been activity in several state legislatures, and in June 2000, the State of New York enacted the first bill directing the development of a cigarette fire safety standard by January 2003. That regulation uses ASTM E-2187-02b, Standard Test Method for Measurement of the Ignition Strength of Cigarettes, which is the result of the NIST work. In December 2002 the team of Richard Gann, Emil Braun, Keith Eberhardt, John Krasny, Randy Lawson, and Tom Ohlemiller were honored with ASTM's Simon H. Ingberg Award for the research leading to the Standard.

On January 11, 2000, a major manufacturer of cigarettes announced that it would soon be test marketing a modification of one of their cigarettes that would make them less likely to start a fire. The cigarette design evolved from one of the patented ideas tested (with positive results) under the Cigarette Safety Act of 1984, entailing adding circumferential bands of low air permeability paper to the paper that wraps the tobacco column. The manufacturer's ignition propensity test data, using the Mock-up Ignition test Method, indicated this design would be distinctly less likely to start a fire. The public safety community anticipated the potential for a significant reduction in life loss and injury; the regulatory community anticipated the existence of a product that would make a less fire-prone cigarette standard feasible.



Demonstration of the results of NIST research on the cigarette properties that affect the propensity of a cigarette to ignite a chair or bed. The cigarette on the left could have led to a serious fire. The cigarette on the right has properties that make it unlikely to ignite upholstered furniture.

In May 2000, soon after the test marketing of the modified cigarettes began, the Federal Trade Commission requested that the NIST Building and Fire Research Laboratory conduct tests to determine whether and to what extent this cigarette does reduce the risk of ignition. While NIST does not routinely perform product tests, it recognized the important role of the Federal Trade Commission in assuring the public of the veracity of product claims and the high potential for less fire-prone cigarettes to reduce fire deaths and injuries and agreed to measure the ignition propensity of these test cigarettes relative to the performance of the unmodified product. The NIST tests show that the banded cigarette does have a lower relative ignition propensity than its conventional counterpart and performs far better than the best selling cigarettes from 1993 [11]. That cigarette is now in commercial production.

Thus, NIST research has paved the way for reducing the single most frequent cause of fatal fires. As governing bodies proceed toward cigarette safety standards, NIST continues to provide them with guidance on the technology to make such standards effective.

John Krasny received the Bronze Medal Award of the Department of Commerce in 1980 for his studies of self-extinguishing cigarettes, and Joseph Loftus, also in 1980, received the Bronze Medal for his studies of cigarette ignition resistance of materials. Richard Gann received the Silver Medal Award of the Department of Commerce in 1994 for his leadership of the studies of cigarette ignition propensity.

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12.9 ALTERNATIVE FIRE SUPPRESSANTS

The ability to control fire is universally and exclusively human. While about 400,000 years ago homo erectus had learned how to "capture" and use fire, their effort was directed at keeping the fire from going out. The first formal requirement for fire suppression appeared in ancient Rome, the first water pump and hose was implemented in 1725, and the automatic sprinkler was invented in 1812. Today, the application of chemicals, manually and by mechanical devices, to control fires has become a mainstay of safety in modern society.

Carbon tetrachloride, first mass produced early in the 20th century, was the first "clean" agent, i.e., unlike water it caused no damage to a building or its contents and left no residue itself. It was also the first halon. However, concerns soon arose about its toxic effects on firefighters and others at the fire scene. The same held true for other early halons.

In 1948, the U.S. Army commissioned a search for a fire suppressant of high efficiency but low toxicity. Two compounds emerged and became commercial successes. Halon 1301 (CF_3Br) found widespread use as a total flooding agent and halon 1211 (CF_2ClBr) became the predominant streaming agent. By the 1980s, most computer rooms, nearly all commercial and military aircraft, and numerous museums were typical of the high value properties protected by these halon systems.

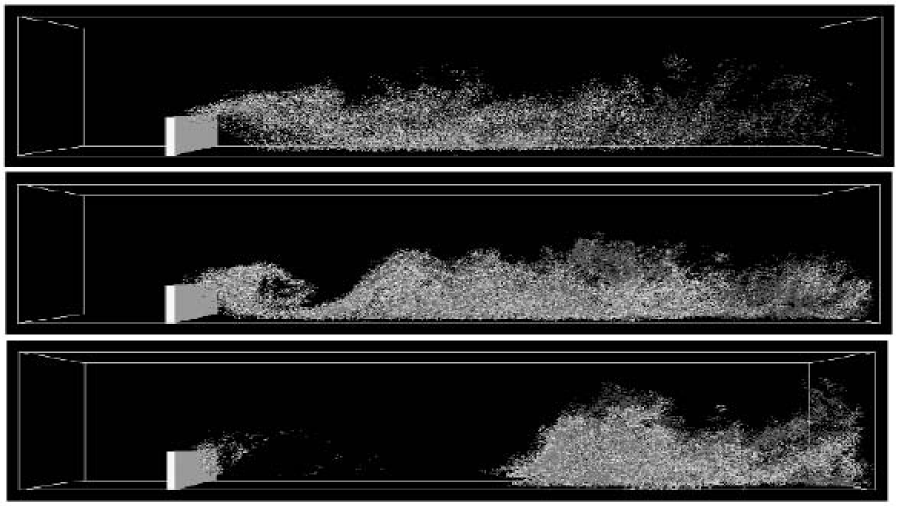
The National Bureau of Standards became involved in fire suppression during this period. Beginning in the early 1960s, Carroll Creitz developed new ways of studying inhibited flames and proposed a mechanism for the effectiveness of halogenated flame inhibitors [1,2]. In the mid 1970s, the Center for Fire Research (CFR) hired Richard Gann, who had done research on halogenated fire suppression with the Naval Research Laboratory, and Gary Mallard, who had done similar research with the Bureau of Mines. Together, they began looking for halons that might be more effective than halon 1301.

In the 1970s, it was found that when these halons were released into the atmosphere, they would rise to the stratosphere where they would deplete the earth's delicate protective ozone layer. Under the 1987 Montreal Protocol on Substances that Deplete the Ozone Layer and its subsequent amendments, production of halons 1301 and 1211 was restricted, and in January 1994, nearly all production ceased.

In 1989, the newly organized industry/government Halon Alternatives Research Consortium commissioned a team led by Gann to formulate a comprehensive plan to identify new, environmentally safe fire suppressants. The first two projects were funded at NBS by the Air Force. Led by Gann, a team from CFR, the Center for Chemical Technology (CCT), and the Materials Science and Engineering Laboratory, developed a set of tools to screen possible candidates [3]. A second team, lead by William Pitts of the CFR with staff from the CCT, scoped the world of chemicals to be examined [4]. Little further public research was done, as companies began to market as fire suppressants chemicals that had emerged from the search for alternate refrigerants, a far larger market. Many users of the halons converted to these other suppressants or ceased providing fire protection altogether.

However, the Department of Defense (DoD) was faced with a critical problem. Fires and explosions were (and continue to be) among the greatest threats to the safety of personnel and the survivability of military aircraft, ships, and land vehicles in peacetime and during combat operations. For these, halon 1301 had become the fire suppressant of choice. In 1992, the DoD initiated a massive program to identify the optimal commercially available replacements for all their ozone-depleting substances, including the halons. A large team of staff from the Building and Fire Research Laboratory and other NIST Laboratories, led by Gann, played a major role in the search for alternatives to halon 1301 for aircraft applications, establishing new science and engineering in a broad range of topics: [5,6]

- Thermodynamic properties of alternate agents: Jiann Yang, Brett Breuel
- Fluid dynamics of agent discharge: William Pitts, Jiann Yang, Grzegorz Gmurczyk, Leonard Cooper, William Grosshandler, Carole Womeldorf, Michelle King, Thomas Cleary; Marcia Huber, William Cleveland, Cary Presser (Chemical Science and Technology Laboratory, CSTL)
- Flame suppressant effectiveness: Anthony Hamins, Grzegorz Gmurczyk, William Grosshandler, Isaura Vazquez, Thomas Cleary, and Cary Presser
- Flame inhibition chemistry and the search for additional fire fighting chemicals: Marc Nyden, Gregory Linteris; Donald Burgess; Wing Tsang, Michael Zachariah (CSTL)
- Agent stability under storage and discharge residue: Richard Peacock, Thomas Cleary, Richard Harris
- Corrosion of metals: Richard Ricker and Mark Stoudt (Materials Science and Engineering Laboratory, MSEL)
- Elastomer seal compatibility: Gregory McKenna and William Waldron (MSEL)
- Human exposure and environmental impact: Emil Braun, Richard Peacock, Glenn Forney, George Mulholland, Barbara Levin
- Suppression of high-speed flames and quasi-detonations: Grzegorz Gmurczyk, William Grosshandler
- Photodegradation of CF_3I: Marc Nyden
- Effects of suppressants on metal fires: Thomas Ohlemiller, John Shields
- Suppression of engine nacelle fires: Anthony Hamins, Thomas Cleary, Kevin McGrattan, Glenn Forney, William Grosshandler; Cary Presser
- Prediction of HF formation during suppression: Gregory Linteris
- Real-time suppressant concentration measurement; William Pitts, George Mulholland, Bret Breuel, Eric Johnsson, Richard Harris
- Identification of a halon 1301 simulant for use in engine nacelle certification tests: Carole Womeldorf, William Grosshandler



The Transient Application, Recirculating Fire (TARPF) Facility was the first laboratory-scale apparatus that enabled measuring the effectiveness of new fire suppressants in the complex environment of aircraft engine nacelles. The picture shows the progression from stable flame to one that is about to be extinguished.

William Grosshandler was awarded the Department of Commerce Silver Medal in 1995 for his prime research role in this program.

The outcome of this work was the military's concurrence on the NIST recommendation of C2HF5 as the optimal commercially available chemical to replace halon 1301 for use in engine nacelles and dry bays. Unfortunately, this chemical is about 2-3 times less efficient than halon 1301, requiring significant and costly modification of the aircraft for its implementation. [However, recent re-engineering of the Navy's F/A-18 C/D aircraft has made C2HF5 the leading halon 1301 replacement contender for that use.]

In 1997, the DoD initiated the Next Generation Fire Suppression Technology Program (NGP) to develop retrofitable, economically feasible, environmentally acceptable, and user-safe processes, techniques, and fluids that met the operational requirements satisfied by halon 1301 systems. The new technologies would be of low mass and volume and compatible with the host weapons system design. Any new chemicals would have high suppression efficiency and perform well in evaluations of ozone depletion potential, global warming potential, atmospheric lifetime, reignition quenching, residue level, electrical conductivity, corrosivity to metals, polymeric materials compatibility, long-term storage stability, toxicity of the chemical and its combustion and decomposition products, speed of dispersion, and occupational safety requirements. Again, Gann was appointed to lead the program.

In the first four years of the NGP, now focused on aircraft applications, about one fourth of the research was performed at NIST, mostly within BFRL with contributions from CSTL and PL. The NIST findings have led to new insights into the fire suppression process, accurate metrics for the performance of potential fire suppressant chemicals, and identification of candidate suppressants: [7,8]

- Screening tests for fire suppression efficiency: [9,10] Jiann Yang, Michelle Donnelly, William Grosshandler
- Screening protocol for agent toxicity, environmental impact, and materials compatibility: [11] Marc Nyden
- Measurements of environmental impact of suppressants: [12] Robert Huie (CSTL)
- New fire suppressant chemicals: [13-16] Gregory Linteris, Valeri Babushok, William Pitts, Linda Blevins, Jiann Yang; Wing Tsang, Marcia Huber (CSTL)
- Real-time measurement of suppressant concentration: [17] George Mulholland, Erik Johnsson; Gerald Fraser (PL)

As the research continues for new suppressants and more efficient methods of delivering them to the fire, the NIST approach has made its mark on the entire NGP:

- use of sound science, archival and new, in planning the research and interpreting the results,
- bringing the full suite of expertise at NIST to bear on the problem,
- close collaboration with outside experts in the contributing disciplines, and
- detailed documentation of the findings and the processes that led to them.

Jiann Yang received the Department of Commerce Bronze Medal Award in 2000 for his studies of the suppression effectiveness of liquid agents.

Driven by a continuing sequence of new demands, research on fire suppressants has continued for over a century. It is likely that new criteria will continue to arise, and the NIST findings of this century will become the basis for the investigations of the next.

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12.10 FURNITURE FLAMMABILITY

Upholstered furniture fires have, for decades, shown up in U. S. fire statistics as one of the leading causes of fire deaths. These fires typically start through the careless use of smoking materials, particularly cigarettes, but, in recent years, children playing with matches have also been shown to be significant contributors. There are thus two major modes of ignition: smoldering, through contact with cigarettes, or flaming, through direct small flame contact. Either mode of ignition may eventually lead to a large flaming fire that poses a major life hazard. BFRL research on furniture flammability has largely been in support of the development of both voluntary and governmentally-mandated tests to establish the degree of hazard and to enable the development of lesser hazard designs. An implicit goal has been the development of an understanding of the ignition and burning processes as a means of assuring that meaningful measurements are at the heart of test methods.

A furniture mock-up subjected to the California Technical Bulletin 113 gas flame igniter that was developed at NIST. To the left of the burner are two heat flux gages measuring the energy feedback from the flames.

The above goals have led in several directions. The cigarette smoldering ignition mode [1], for example, led to fundamental experimental and modeling studies of smolder initiation and propagation in upholstered furniture material composites (e.g., fabric over polyurethane foam) and to development of test methods to establish the ignition propensity of both furniture materials and, separately, cigarettes themselves. The fundamental smoldering combustion studies and the cigarette ignition propensity studies are treated separately under appropriate headings in this history. The study of the tendency of various furniture material combinations to ignite to smoldering as a result of cigarette contact led to a test method that has been the basis for a voluntary industry standard for more than two decades.

The other major thrust that emerged from the above goals focused on measuring the flaming fire behavior of furniture and predicting this behavior from small-scale tests. Both of these were very much tied up with the development of techniques to measure the rate of heat release from a fire by measuring its oxygen consumption. Heat release rate emerged clearly as the most meaningful measure of the size of any fire; oxygen consumption was the only truly practical and accurate means to measure this variable. It was applied to full-size chairs and sofas in the context of a furniture calorimeter developed at NIST [2]. It was applied to small samples of materials taken from furniture in the context of the Cone Calorimeter, also developed at NIST [3]. Efforts to use the small scale results to predict the full-scale behavior have met with limited success and efforts along these lines continue to this day [4]. The challenge lies in the extremely complex behavior of the burning furniture. The most recent efforts focus on bed fires that present very similar problems and challenges (with some unique slants) [6].

Throughout these studies, NIST/BFRL has worked interactively with the Consumer Products Safety Commission, which has regulatory authority in the area of furniture flammability. Each advance in testing methodology has supported CPSC efforts to implement improved flammability standards for the upholstery and bedding industries. In a similar manner, BFRL interacted with the California Bureau of Home Furnishings, which has regulatory authority in that state, to enable them to put implement more effective test methods [5]. This agency has been a strong advocate for fire safety and the impact of their testing philosophy has reached well beyond the state of California.

James Winger received the Silver Medal Award of the Department of Commerce in 1978 for his early studies of the flammability of furniture and fabrics.

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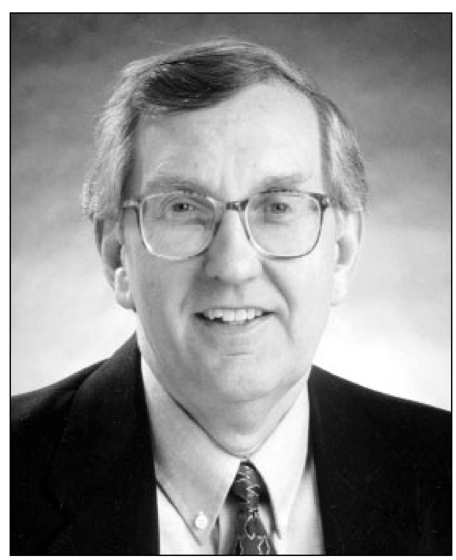
13. MATERIALS

13.1 CONSTRUCTION MATERIALS REFERENCE LABORATORIES

In the early part of the 20th century, there was concern about the inconsistency of testing of portland cement which was becoming an important material used in construction. In response, a number of organizations, including NIST, ASTM International, and the Portland Cement Association collaborated in studies directed towards improving standardized specifications and test methods for portland cement. This response lead to the formation of the Cement Reference Laboratory in 1929 as a research associate program at NIST, managed by NIST but under the sponsorship of ASTM Committee C01 on Hydraulic Cement [1]. In 1960, ASTM Committee C09 on Concrete and Concrete Aggregate was added as a sponsor, and the name was changed to the Cement and Concrete Reference Laboratory (CCRL). J. R. Dwyer who was actively involved with establishing CCRL was its Manager from 1929 to 1965. He was followed by John R. Dise in 1965 who added the title of Manager of AMRL and served as Secretary of ASTM Committee C01 for the whole of his time with CCRL. James H. Pielert became Manager of AMRL and CCRL in 1983, a position he still occupies. John Haverfield was the Assistant Manager of CCRL until 1985 when Raymond Kolos assumed the position.

The AASHTO Materials Reference Laboratory (AMRL) was established at NIST in 1965 under a similar arrangement with the sponsorship of the

James Pielert, leader of Construction Materials Reference Laboratories.



American Association of State Highway and Transportation Officials (AASHTO) [2]. This formation was in response to an investigation of the Interstate Highway System Program by Congressman Blatnick in the early 1960s, which identified problems with the consistency of testing of materials used in highways. NIST was selected because it was already hosting the CCRL, which became the model for AMRL, and because of its reputation, could provide an unbiased evaluation of laboratory performance. Oakley McIntosh was the Assistant Manager of AMRL until 1985 when Peter Spellerberg assumed the position.

The primary mission of AMRL and CCRL is to improve the quality of testing in laboratories that test construction materials. This is accomplished through on-site visits to laboratories, distributing proficiency samples to laboratories for testing, participating in the work of standards committees, and conducting research related to development of tests for construction materials. Construction materials covered include hydraulic cements, portland cement concrete, masonry materials, reinforcing steel, pozzolans, aggregates, soils, asphalt binders, hot-mixed asphalt, plastic pipe, and paints used in transportation systems.

The last quarter of the 20th century was a period of substantial change in AMRL and CCRL as, with the increasing emphasis on quality in construction, their programs gained increasing recognition by the construction community. The number of laboratories participating in AMRL and CCRL programs more than doubled during this period resulting in more than 1400 laboratories participating in 2003. This participation includes laboratories from all 50 of the United States and 20 other countries. New programs were added in masonry materials, pozzolans, blended cements, hot-mixed asphalts, and paints used in transportation systems.

The AMRL and CCRL Laboratory Assessment and Proficiency Sample Programs have become important components of the laboratory accreditation system in the United States [3]. AMRL and CCRL Proficiency Sample Programs are used by the three major accreditors of construction materials testing laboratories; the AASHTO Accreditation Program (AAP), the American Association for Laboratory Accreditation (A2LA), and the National Voluntary Laboratory Accreditation Program (NVLAP). AMRL and CCRL Laboratory Assessment programs are used by the AAP. Additionally, AMRL provides technical support to the AAP, which was established by AASHTO in 1988, and it currently has more than 800 laboratories accredited.

AMRL has had an important role in the implementation of technology resulting from the National Academies' Strategic Highway Research Program (SHRP). SHRP was established by Congress in 1987 as a five year, $150

Kathryn Tice, AMRL research associate, is preparing hot performance graded asphalt binder test samples for placement in a pressured aging vessel for optimizing use in highway construction.

million research program to improve the performance and durability of the nation's highways, and to make those highways safer for both motorists and highway workers [4]. At the time SHRP concluded in 1993, it had developed 130 products in support of its mission, and the implementation of SHRP technology became an important follow-up activity. AMRL supported the drafting of more than 70 standards resulting from this research, which are being processed through the AASHTO and ASTM standards process. The resulting standardized test methods and practices have been added to AMRL's Laboratory Assessment and Proficiency Sample Programs, and to the scope of AAP. In addition, AMRL has assembled a state-of-art liquid asphalt laboratory.

In the mid-1990s, AMRL had a lead role in the metrication of AASHTO's materials standards as part of the movement toward the use of the metric system of measurement in the United States.

The relationship between NIST, ASTM, and AASHTO on the AMRL and CCRL programs was strengthened in 1999 with the signing of a new Memorandum of Agreement calling for the development of a standards-oriented research component which would complement the BFRL research program. This will ensure the continued excellent relationship between the three parties to the agreement.

AMRL and CCRL have had a significant impact on the quality of testing of construction materials during their 70 year history. The increasing concern currently being expressed about quality on the international level indicates that the programs can still make a valuable contribution in promoting the quality of testing of construction materials. These programs are unique examples of Federal government, state government, and private sector cooperation in addressing a problem of common concern. Their customers were strong and effective proponents before Congress for the continued existence of CBT during the budget crisis of the 1980s.

The AMRL and CCRL have developed a large amount of data from the standard tests carried out by participants in the proficiency programs. The CCRL cement and concrete databases are of great value to BFRL's Virtual Cement and Concrete Testing Laboratory (VCCTL) program in which they are being used in testing the validity of VCCTL models for simulating performance of cement and concrete [5].

The strong leadership provided by Dwyer and Dise in the first half century of CCRL and AMRL's existence put these organizations in leadership positions in promoting the quality of laboratory testing. Through Pielert's thoughtful management, strong interpersonal skills, and interest in keeping up with technological developments and foreseeing future needs have led to increased professional stature and high morale for the research associates who staff the CMRL, good relations with sponsors in ASTM and AASHTO, and strong synergy with research activities in BFRL.

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13.2 SERVICE LIFE PREDICTION OF CONSTRUCTION MATERIALS

13.2.1 INTRODUCTION

Although most building and construction materials are expected to have service lives of several decades, no methods have been available for making reliable predictions of long service lives either from short-term tests or from first principles. The lack of generally-accepted methods for service life prediction has been a barrier to the most effective selection, use and maintenance of building and construction materials, and has been cited as an important contributor to premature failures. It is also a barrier to innovation since designers are reluctant to specify products for which evidence of performance over time is lacking. The need to reduce costs associated with repair, replacement and maintenance, and to assess the service lives of innovative materials without decades of testing led to the initiation, in 1973, of CBT's research program on service life prediction. In that year, Geoffrey Frohnsdorff joined CBT in 1973 as Chief of the Materials and Composites Section, at a time when the Section was heavily involved in durability studies in support of HUD's Operation Breakthrough. Larry Masters and Winfred Wolfe had prepared a report [1] on weather and climatological data to provide a basis for relating outdoor exposure tests performed at sites such as those used by NBS at the Roosevelt Roads Naval Base in Puerto Rico, and at Nellis Air Force Base in Nevada, as well as at the NBS site.

During the planning of a project to evaluate the durability of several types of adhesively-bonded sandwich panels, Frohnsdorff pointed out the need for a general methodology for service life prediction. He then obtained agreement from HUD that such a standard methodology should be developed, and he arranged for a new subcommittee, E-6.22, Durability Performance of Building Constructions, to be established in ASTM Committee E06, Performance of Buildings. As chairman of the new subcommittee, Frohnsdorff appointed Peter Sereda of the National Research Council of Canada (NRCC) as vice-chairman, and Masters was appointed chairman of a task group to develop the needed standard methodology. Frohnsdorff, Masters and Sereda shared the ambitious goal of developing a fundamental, science-based understanding of materials degradation that could provide the technical basis for a new generation of durability standards .

13.2.2 STANDARD PRACTICE FOR DEVELOPMENT OF ACCELERATED TESTS AND A NEW SYSTEM OF SERVICE LIFE PREDICTION STANDARDS

By 1978, Masters had the first of the needed service life prediction standards in place as ASTM E-632, Standard Practice for Developing Short-Term Accelerated Tests for Prediction of the Service Life of Building Materials and Components. Also in 1978, as a result of the collaboration between Frohnsdorff and Sereda in ASTM Committee E06, an International Conference on the Durability of Building Materials and Components was held in Ottawa with NRCC, NBS/NIST, ASTM, and RILEM as sponsors. A keynote paper [2] on "The Meaning of Durability and Durability Prediction" that Frohnsdorff and Masters presented at the conference suggested that the reliability approach might be brought in to service life predictions of building materials. That led to hiring Jonathan Martin, a reliabilist from the University of Washington. Thus, in 1978, three major seeds of what has become BFRL's world-leading service life prediction program for building materials were planted - the hiring of Martin, the publication of ASTM E-632, and the holding of the International Conference; the conference became the first in the series of triennial International Conferences on the Durability of Building Materials and Components (DBMC) sponsored by NRCC, NBS/NIST, RILEM and CIB. The Second International Conference (2DBMC) was held at NBS in 1981 with Frohnsdorff as chairman. Subsequent conferences in the series have been held in Espoo, Finland; Singapore; Brighton, England; Tokyo; Stockholm; Vancouver; and Brisbane.

In 1980, for his achievement in leading the development of ASTM E-632, Masters received the Department of Commerce Bronze Medal. In the same year, Frohnsdorff was appointed to RILEM's Research Advisory Group (RAG) and, in 1983, when he was chairman of the Advisory Group, Frohnsdorff arranged for the establishment of a RILEM Committee on Service Life Prediction, Committee 71-SLP, with Masters as chairman. The main products of this committee were Masters' report [3] based on ASTM E-632, and a later report prepared by Masters and Erik Brandt, a guest researcher from Denmark. RILEM recognized the importance of the later report by giving it pre-standard status by designating it a RILEM Technical Recommendation [4]. It is noteworthy that both the Principal Guide to Service Life Planning [5] of the Architectural Institute of Japan and a key portion of British Standard BS 7543, Guide to Durability of Buildings, and Building Elements, Products and Components" [6] draw on ASTM E-632 or have portions patterned on it. The needs identified in Masters' work provided the justification for the 1984 NATO Advanced Research Workshop on Problems in the Prediction of the Service Life of Building and Construction Materials [7] at which Masters brought together leading European and U.S. durability researchers.

CBT and other laboratories made many applications of the ASTM E-632 methodology during the 70s and 80s. For instance, CBT supported the Department of Energy and the emerging solar energy industry with studies and recommendations that provided the technical basis for many standards for the durability of materials used in solar energy systems [8]. CBT's knowledge on matters relating to durability and related aspects of performance of building materials was also applied on several projects of national importance. The work of Paul Campbell, Mary McKnight, and Larry Masters in providing detailed specifications for the restoration and maintenance for the paint on the White House was described [9] as one of the most sophisticated and professional paint studies ever conducted. Then, for a study concerning the possible use of stone preservative treatments in the restoration of the West Front of the United States Capitol [10], James Clifton received a National Historic Preservation Award in 1988; the citation for the award stated, "technically it has broken much new ground; it is a model for archival and curatorial work." For other durability-related studies, Mary McKnight received the Department of Commerce Bronze Medal in 1994 for contributions to improved coatings practices, and, for his work in modeling the degradation of coatings, Tinh Nguyen received the Bronze Medal in 1994.

In 1990, Frohnsdorff and Masters presented a paper [11], "Suggestions for a Logically-Consistent Structure for Service Life Prediction Standards," at the 5DBMC Conference. It recommended the development of a system of service life standards with three levels. The first level would consist of a single generic standard, such as ASTM E-632 or the RILEM Technical Recommendation, that outlined the methodology for predicting service life. The second level would consist of about six generic standards addressing topics called out in the standard in the first level including: characterization of service environments, characterization of materials and components, identification of degradation mechanisms, modeling the kinetics of degradation, determination of times-to-failure, and reporting of results. The third level would consist of an indefinite number of material- or product-specific standards that described how the generic standards in the two higher levels should be applied in predicting service lives of specific materials. This hierarchy has been adopted as a model for the development of international standards for service life prediction in cooperative activities involving the joint CIB/RILEM Committee on Service Life Prediction and ISO TC59/SC14 on Design Life (see next paragraph). The European Community is relying on the development of such standards for full implementation of its Construction Products Directive.

In 1993, Frohnsdorff proposed to ISO Technical Committee TC59, Building Construction, that it should establish a Working Group on Design Life of Buildings. The proposal was accepted and Working Group 9 was established in Subcommittee 3 of TC59, with Frohnsdorff as chairman. In 1997, in recognition of the progress made, Working Group 9 was elevated to subcommittee status as ISO TC59/SC14, Design Life of Buildings and Constructed Assets [12]. The Subcommittee is drafting an eight-part standard, ISO 15686, Buildings and Constructed Assets: Service Life Planning. Taken together, the parts will, for the first time, recommend that designers call for service life data, or standard service life predictions, for products to be used in their designs.

13.2.3 THE RELIABILITY-BASED APPROACH TO SERVICE LIFE PREDICTION

When Jonathan Martin joined CBT's materials research staff in 1978, he introduced the reliability-based approach to service life prediction. The reliability-based methodology [13], with its rigorous experimental procedure and strong scientific basis, had already had a long history of successful application in the electronics, aerospace, nuclear, and medical fields. In a reliability-based methodology, since weathering factors cannot be controlled, results of field exposure experiments are not the standard of performance -- however, they may be an important source of data if the weathering factors can be monitored just as they are in the laboratory. The standard of performance is now based on laboratory experiments that can be made repeatable and reproducible if the sources of experimental error are minimized; with proper design, the experiments can provide data from which service life under any expected conditions can be predicted. There is no longer a need to try to design laboratory experiments that simulate outdoor exposures since the laboratory experiments can cover the range of exposure conditions that a product will be exposed to in the field. With the paradigm shift accompanying adoption of the reliability-based methodology, laboratory accelerated aging and fundamental mechanistic experiments are, for all practical purposes, equivalent except for the number of experimental variables under investigation. For his leadership in developing the reliability-based approach to service life prediction of coatings and other polymeric building materials, Martin received the Department of Commerce Bronze Medal in 1996.

The industrial significance of Martin's work was first recognized by the coatings community. In 1994, a strong research consortium -- the Coatings Service Life Performance Consortium involving industry, government and academe -- was established. The consortium, managed by Martin, included several leading coatings manufacturers among its members. Its objective is to apply a reliability-based methodology in estimating the service life of a coating or other polymeric building material subjected to ultraviolet radiation and other weathering factors. Though initially established for a three-year period, the achievements of the consortium have been sufficiently encouraging that it has already been extended for two additional three-year periods. In view of the need to disseminate knowledge of the reliability approach, Martin, with David Bauer of the Ford Motor Company, initiated a series of international conferences, sponsored by the American Chemical Society, on prediction of service life of coatings, and on polymeric materials in general. The first two conferences were held in 1997 [14] and 1999 [15].

The reliability-based methodology requires the sets of data collected from the three primary sources of service life data (field, accelerated laboratory, and fundamental mechanistic studies) to have the same data elements and to be of comparable quality. Data is needed on the initial properties of a material, on changes in the properties of the material as functions of time, and on the weathering factors (i.e., degradative factors) in the exposure environment as functions of time. Data needed on the exposure environments, whether in the laboratory or field, are usually spectral irradiance, spectral distribution, specimen temperature, and specimen moisture content.

With the need for measurements to improve reliability-based service life predictions, Martin designed a completely new laboratory exposure device to minimize the temporal, spatial, systematic, equipment, and operational sources of error encountered in earlier devices. In the new device [16], each of 32 similar ports on the surface of a 2 m diameter integrating sphere opens into the sphere's interior. The interior is illuminated by an intense source of visible and ultraviolet radiation at the top of the sphere. The ports provide essentially-identical sources of radiation for exposure chambers attached to the ports through parabolic cone concentrators. Because of the uniformity of the radiation within the sphere, monitoring the radiation emitted from a single port is equivalent to monitoring the radiation emitted from every port. Conditions within any of the exposure chambers could be controlled for spectral radiation, temperature, and relative humidity, and for almost any other factor of interest; where necessary, mechanical loads could be applied to some specimens. Large numbers of small specimens can be exposed in each of the chambers, and the specimens can be easily removed for analysis to determine the degree of degradation. The ability to provide a variety of precisely-controlled exposures of large numbers of specimens greatly increases the power and practicality of applying the reliability approach to prediction of service lives under any specified conditions. In an ancilliary development, to provide for frequent analyses of the large number of specimens from the exposure chambers, the presentation of specimens for infra-red and ultraviolet spectrophotometric measurements was automated. One of the early findings from the reliability-based experiments was the unexpectedly strong dependence of rate of photodegradation on the moisture content within a coating [17].

The need for high-quality field data for use with data from the new exposure

Tinh Nguyen, physical scientist, is using a Fourier transform infrared microscope to study factors affecting the failure of organic protective coatings on steel.

device in predicting the service lives of materials in the field, was accompanied by a need for access to strategically-located, well-instrumented, field exposure sites. The establishment of eight such sites at widely-spaced locations within the U. S. was carried out as a cooperative project among four Federal Agencies with overlapping interests -- NIST, the Smithsonian Environmental Research Center (SERC), the USDA UV-B Network Program, and the Forest Products Laboratory (FPL) at Madison, WI [18]. With the establishment of these sites, NIST now has in place all the necessary components for development and demonstration of its world-leading capability to apply the reliability approach to the prediction of the service lives of polymeric building materials including paints and coatings, building joint sealants, and composites.

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13.3 CORROSION PROTECTION FOR REINFORCING STEEL

The deterioration of concrete highway bridge decks exposed to deicing salts was identified as a national problem by the mid 1960s. The lifetime of bridge decks was only 5 to 10 years in northern states where deicing salts were heavily used. The Federal Highway Administration (FHWA) estimated that $25 billion was needed over the next decade to repair the failing decks.

FHWA engaged CBT to develop performance criteria and test methods for organic coatings to protect reinforcing bars from corrosion while providing needed structural reinforcement. The research carried out by James Clifton, Robert Mathey, and Hugh Beeghly [1, 2] showed that only four of the forty eight coatings evaluated met the performance criteria. All four were spray-applied powdered epoxy resins.

Standards based on this research for epoxy-coated steel reinforcing bars were adopted by the American Association of State Highway and Transportation Officials, ASTM, and the Concrete Reinforcing Steel Institute [3, 4]. A new industry represented by the Fusion-Bonded Coaters Association developed to supply epoxy-coated reinforcing. Forty six states specify epoxy-coated reinforcing in bridge deck construction. By 1990, over 272.2 x 10^6 kg of epoxy-coated steel reinforcement, about 5.5 percent of all reinforcing bars, were used in the U.S. In recognition of the importance of their work, Clifton and Mathey received the Department of Commerce Silver Medal in 1975, and the Alfred E. Lindau Award from the American Concrete Institute in 1987.

Findings from FHWA indicate the coated reinforcing extends the life of a bridge deck exposed to deicing salts, from 5 to 10 years without coating, to more than 40 years. Considering the 25 percent additional cost of coated reinforcing to be insignificant compared to the total labor and material cost for a bridge deck replacement, the 1990s annual expenditure of $500 million for bridge deck replacement, and a discount rate of 7.6 percent, the annual present value savings by use of coated reinforcing to extend life from 10 years to 40 years is $745 million.

James Clifton, leader of inorganic building materials research.

James Clifton, who earned a Ph.D. in Inorganic Chemistry from Oregon State University, joined the Building Research Division in 1969 and led research in durability of inorganic building materials until his death in 1999. He was a quiet, cheerful man with endless enthusiasm for research and the accomplishments of his colleagues. Robert Mathey joined BRD in 1955, worked 14 years in structural research, and then in materials research until his retirement in 1991. His warmth, responsibility and cooperation were appreciated by colleagues in NBS, collaborating and sponsoring federal agencies and professional and standards committees. Hugh Beeghly worked for CBT for a few years in the 1970s following a long career in research in the steel industry.

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13.4 ROOFING RESEARCH

In 1969, C.W. Griffin [1] wrote that "the volume of built-up roofing annually installed in the United States totals 2 billion square feet… Probably 10 to 15 percent of the roofs ... fail prematurely." Statements such as Griffin's made it evident that the U.S. membrane roofing industry urgently needed to improve the performance of its products. One of the major problems of the era was poor characterization of the engineering properties of built-up-roofing (BUR) membranes. Consequently, specifications detailing the performance requirements for completed BUR membranes were non-existent. In contrast, prescriptive specifications indicating the type and number of reinforcing plies, and the type and amount of bitumen were the norm. A common result was that installed membranes had inadequate properties to perform satisfactorily.

This situation changed dramatically, when in 1974, Robert G. Mathey and William C. Cullen published Building Science Series (BSS) 55, Preliminary Performance Criteria for Bituminous Membrane Roofing [2]. For the first time, the U.S. membrane roofing industry had guidance for selecting membranes based on their performance properties. Mathey and Cullen identified 20 performance attributes considered important to the satisfactory performance of BUR membranes, and they suggested performance criteria for 10 of these attributes. The performance concept, applied to BUR membranes, was widely embraced by the industry. Specifiers selected membranes on the basis of their conformance to the criteria, manufacturers promoted (where appropriate) existing products, and developed new products, meeting the criteria. Consultants investigating performance problems with in-place membranes compared properties with the BSS 55 recommendations. Roofing contractors were perhaps the most vocal group of supporters and, in this regard, the National Roofing Contractors Association (NRCA) Manual incorporated recommendations that installed membranes have performance properties in accordance with BSS 55 criteria.

The impact of BSS 55 has been long lasting. By way of example, at an NRCA annual convention in the late 1980s, the Owens-Corning Company made a presentation on the history and performance of BUR systems in the U.S. The development of BSS 55 was recognized as a significant milestone in the industry's history, and a major driving force behind the significant improvements in BUR performance that occurred over the 15 year period after the report's publication.

Another major issue that faced the BUR industry in the early 1970s centered on restrictive requirements that severely limited the temperature to which asphalt could be heated during installation of built-up membranes. At the time, asphalt was classified into four Types, I, II, III & IV, based on the results of tests such as softening point and penetration. Although it was generally considered that the higher the type, the less likely the asphalt would flow at a given temperature, specifications for asphalt application did not usually recognize such differences. One consequence was that asphalt was often applied at temperatures too low for proper flow. Improper flow results in excessively thick, non-uniform asphalt layers that may contain voids and that may be inadequately adhered to membrane reinforcing felts. As a solution to this asphalt heating problem, industry task groups proposed the Equiviscous Temperature concept. According to this concept, asphalt was to be applied at a temperature at which it would flow sufficiently (i.e., have adequately low viscosity) to achieve well-adhered, uniformly thin, void-free layers between membrane plies. Equivalently said, the viscosity of the heated asphalt at application was proposed to be in the range of about 100 centistokes to 150 centistokes. In support of the industry efforts, Walter J. Rossiter and Mathey authored BSS 92, The Viscosities of Roofing Asphalts

Sampling built-up-roofing membranes for measuring its performance properties.

at Application Temperatures [3]. This report, which described a combined laboratory and field study, was a cornerstone of the technical foundation for the Equiviscous Temperature concept. In the laboratory, the viscosities of 20 typical roofing asphalts were measured over their application temperatures, and compared with softening points and penetrations. These data demonstrated that different asphalts had different viscosity-temperature relationships, and that asphalt application temperatures should be determined on the basis of viscosity. In the field, BUR membrane samples were prepared using typical roofing asphalts heated at different temperatures encompassing the range of application temperatures encountered in practice. These BUR samples were analyzed to relate the quality of the asphalt application to the application temperature and, in turn, the viscosity at application. The major recommendation was that the optimum viscosity of asphalt at the time of application should be within the range of 50 centistokes to 150 centistokes. Soon after publication of BSS 92, the industry adopted the Equiviscous Temperature concept which remains in use today.

As noted above in the quote from Griffin, at the beginning of the 1970s built-up roofing had a monopoly on the U.S membrane market. However, that monopoly was soon to be broken. Because of the all-too-frequent problems with BUR membranes in the early 1970s, many owners, architects, specifiers, and others responsible for roof system selection were eager to find alternative membrane materials. In response, material suppliers emerged who provided, at competitive costs, alternative systems based on elastomeric and thermoplastic polymeric membranes, and polymer-modified bituminous membranes. The growth in use of these products was explosive. Although their use was almost non-existent in the mid-1970s, by the end of the 1980s they accounted for about 70 percent of the membranes installed in the U.S. -- a figure that has remained reasonably constant through today. However, the growth in use was not problem free. These membranes had been introduced into the market without consensus standards to assist in their proper selection and use. Research was needed to understand better the performance of these systems, to develop solutions to the problems that were arising, and to contribute to the technical bases of the much needed consensus standards.

Of the new membrane materials that entered the market in the mid-1970s, EPDM (ethylene-propylene-diene terpolymer) rubber, manufactured as preformed single-ply sheets ready for field installation, experienced the most rapid growth. By the mid-1980s, it accounted for about 35 percent of the membrane market. EPDM is rather chemically inert rubber, which makes it attractive for outdoor use as a membrane material. However, this chemical inertness becomes a limitation when bonding adjacent sheets in the field to form the seams of a waterproofing membrane. At the time, these seams were typically fabricated with contact-type, polymer-based, liquid adhesives. In the mid-1980s, unsatisfactory seam performance accounted for about 50 percent of the EPDM membrane problems reported to the NRCA in surveys of member contractors. BFRL initiated research to elucidate the factors affecting performance and to develop solutions for improved performance.

Reports from NRCA indicated that many seam defects developed within the first three years of service.

Additionally, BFRL field inspections of EPDM roofing provided evidence of seams that were leak-free for 4 years to 5 years, at which time problems occurred. In these cases, disbonded seams were seen to be located at buckles and ripples in the EPDM membrane. BFRL researchers reasoned that many of these early failures were related to the rheological behavior of the adhesive and not to chemically-induced deterioration. Consequently, BFRL research staff in the Building Materials Division began studies to elucidate the major factors affecting the capability of seams to sustain loading. They developed creep-rupture test protocols, suitable to EPDM seams, in which joint specimens were stressed under constant load and the time over which they sustained the load was recorded. The better performing seams had longer times-to-failure. The factors investigated included material parameters such as the adhesive and its applied thickness, mechanical parameters such as the magnitude and type (i.e., peel and shear) of load, environmental parameters such as temperature, moisture and ozone, and application parameters such as the cleanness of the EPDM rubber surface.

Initial creep-rupture experiments and major findings were described in BSS 169, Strength and Creep-Rupture Properties of Adhesive-Bonded EPDM Joints Stressed in Peel, by Jonathan W. Martin, Edward Embree, Paul E. Stutzman, and J. A. Lechner [4]. Chief among the findings was that the thickness of the adhesive layer was an extremely important parameter affecting performance, as time-to-failure increased exponentially with adhesive thickness. Additionally, the cleanness of the EPDM rubber at the time of adhesive application was also shown to be significant. Although industry had always required that EPDM rubber was to be thoroughly cleaned before adhesive application, until BSS 169, the important influence of adhesive thickness on seam performance had been given little attention by practitioners. BFRL observations from field inspections showed, for example, that the thickness of adhesive layers often was less than EPDM manufacturers' recommendations. Although the relationship between adhesive thickness and seam performance was surprising to many, its implications were taken seriously. In 1991, the NRCA published [5], with BFRL assistance, a feature article entitled, "Is Your Adhesive Layer Thick Enough?" to alert contractors to the importance of adhesive thickness. At least one EPDM membrane manufacturer made available wet-film thickness gages to help ensure that the amount of applied adhesive was within prescribed limits.

BSS 169 demonstrated the importance of creep-rupture tests in evaluating seam performance. In 1993, ASTM issued Standard Test Method D5405, Conducting Time-to-Failure (Creep-Rupture) Tests of Joints Fabricated from Nonbituminous Organic Roof Membrane Material. This test method is based on BFRL seam research, and provides a sensitive procedure for investigating factors affecting seam performance under loading conditions that may lead to failure in the field.

As BFRL was completing its studies on liquid adhesives and ASTM Test Method D5405 was under development, EPDM roofing manufacturers introduced a new generation of adhesives based on preformed, polymer-based, tape adhesives. The introduction of tape adhesives was received with little enthusiasm by many practitioners, as they had become confident of the liquid adhesives being used at the time. On the other hand, proponents believed that tape adhesives had advantages over liquid adhesives such as enhanced seam performance, lessened environmental impact because they were solvent-free, and lower seam fabrication costs. In 1994, the EPDM industry formed a consortium with BFRL to conduct laboratory and field research to further the understanding of this innovative EPDM seam-adhesive technology. The consortium was comprised of three EPDM membrane material manufacturers, two tape adhesive manufacturers and two industry associations. The objectives were to:

- compare the creep-rupture performance of tape-bonded and liquid-adhesive-bonded seams of EPDM membranes, and
- recommend a test protocol for evaluating creep-rupture performance of such seams.

The results of the tape-bonded seam studies were published in BSS 175, BSS 176 and BSS 177 [6-8]. BFRL

Kevin Kraft and Edward Embry, BFRL materials staff, are examining the status of EPDM creep rupture experiment.

staff participating in the studies were Rossiter, Kevin Kraft, Embree, and James Seiler, who were assisted throughout by Mark Vangel of the NIST Statistical Engineering Division. Among the key findings, it was shown that tape-bonded seams had times-to-failure that were, in most cases, comparable to, or greater than, those of the liquid-adhesive-bonded seams. Moreover, the times-to-failure of tape-bonded specimens prepared with primed, clean EPDM were not affected by the application temperatures and pressures investigated. This finding was significant because application temperatures and pressures are difficult, if not practically impossible, to control in practice. Also, tape-bonded seams prepared with properly cleaned and primed EPDM rubber had longer times-to-failure than those fabricated without adequate cleaning and priming of the EPDM. This result, although not unexpected, emphasized to contractors in particular that proper application is a critical parameter affecting tape-bonded seam performance.

The consortium study hastened the acceptance of the innovative EPDM tape-bonded seam technology. In 1998, the NRCA marked the study conclusion in summarizing key findings and acclaimed its success in stating that "laboratory and field studies confirm the viability of tape-bonded seams" [9]. Additionally, the second study objective was successfully met, as the results provided the technical basis of ASTM Standard Practice D6383, Time-to-Failure (Creep-Rupture) of Adhesive Joints Fabricated from EPDM Roof Membrane Material. Among its benefits, this Standard Practice allows for evaluating the creep-rupture performance of newly developed adhesives for fabricating EPDM seams. The significance of this Standard Practice was made clear as the consortium study was concluding. At that time, two new tape adhesives for EPDM seams entered the market, which doubled the number available when the study began.

Throughout the 1970s, 80s, and 90s, BFRL staff played an important role in the dissemination of the results of roofing research to the U.S. roofing industry and in the development of the ASTM standards that were urgently needed by the roofing industry. Over these decades, BFRL teamed with the National Roofing Contractors Association (NRCA) to co-sponsor the biennial Conferences on Roofing Technology. In the 1970s, William Cullen received the NRCA Piper Award and also the ASTM Voss Award for his contributions to elucidating factors affecting the performance of roof membranes. Cullen's efforts were further acknowledged in 1980 when he received the Gold Metal Award of the Department of Commerce for his contributions to performance standards for membrane roofing. In the early to mid-1990s, Rossiter was chair of the ASTM Committee D08 on Roofing and Waterproofing. Previously, he had served a lengthy appointment as chair of Subcommittee D08.18, which has responsibility for standards for elastomeric and thermoplastic polymeric membranes. His contributions were acknowledged when he received the ASTM Award of Merit and the ASTM Voss Award for his standards development efforts and for advancing the understanding of the performance of seams in EPDM membranes. Rossiter was also chair of the joint CIB/RILEM Committee on Roofing that provided recommendations on needs for roofing standards. Based on this Committee's recommendations, five standards were issued by ASTM.

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13.5 LEAD HAZARD ABATEMENT IN RESIDENTIAL BUILDINGS

Walter Rossiter, research chemist, obtains paint sample for lead content analysis. He is investigating the presence of lead in household paints.

From the early 1970s, NIST has conducted research and field studies to support the programs of the U.S. Department of Housing and Urban Development (HUD) to identify lead-based paint in housing and provide appropriate, cost-effective remediation actions. HUD programs were developed in response to federal legislation (the Lead-based Paint Poisoning Prevention Act of 1971 and its amendments of 1973, 1987, 1992) that aimed to reduce the number of children having excessive blood-lead levels. In the United States in 1978, the number of children with excessive blood-lead levels was approximately 14.8 million, while in the early 1990s the number was approximately 1 million.

In the 1970s NIST research by Stanley Rasberry [1], Phillip Cramp, and Harvey Berger [2] led to specification and evaluation of new instruments to determine the content of lead in paint films and to the development of cost-effective abatement strategies. Lead-based paint abatement options were evaluated by David Waksman, Leo Skoda, Elizabeth Clark [3] and others. Robert Chapman and Joseph Kowalski [4] conducted economic studies and developed cost models for lead-based paint abatement. Harvey Berger received the Department of Commerce Bronze Medal Award in 1976 for leadership of the lead-based paint hazard abatement research.

In the late 1980s, NIST conducted research in several areas to assist HUD in developing regulations in response to new legislation. In BFRL, Mary McKnight led research to evaluate the performance of new portable instruments to determine the lead content of paint films [5]. Walter Rossiter developed performance criteria for coatings used to overcoat existing lead-based paint films [6]. BFRL also collaborated with NIST's Chemical Science and Technology laboratory in the development of Standard Reference Materials for lead in paint films and other environmental media [7]. A total of 17 materials were developed.

In early 1991, HUD recognized an urgent need for standards for detecting, controlling, and abating lead hazards associated with housing, and requested that ASTM initiate their development. In response, in late 1991, ASTM formed Subcommittee

Mary McKnight, leader of lead paint hazard mitigation research.

E06.23 on "Lead Hazards Associated with Buildings" with McKnight as its chair. Under her leadership, E06.23's work was swift and broad [8]. By the end of the decade, more than 20 new standards were issued. In recognition of her efforts, McKnight received the National Lead Abatement Council Technical Recognition Award in 1993, the Department of Commerce Bronze Medal Award in 1995, and the Standards Engineering Society (SES)/ASTM Robert J. Painter Award in 1996.

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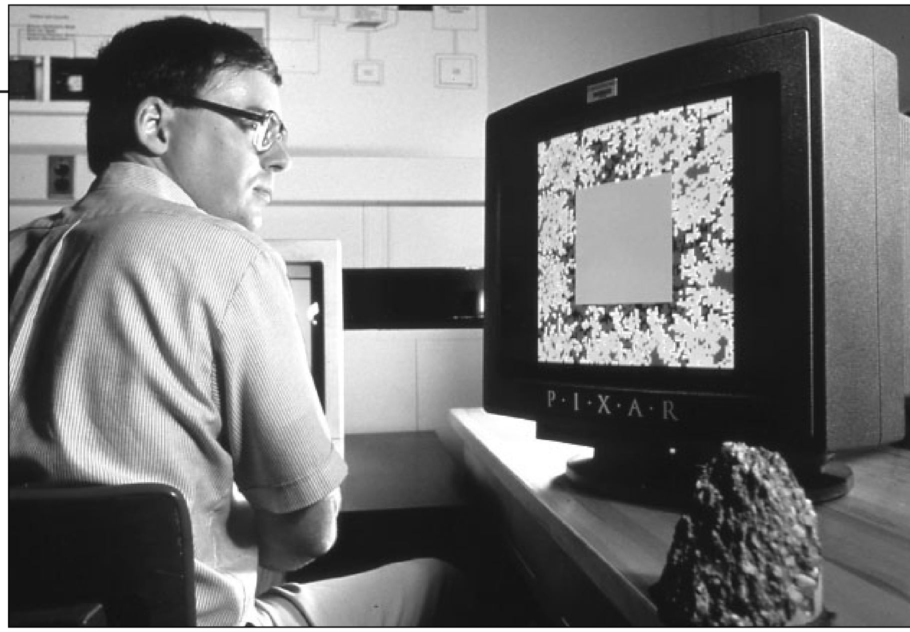
13.6 HIGH-PERFORMANCE CONCRETE

NIST has a long history of research on concrete as a material and on the structural performance of concrete. However, NIST's research on the material aspects of concrete fell to a low level from the mid-50s until a new era began in the 1970s. The new research was in accord with the performance concept [1] and, in broad terms, its goal throughout has been: To develop or improve methods for characterizing concrete materials and for measuring and predicting the performance, including service life, of concrete, and to disseminate the knowledge gained so as to facilitate innovation and advance concrete technology. The general approach has been to identify and prioritize needs for measures of performance and tools for performance prediction; then, to the extent possible with available resources, to develop needed knowledge, measures, and tools that have a sound basis in the materials science of concrete and concrete materials. The results have had a significant influence on concrete technology and, by providing tools for predicting performance, the latest ones appear to be leading a revolution in the technology.

In 1973, at the suggestion of Geoffrey Frohnsdorff, ASTM Committee C01, Cement, established a task group under his leadership to develop performance specifications for blended cements. This led, 19 years later, to the first ASTM performance specification for hydraulic cements, ASTM C1157-92 [2]. Though the specification was initially only for blended cements, by 1997 it had been broadened to apply to all cements for general construction. While BFRL was only one of many contributors to development of the specification, its final approval came about when the ASTM C01 was chaired by Frohnsdorff. The importance of the performance specification is in its potential for facilitating innovation in cement technology. Among the benefits it is expected to bring is facilitation of increased use of waste and by-product materials in



Edward Garboczi, physicist, develops computer models that simulate the microstructure of concrete during the setting process. These models are used to predict concrete performance, strength, and durability.

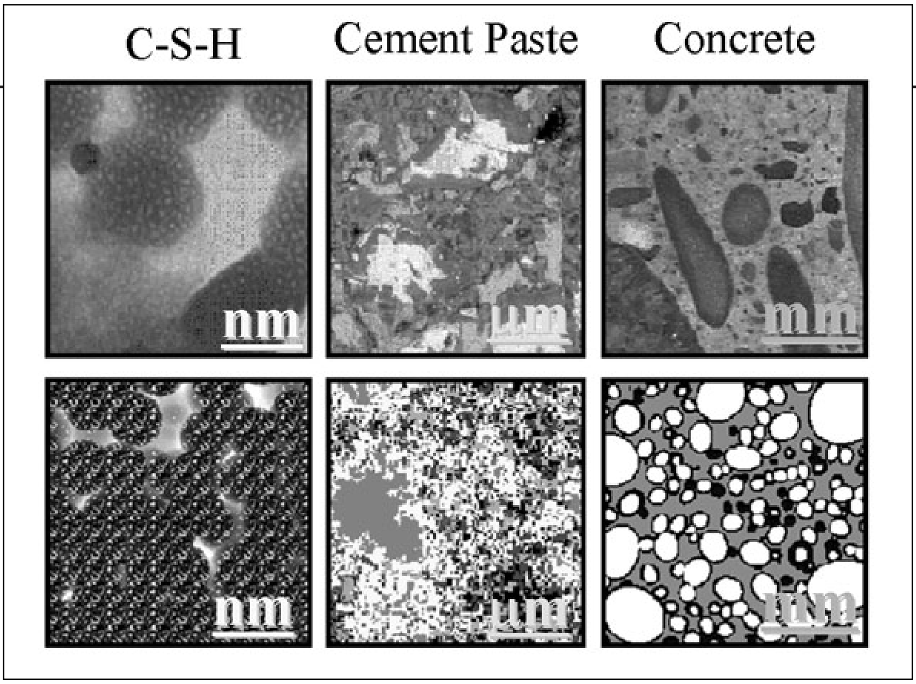
cement manufacture, thereby reducing fuel consumption, reducing the quantity of carbon dioxide liberated into the atmosphere, and reducing the need for stockpiling of wastes. The potential was noted in the report from the 1979 NIST/DoE workshop, Possible Contributions of Cement and Concrete Technology to Energy Conservation by the Year 2000 [3]. In the same year, Frohnsdorff, James Clifton and Paul Brown received the P.H. Bates Memorial Award from the ASTM C01 for their review of the history and status of standards relating to alkalis in hydraulic cements [4]; (P.H. Bates, for whom the award was named, was a renowned cement researcher at NIST in the 1920s).

The year 1978 may be looked upon as the one in which the seeds of BFRL's present high-performance concrete program were planted. In that year, with support from the NEL Director's Reserve fund, a project was undertaken to model the reactions with water of a single, spherical, monophase cement particle. While the problem was greatly simplified, and the available computational capability limited, the results published by James Clifton and guest researcher James Pommersheim [5] laid the groundwork for a successful 1981 competence initiative to develop mathematical models for simulating cement hydration and to generate experimental data for their validation.

The Cement Hydration competence project, led by Paul Brown with Hamlin Jennings in Clifton's Inorganic Building Materials Group, made excellent progress. By 1986, the project was sufficiently advanced for Jennings and Stephen Johnson to receive the Brunauer Award from the American Ceramic Society's (ACerS) Cements Division for their paper on computer simulation of microstructure development in a model cement paste [6]. Unfortunately, at about this time, as the work was gaining recognition, Brown and Jennings left CBT for academic positions, Brown going to Penn State and Jennings to Northwestern. However, on the recommendation of Jennings, James Clifton recruited Edward Garboczi, and he also brought back Dale Bentz from industry, to continue the work.

With BFRL becoming recognized as the leader in the computational materials science of cement-based materials, it was invited to join with Northwestern University and three other major universities (Illinois, Michigan, and Purdue) in a 1988 proposal to the National Science Foundation for establishment of a Center for the Science and Technology of Advanced Cement-Based Materials (ACBM). The proposal was successful, in spite of NSF's normal policy of not funding research in Federal agencies, and the ACBM was established in 1989 with the period of NSF support being renewable up to a maximum of 11 years. During the 11 year period, the ACBM, with NIST as an important participant, did much to strengthen the material science base of concrete technology.

NIST's contributions, often in collaboration with university researchers, e.g. [7], including its organization of annual modeling workshops, further enhanced its standing as the leader in the computational materials science of cement and concrete. In the first 12 years, the modeling workshops, all organized by Garboczi, introduced more than 300 persons to the computational and experimental techniques developed by BFRL and collaborating



Material-science-based predictions of the performance of concrete require knowledge of the structure-property relationships at all scales from nanometers to meters. The structure can be determined experimentally (top row), but it is becoming practical to use computer simulations (bottom row) as the basis for performance predictions.

researchers. When the NSF funding ceased in 2000, sufficient industrial support was obtained to keep the ACBM viable with Northwestern University, the University of Illinois, and BFRL being the core members. At about that time, Leslie Struble, a former BFRL researcher who had started to build BFRL's X-ray diffraction capability before moving to the University of Illinois, was appointed Associate Director of the ACBM.

BFRL's world-leading capability in computational materials science of concrete has been demonstrated in a continuing series of papers on simulation of the development of the 3-dimensional microstructure in cement paste, mortar, and concrete, and the heat liberation and changes in transport and mechanical properties accompanying microstructure development [8, 9, 10, 11]. These papers, and many others from the BFRL program, have been widely disseminated through the pioneering, continuously-growing, "electronic monograph" that was first put on the World-Wide Web by Garboczi and Bentz in 1997 [12]. By the end of 2001, the electronic monograph had five authors and had grown to the equivalent of a 2300-page document and, each month, it was being accessed from more than 7000 locations, and from more than 70 countries. The excellence of the work of Garboczi and Bentz was recognized internationally, with each being honored by the award of the RILEM Gold Medal -- Garboczi received the medal in 1992, and Bentz in 1997; (RILEM is the International Union of Research and Testing Laboratories for Structures and Materials). The significance of their honor is apparent from the fact that, although this award was established over 30 years ago, only two other Americans have received it.

BFRL's advances in ability to simulate the behavior of cements demanded advances in the ability to characterize cements and cement-based materials. Techniques have been developed for determining distributions of size, shape and chemical phases among cement particles and for comparable determinations of distributions of phases, pores and microcracks in concrete. BFRL's contributions to establishment of the first ASTM standard method for the use of X-ray diffraction in identification of the phase composition of a portland cement or a portland cement clinker was initiated by Struble and reported in a paper [13] with Howard Kanare of the Construction Technology Laboratory. The work was continued by Paul Stutzman and brought to fruition as ASTM C 1365 under his leadership [14]. Similarly, the first ASTM standard method for use of the petrographic microscope in determining the phase composition of a portland cement clinker, ASTM C 1356, was also established under Stutzman's leadership [15]. These two techniques, complemented by scanning electron microscopy - a technique for application of which [16] he had received the P.H. Bates Memorial Award from the ASTM Cements Committee in 1991 -- were applied by Stutzman [17], in collaboration with Stephan Leigh of ITL, in characterizing the members of the first suite of Standard Reference Materials for the phase composition of portland cement clinkers (SRMs Numbers 2686, 2687, and 2688).

The national importance of BFRL's concrete research on prediction of performance and service life is apparent from some of its applications. For example, the work of Nicholas Carino and guest researcher Rajesh Tank [18] in developing maturity functions for predicting the effects of early-age temperature variations on strength development in concretes of a wide range of compositions was recognized by award of the 1994 Wason Medal for Materials Research from ACI; their important work also provided the technical basis for ASTM and ACI standards. Another example was Kenneth Snyder and Clifton's development of software, 4SIGHT [19], for use by the Nuclear Regulatory Commission in predicting the service life of concrete used to contain low-level nuclear wastes when exposed to any likely combination of degradation factors. In another application, Stutzman used BFRL's ability to describe concrete in mathematical terms in determining, in 1999, the most probable cause of widespread deterioration of concrete highway pavements in Iowa and five other midwestern states [20]. And in yet another, Bentz developed a model for the FHWA to use in predicting the surface temperature and time-of-wetness of concrete pavements and bridge decks [21], an essential step in service life prediction. In other work related to steel-reinforced concrete bridge decks, Snyder, Ferraris, Martys, and Garboczi coupled computer simulations with impedance spectroscopy measurements to show limitations of the widely-used rapid chloride test method for determining the electrical conductivity of concrete [22].

An essential attribute of fresh concrete in almost every application is that its flow properties should allow ease of placement and consolidation. Nevertheless, no standard for measuring the flow properties of concrete in fundamental physical units has yet been achieved. This reflects experimental difficulties caused by:

a) concrete's non-Newtonian behavior,
b) changes in properties resulting from ongoing chemical reactions of the cement,
c) settling of aggregate particles under gravity, and
d) the necessity for direct tests to be carried out on a large scale because of the presence of large aggregate particles.

To begin to address the problems, Chiara Ferraris, with Nicos Martys and French guest researcher, François de Larrard, published a survey of methods for studying the rheological properties of cement pastes, mortars and concretes, including the possibility of predicting the flow properties of concrete from measurements on cement paste [23]. Then, as chair of an ACI subcommittee set up on her recommendation, Ferraris led an international inter-laboratory comparison of the five main types of concrete rheometer in 2000 [24]. At the same time, to aid understanding and prediction of flow properties of cement-based materials, Martys, with Raymond Mountain of CSTL, developed a dissipative particle dynamics model to simulate the flow of concrete [25]; this provided a generic capability to model the flow of concrete in rheometers with different geometries.

Although modern concretes tend to have lower water/cement ratios than older concretes, ACI guidelines for the curing of concrete have not yet been changed to take lower water/cement ratios into account. Following their critical review [26] of ACI's curing guidelines, Carino and guest researcher Kenneth Meeks, cooperated with the FHWA in detailed studies of moisture movements during the curing of concretes of different formulations under different environmental conditions [27]. The experiments were complemented by experiments and computer simulations of moisture movements in concrete by Bentz in collaboration with Hansen of the Technical University of Denmark [28]; subsequently, Bentz and Snyder continued the studies of moisture movements in an investigation of the benefits of using unsealed, porous aggregates as internally-distributed water reservoirs to aid the curing of concrete with a low water-cement ratio [29]. The results are being used by Carino to support recommendations to ACI Committee 308, Concrete Curing, to change ACI's curing guidelines.

With serious questions about the fire resistance of high-strength concrete being raised in the early 90s, Long Phan published a review of the literature in 1996; in it, he presented the evidence that high-strength concrete has a greater tendency than normal-strength concrete to spall rapidly in a fire [30]. Then, to provide a technical base for guidelines for assessing fire-related risks in using high-strength concrete, Phan, with Randy Lawson and Frank Davis, carried out an extensive series of experiments to investigate the effects of heating to high temperatures on the mechanical behavior of concretes of different formulations, both unconstrained and under a compressive load [31]. The experimental work was accompanied by computer simulations of internal pressure caused by evaporation of water as the concrete was heated. Some of the simulations, like some of the tests, included concretes containing small volume fractions of thermoplastic fibers; results of the simulations carried out by Bentz supported reports that inclusions of thermoplastic fibers could reduce the spalling tendency [32]. The results of the BFRL research are providing the technical basis for guidelines on the fire resistance of concrete being drafted in the ACI Committee 216, Fire Resistance and Fire Protection of Structures, chaired by Phan.

On the international standards level, BFRL, through the efforts of James Gross, was instrumental in arranging, in the mid-90s, for the secretariat of ISO Technical Committee TC71 on Concrete, Reinforced Concrete, and Prestressed Concrete to be transferred from Austria, where it had been dormant for many years, to the United States, with ACI as the secretariat. The committee and its subcommittees gained new life when ACI took on the responsibility in 1995; in response to a recommendation from Frohnsdorff, a new subcommittee, SC7, Service Life Design of Concrete Structures, was set up in TC71 in 2001.

In 1990, BFRL and ACI cosponsored a workshop on high-performance concrete, that resulted in publication, by Clifton and Carino, of the report, A National Plan for High-Performance Concrete [33]. The use of the term "high-performance concrete" in the title of the workshop was one of the first uses of a term that is now in common use and which has helped give concrete technology an improved image. (Subsequently, Frohnsdorff led the task group that defined the term for the ACI.) The plan helped set the pattern for BFRL's later concrete research as well as influencing the National Plan for High-Performance Construction Materials and Systems published by CERF (the Civil Engineering Research Foundation) in 1993 [34]. Preparation of the CERF plan was led by a committee chaired by Richard Wright, with Frohnsdorff leading the subcommittee on high-performance concrete, and John Gross the subcommittee on high-performance steel; the plan recommended formation of an industry council to facilitate implementation of the plan. This was the genesis of the CONMAT Council set up by CERF in 1994 to promote research on high-performance construction materials of all major categories. In 1995, a successful NIST Material Science and Engineering Laboratory-led programmatic initiative for materials research brought increased funding to BFRL for a high-performance construction materials program, with high-performance concrete as a major component. The concrete program was later renamed the Partnership for High-Performance Concrete Technology, or the HYPERCON Program for short [35].

The program goal was:
In partnership with industry, to enable reliable application of high-performance concrete in buildings and the civil infrastructure by developing, demonstrating, and providing assistance in implementing a computer-integrated knowledge system incorporating verified multi-attribute models for predicting and optimizing the performance and life-cycle cost of HPC.

The remarkable progress made towards the achievement of this goal is a result of collaboration among all the units of BFRL-the Divisions and the Office of Applied Economics.

In another important activity started in 1995, Shyam Sunder worked with

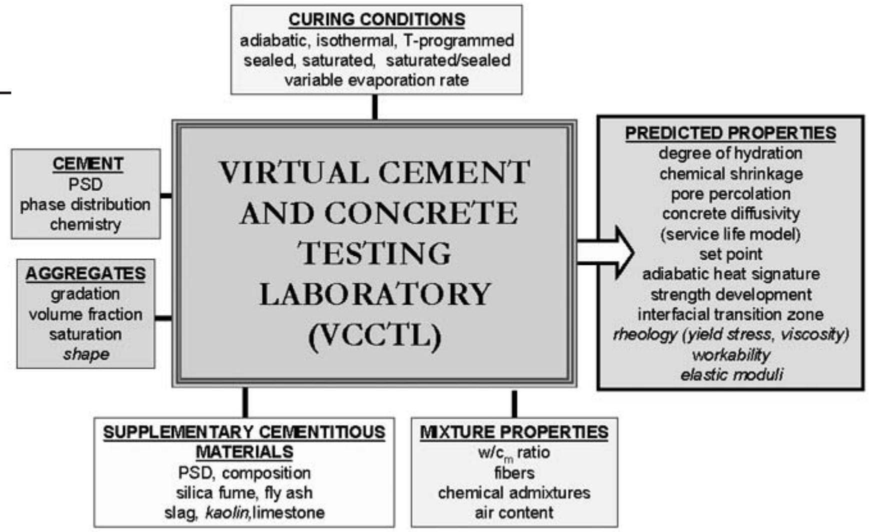
William Plenge of ACI to develop, with broad industry support, a white paper proposing establishment of a $100M focus area on high-performance concrete in NIST's Advanced Technology Program (ATP). Although the proposal could not be accepted because of an unexpected reduction in the funds available to the ATP, sustained industry enthusiasm for it resulted, in 1997, in ACI's formation of a Strategic Development Council (SDC) to provide a mechanism for formation of consortia to advance concrete technology [36]. In 2000, the SDC, of which BFRL was a charter member, published Vision 2030 [37] to put on record industry leaders' vision of what the concrete industry could, and should, be like by the Year 2030. Drafting of the "vision" required strong cooperation from all segments of the industry that is being continued with the drafting of a research road map to lead to achievement of the vision.

While simulation models have been a major element of BFRL's concrete research, other applications of information technology have also been important. The first widely-used knowledge-based expert system for use as a decision-support tool relating to concrete was HWYCON (for HighWaY CONcrete) [38]. It was developed by Larry Kaetzel and Clifton in consultation with the late Paul Klieger of the Portland Cement Association. HWYCON, which was produced under the National Academy's Strategic Highway Research Program (SHRP), aids identification of causes of distress in concrete highway bridges and pavements, and suggests repair methods and materials. Three thousand copies of the HWYCON software and manual were issued by the Transportation Research Board in 1993, with copies being distributed to Departments of Transportation of all 50 states. HWYCON was judged to be one of the top three products from the $100M, 5 year, SHRP program.

In the 1990s, to help advance the materials science of concrete, BFRL successfully recommended the establishment of four ACI committees. The committees, and their first chairmen, were: ACI 126, Database Formats for Concrete Material Property Data (chair, Frohnsdorff); ACI 235, Knowledge-Based Systems and Mathematical Modeling of Materials (chair, Kaetzel); ACI 236, Materials Science of Concrete (chair, David Lange, University of Illinois); and ACI 365, Service Life Prediction (chair, Clifton); ACI 236, and its subcommittee 236A, Rheology, are now both chaired by Ferraris. These committees produced the first recommended formats for concrete materials property data (39), the first ACI state-of-the-art report on service life prediction of concrete [40], the previously-mentioned report on the international comparison of concrete rheometers [24], and a report on computerized knowledge in concrete technology [41]. Much earlier, in 1985, as chair of ACI Committee 225 on Hydraulic Cement, Frohnsdorff led the writing and editing of the first version of the ACI Guide to Selection and Use of Cements [42]. Building on this, Frohnsdorff is now leading an ACI inter-committee coordinating group overseeing development of a Web-based interoperable version of the Guide. If acceptable to ACI, this could become ACI's first interoperable committee document. The coordinating group includes representatives of ACI Committees 225, 235, and 236.

In 1996, Bentz, Clifton, and Snyder published a prototype computer-integrated knowledge system (CIKS) for predicting the service life of steel-reinforced concrete exposed to chlorides, as in a concrete bridge deck [43]. The CIKS gave results that, according to bridge engineers with the New York Department of Transportation (NYDoT), were of the correct order of magnitude observed in NYDoT bridges. The CIKS was later used in conjunction with the life-cycle costing model, BridgeLCC [44], that Mark Ehlen had developed to aid decisions concerning the use of high-performance concrete, or other innovative materials, in highway bridge decks.

Just as life-cycle cost is normally important when considering the use of high-performance concrete, or any innovative material, so, in the future, life-cycle analyses to estimate life-cycle ("cradle-to-grave") environmental impacts will be important in material selection. The BEES (Building for Economic and Environmental Sustainability) software [45], devel-



The VCCTL program will make it possible to predict the properties of concrete listed on the right-hand side from knowledge of the materials and processing conditions listed on the other three sides (from Reference 47).

oped by Barbara Lippiatt to aid such decisions, has been applied by her to life-cycle analyses of concretes formulated with and without supplementary cementing materials (fly ash and ground granulated blast furnace slag). Inclusion of BEES enhanced the HYPERCON Program and justified adding some important words to the last sentence of the goal statement:

...... optimizing the performance, life-cycle cost, ***and life-cycle environmental impact of HPC****.*

In 1995, Frohnsdorff, Clifton, Garboczi, and Bentz published a paper entitled, "Virtual Cement and Concrete" [46], in which they speculated on the possibility of predicting the performance of cement and concrete from knowledge of the chemistry and physics of the system. In 1999, under the HYPERCON Program, Bentz initiated a pioneering project, the Virtual Cement and Concrete Testing Laboratory (VCCTL), to bring this about and use the results of BFRL's theoretical and experimental research to reduce the amount of costly long-term testing in concrete laboratories, whether for research purposes or for mixture design and quality assurance. The attractiveness of the VCCTL concept, as documented in the user's guide written by Bentz and Glenn Forney [47], was shown when a VCCTL Consortium was established in 2001 with six industrial participants, including units of three of the world's largest cement companies and the two largest U.S. manufacturers of chemical admixtures for concrete. It is expected that, as the VCCTL concept is further developed, it will be applicable to prediction of the performance of concrete in service in the field.

Throughout the period of this history, most of the research mentioned was carried out in BFRL's Inorganic Building Materials Group. Until 1999 when he died, the Group was ably led by James Clifton. Clifton was a prolific author who transferred his enthusiasm, and gave wise guidance, to his Group in its efforts to advance concrete technology. It was a great loss when he died, but his outstanding Group, now led by a worthy successor, Edward Garboczi, remains as a living tribute to his leadership [48].

In summary, during 1974 to 2000, BFRL's research on the materials aspects of concrete grew from a small NEL Director's Reserve project in 1978, to a competence project in 1981, and to the world-leading program in the computational materials science of concrete by 2000, where it was well-placed to achieve its goal of making the performance of concrete predictable, thereby revolutionizing concrete technology.

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14. STANDARDS AND CODES

14.1 HOUSING STANDARDS

Historically, the Building Research Program at NBS had a strong component addressing technology and standards for housing. Following Operation BREAKTHROUGH of the early 70s, CBT continued housing research at the request of and with the support of the Department of Housing and Urban Development (HUD).

In order to stimulate technical innovation in housing, a project led by Thomas Faison was undertaken to develop Performance Standards for Special and Innovative Construction. This document was prepared to provide a performance approach to the more prescriptive Minimum Property Standards of HUD. The results were published in 1977 as an NBS Interim Report [1]. Numerous HUD-sponsored projects continued over the years. Of particular note were projects on mobile home performance, lead paint mitigation, wind and earthquake performance and structural requirements, and energy conservation and plumbing system requirements.

In the early 1990s it remained evident that prescriptive U.S. codes and standards were barriers to housing innovation [2]. Also, there was much interest in export of U.S. building products, housing systems and knowledge, but there were no international performance standards as the basis for sale of these products. U.S. housing innovation was limited and occurred mostly in relation to amenities and popular styles rather than in the development of long-term performance and increased value. While the housing industry has performed well in the United States, it has had very limited success in exporting housing systems, housing products, and housing know-how.

To a large extent, the constraints on acceptance of housing innovation in the United States and the acceptance of U.S. products and know-how in the global marketplace could be overcome by the development of consensus performance criteria for housing. An international consensus would need to recognize differences in cultural and economic capability and would specifically address innovation; i.e., nonstandard products and systems. The best opportunity to develop such a consensus would be in the development of national and international performance standards for housing.

A program to develop a comprehensive set of national and international performance standards for specifying and evaluating dwelling construction was proposed by BFRL. This goal had two objectives:

- ***stimulate and remove barriers to innovation in the design and construction of U.S. housing; and***
- ***provide the basis for increased global trade in housing products, components, systems, and know-how.***

Performance has meant different things to different people, including those in the field of construction. For purposes of this work, the performance concept was defined as a framework for specifying and evaluating qualities of building products and systems to meet user needs without limiting ways and means [3].

Some considered the performance concept to be based upon general goals with nonquantitative objectives and subjective evaluation, which might be termed the "wish list" approach. However, the performance concept, as developed and applied to this standards program was based upon specific criteria with a rigorous methodology dependent upon quantitative criteria, measurable responses, and objective evaluation.

At the October 1995 meeting of the ASTM E6, Performance of Buildings, James Gross made a proposal for a new standards activity on Performance Standards for Dwellings which was endorsed along with the concept of providing a technical advisory group to ISO, providing that ISO develops a counterpart standards activity. A similar proposal had been discussed with ISO. An introductory meeting to launch standards development was conducted in March 1996 at the regular semiannual meeting of ASTM E6 in Orlando.

In October 1996, the first working meeting of ASTM Committee E6.66 was held in New Orleans, James Gross was elected chairman. The Building and Fire Research Laboratory of NIST provided a report for Committee consideration entitled Resource Document for Performance Standards for One and Two Family Dwellings. The report had been prepared with the assistance of consultant, David Hattis. The Committee decided to develop a series of Standard Guides around the attribute chapters in the Resource Document. These were Functionality, Structural Safety and Serviceability, Fire Safety, Accident Safety, Health and Hygiene, Indoor Environment, Illumination, Acoustics, Aesthetics, Durability, Maintainability and Accessibility. Since that time the committee expanded the list to include Security, Economics, Adaptability and Sustainability.

The Building and Fire Research Laboratory (BFRL) of NIST took the technical lead in the development of prestandardization documents with assistance from consultants, both in the drafting of documents and in their review [4)]. Further, this activity identified research needed to fill gaps found in the development of these prestandardization documents. The documents themselves were based upon current building technology and the state-of -the-art with further research undertaken for maintenance and improvement of these standards over time.

ISO is a worldwide federation of national standards bodies that promotes standardization to facilitate the exchange of goods and services. ISO is the major international organization for the development of building and construction standards with approximately 30 technical committees devoted to building and construction. These comprise approximately 20 percent of all the ISO standards committees. One of the standards committees in ISO is TC 59 - Buildings. TC 59 is a broad-based committee quite comparable to ASTM E6 on Performance of Buildings. In an April 1995 meeting of the full committee of TC 59, an informal proposal was presented to develop performance standards for dwellings with the possibility that this activity could be within TC 59. TC 59 approved, in principle, this informal proposal providing a formal proposal was made and the activity was assigned to TC 59.

In May 1996 at a meeting of ISO TC 59 Subcommittee 3 in Stockholm, a new Working Group on Performance Standards for One and Two Family Dwellings was approved (WG 10). Australia and the United States took this action following expressed support for this activity. Australia was assigned the responsibility of conveyor. In 1998 the activity was raised to subcommittee status (ISO-TC59-SC15). The principal work to date has been on Structural Safety and Serviceability and Durability guides.

The ASTM E6.66 subcommittee has continued to develop standard guides, four of which reached the balloting process by January 2001. Main committee E6 had approved the Durability Guide, and the Indoor Air Quality, Economics and Functionality guides were in the ASTM balloting process. Task groups were named to develop the Fire Safety and Acoustic standard guides.

James Gross was a sustained and forceful proponent of housing research in CBT and BFRL in his successive capacities as chief of the Office of Housing Technology, chief of the Building Economics and Regulatory Technology Division, deputy director of CBT and associate director of BFRL. Following Gross' retirement in 1997, Joel Zingeser led BFRL's housing research and standards activities which were diminished substantially with Zingeser's departure from BFRL in 2000.

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14.2 MOBILE HOME RESEARCH

BFRL conducted research on mobile homes (currently known as manufactured housing) in the mid to late 1970s as concerns surfaced about their safety and durability. Research was conducted in the areas of maintenance and durability, structural performance, thermal performance, and the response of mobile homes to fire. HUD funding was the primary sponsor for this research in support of its Federal Manufactured Home Construction and Safety Standard. However NIST and other Federal agencies also supported the program.

Damage to housing in the Wilkes-Barre, Pennsylvania area caused by Hurricane Agnes in 1972 provided an opportunity to study the performance of over 17,000 mobiles homes which were used as temporary housing by the U.S. Department of Housing and Urban Development (HUD) following the disaster. Comprehensive maintenance records were available for these mobile homes which represented a broad population of manufacturers, locations of manufacture, and ages of units. The objective of the project was to study the performance records of the units to (1) identify and document mobile home performance problems, (2) determine the relationship of the identified problems to provisions of the ANSI A119.1 Standard for Mobile Homes, and (3) identify areas of needed research. The results of this study [1,2,3] were used by HUD to prepare the Federal Manufactured Home Construction and Safety Standard to which mobile homes are currently constructed. This research resulted in James Gross and James Pielert receiving a Department of Commerce Silver Metal in 1977 for "significant contributions in increasing the safety, livability, and durability of mobile homes."

Research aimed at providing windstorm protection for manufactured homes' located in hurricane-prone regions.

The BFRL Structures Division conducted research on the structural performance of mobile homes when subjected to wind, flood and seismic forces. In addition to NIST funding, this research was supported by HUD and the U.S. Agency for International Development. Richard Marshall conducted research on the effects of wind on mobile homes including both wind tunnel [4] and full scale testing of instrumented units [5]. This research lead to recommended changes to the Federal Manufactured Home Construction and Safety Standard [6]. Felix Yokel led a research team investigating the performance of mobile home foundation systems when subjected to wind, flood and seismic forces [7,8].

Research in BFRL on the performance of mobile homes in fires involved a series of full-scale fire tests under the direction of Edward Budnick. Specific issues investigated included fire spread along a mobile home corridor [9] and interior finish as a fire safety consideration [10]. Fire detector issues related to mobile homes were investigated by Richard Bright and Richard Bukowski [11]. The 17,000 mobile homes used as temporary housing in Wilkes-Barre after Hurricane Agnes were used to evaluate the effectiveness of smoke detectors. Each unit was equipped with a smoke detector and fire safety performance was closely monitored. Based on the resulting excellent fire loss history, the mobile home industry in 1975 voluntarily adopted the requirement that a smoke detector be placed in each unit. This preceded ordinances requiring smoke detectors in conventional housing. BFRL's fire related research resulted in recommendations for changes to the Federal Manufactured Home Construction and Safety Standard [12].

Mobile home research in the Building Environment Division led by Douglas Burch was concerned with interior ventilation requirements and controlling moisture build-up in walls and roofs in various climatic conditions [13,14]. Much of this research was funded by HUD and resulted in changes to the Federal Manufactured Home Construction and Safety Standard.

In summary, BFRL's research has had a major impact on improving the quality and performance of manufactured housing which is a significant portion of the nation's housing stock.

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14.3 BUILDING REHABILITATION STANDARDS

In the late 1970s, there was increased awareness of the need to more fully utilize existing buildings. It was recognized that existing structures were assets that can be renewed creatively to provide shelter for people, commerce, and industry. Such reuse is beneficial since it avoids the dislocations of razing structures and building from the ground up, and provides urban variety and continuity with our past.

The Building Economics and Regulatory Technology Division under the leadership of James Gross initiated a project to study how building regulations and the regulatory process impact building rehabilitation. The building code is the primary regulatory device used to assure that minimum requirements for public health, safety, and welfare are met in the design and construction of buildings. Initial work in this area was on the impact of building code provisions on the rehabilitation of historic buildings [1]. Testimony given at Senate hearings in 1978 pointed out that building codes oriented toward new construction impede rehabilitation work by adding unnecessary project costs (estimated at 10 percent to 20 percent of total project costs), delaying project approval times (as much as 16 months over comparable new construction projects), and discouraging otherwise feasible rehabilitation projects [2].

BFRL began a study in 1977 to determine the need for improved regulations for rehabilitation of existing buildings. Several reports were published [3,4] which included, among other recommendations, the need to develop technical information pertaining to the building rehabilitation process and to prepare improved regulations for rehabilitation of existing buildings. Technical Note 998 [3] identified the following specific technical needs to support the building rehabilitation process:

a) techniques for evaluating the condition of existing buildings;
b) guidance on the selection of appropriate materials and repair methods;
c) methods for identifying, ranking, and scheduling required maintenance and repair activities; and
d) methods for predicting remaining service life of materials and systems.

In response to the first need, NIST prepared NBSIR 80-2171 which contained available methods for assessing building components and systems [5]. At the urging of NIST in 1983, ASCE formed a standards committee to respond to the need for information on the condition assessment of building [6]. The scope of the committee was "to identify specific needs and to develop consensus standards for the condition assessment and evaluation of existing buildings including both the documentation of available methods and the formulation of new procedures."

Under the chairmanship of James Pielert of NIST, ASCE 11 "Standard Guideline for Structural Condition Assessment of Existing Buildings" was published in 1990, and an updated standard was published in 1999 [7]. ASCE 11 quickly became one of the most popular ASCE standards. The committee also prepared ASCE 30 "Standard Guideline for Condition

Assessment of the Building Envelope" in 2000 [8].

NIST Technical Note 998 concluded that the building code and its enforcement were impediments to the rehabilitation of buildings. At the time, application of existing codes for new construction to buildings being considered for rehabilitation was based on the dollar amount of work being planned. An example of such a requirement is the "25-50 percent rule" which can be summarized as follows. The alteration must be restored to at least its original condition if the renovations are less than 25 percent of the building's value. When the amount of renovation is between 25 percent and 50 percent, it is up to the building official which portion of the renovation must conform to new construction requirements. When the amount of renovation exceeds 50 percent, the entire building must be brought up to new construction standards. These requirements, which often delay or prohibit rehabilitation activities, exert a negative impact on both public safety and quality of the existing building stock.

After reviewing NIST Technical Note 998, the Massachusetts State Building Code Commission, with enthusiastic support of then Governor Michael Dukakis, determined that the State could benefit from a review of its existing building code and the adoption of building rehabilitation regulations. A project was started under the leadership of the National Conference of States on Building Codes and Standards (NCSBCS) with support of NIST, the Commonwealth of Massachusetts, and seven other interested organizations. NIST support was provided by James Gross and James Pielert. The objective of the project was to produce an interim code document containing code provisions for alterations and additions to existing buildings. The final draft of the interim code provisions was completed in August 1978, and after various workshops and code hearings, was incorporated as Article 22 of the Massachusetts State Building Code in June 1979 [9]. Experience with Article 22 showed that it allowed building officials more leeway in accepting design alternatives when rehabilitating buildings, reduced the number of appeals on modifications to existing buildings, and generally expedited the rehabilitation process.

The concept included in Article 22 of the Massachusetts State Building Code has had a significant impact on building codes in the United States. Variations of the approach have been incorporated by the International Conference of Building Officials (ICBO) in their Uniform Code for Building Conservation [10]. The State of New Jersey adopted rehabilitation code provisions that provide a method to balance the need for code compliance and the need to encourage and permit building rehabilitation. These concepts were expanded by the U.S. Department of Housing and Urban Development which developed the Nationally Applicable Recommended Rehabilitation Provisions (NARRP).

In summary, NIST has had a significant impact on the more efficient reuse of the nations' building stock by providing resources needed to make technical decisions, and by supporting the development of innovative regulatory approaches to building rehabilitation.

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14.4 DETENTION AND CORRECTIONAL FACILITIES

Because of the rapid increase in new jail and prison construction in the 1980s, and the lack of performance criteria and standards for building materials, equipment and systems, many correctional agencies have experienced equipment and system performance problems in their facilities. In some instances, these problems have necessitated expensive facility retrofits, repairs, or other fixes. In September 1986, the National Institute of Corrections (NIC), U.S. Department of Justice, initiated a study at NBS, which was led by Robert Dikkers. The general objective of the study was to develop guidelines, test methods and the technical bases for standards which would assist in the selection, application, and maintenance of building materials, equipment and systems for use in detention and correctional facilities.

During the first year of the study, the primary focus was on determining the state-of-the-art in the design of detention and correctional facilities. Specific emphasis was placed on identifying performance problems associated with various materials, equipment and systems, as well as reviewing available guidelines, standards, etc. which are or can be used by architects and correctional officials in the planning and design of new correctional facilities. During the conduct of the study, valuable information, comments, and recommendations were received from many individuals involved in the planning, design and operation of jails and prisons.

The conclusions and recommendations of the initial study were published in 1987 [1]. In brief, it was concluded that were many important criteria and standards that needed to be developed for improving the state-of-the-art of selecting materials, equipment and systems for use in detention and correctional facilities. Nineteen criteria and standards development activities were identified and prioritized by a review committee of correctional officials, consultants, and designers. One of the high priority activities, performance criteria for detention and correctional facilities, was selected and funded by NIC for study in the second year.

Performance criteria, which were developed using a performance format

Robert Dikkers, program manager for correctional facilities standards.

previously used by NBS for industrialized housing systems [2] and solar energy systems [3], had the following objectives: (1) establish performance criteria for materials, equipment and systems which are consistent with the security and custody levels used in detention and correctional facilities; and (2) establish standard performance measures with regard to security, safety, and durability of materials, equipment and systems. The preliminary performance criteria were prepared with the assistance of several consultants and were published in 1989 [4]. They covered the following three areas: (1) facility and site - facility mission, security levels, operational considerations, and site selection; (2) perimeter systems - climate and site, perimeter fencing, and intrusion detection systems; and (3) building systems - structural systems, doors, windows, glazing, locks and locking systems, control center, alarm, and communication systems. After additional development, the performance criteria were intended to serve as a technical resource and reference for correctional officials, architects, engineers, material and equipment manufactures, contractors, and standards writing organizations. The criteria were also expected to benefit jail and prison programs by providing a technical performance assessment base from which project specifications and uniform methods for evaluating materials, equipment, and systems could be developed.

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14.5 NATIONAL CONFERENCE OF STATES ON BUILDING CODES AND STANDARDS

The National Conference of States on Building Codes and Standards (NCSBCS) was formed by the nation's governors in 1967 in response to "the need for intergovernmental reforms in the area of building codes," as recommended by the Advisory Commission on Intergovernmental Relations.

From the inception of NCSBCS to October 1976, the National Bureau of Standards provided NCSBCS Secretariat services. These services included administrative and technical support. The authority to furnish this support is contained in the NIST Organic Act. NBS Building Science Series 75 provides background on the formation of the National Conference of States on Building Codes and Standards. Also, discussed is the working relationship with CBT during the period when NBS provided the secretariat and staff for the NCSBCS.

By 1976 with growth and development, NCSBCS matured to the stage of becoming an incorporated entity with administrative self-sufficiency and independence. When NCSBCS entered into contractual agreements with HUD to develop a National Mobile Home Regulatory Program and monitor the enforcement under the National Mobile Home Construction and Safety Act of 1974 and other Federal Government agencies, it realized, as did NBS, that administrative and logistical support by NBS should be transferred to NCSBCS, while technical research support should be enhanced so as to further the goals of both organizations. In September 1976, NCSBCS opened offices in McLean, Virginia. The organization continues to prosper carrying out programs on behalf of the States. NCSBCS in 2000 had a staff of 70 people.

In 1978 NCSBCS and NBS entered into a Memorandum of Understanding that detailed a series of areas in which each organization would provide the other with mutual support. James G. Gross, who had managed the NCSBCS secretariat at NBS, was named senior technical advisor to the conference under this agreement. The purposes of this agreement were to: (1) set forth a commitment of continued mutual support between NBS and NCSBCS; (2) establish a procedure for appropriate joint Program planning and continued technical cooperation between the two organizations; (3) outline the general conditions under which NBS and NCSBCS cooperative efforts will be formulated and conducted; and (4) set forth those technical and other services to be provided either organization by the other.

Through this cooperative effort, both organizations continued to work together toward the common goal of improving the building regulatory system through the application of research and technology. This contributed to the public welfare by providing a safer, more healthful built environment at less cost. BFRL and NCSBCS also cooperated to improve the international competitive climate for U.S. industry by providing technology and regulatory procedures to remove barriers to the export of building products, systems, and know-how.

Both organizations contributed to international acceptable standards and mutual recognition procedures that help U.S. industry and professionals gain access to global markets.

Many technical studies and much research have been carried out in the Building and Fire Research Laboratory (BFRL) as direct result of stated needs by NCSBCS. Examples of such programs include the Laboratory Evaluation and Accreditation Program, Coordinated Evaluation System, Uniform Regulation of Manufactured Buildings and Mobile Homes, design standards for wind and seismic resistance, programs to reduce moisture problems in buildings, and programs to reduce loss of life and property from fire. The use of these results by NCSBCS has contributed to the NIST goal of transferring research findings and up-to-date technology to the States and ultimately the building owner and user.

Beginning in 1976 NCSBCS and NIST sponsored 15 joint technical research conferences addressing improvement of the building regulatory system. The results were published. Some of these conference proceedings are available from NCSBCS.

In 1986, NCSBCS, NBS, The American Society of Civil Engineers (ASCE) and The Association of Major City Building Officials (AMBCO) signed and released a "Model Agreement on the Investigation of Structural Failures." Under the conditions spelled out in this agreement, a jurisdiction may call on NIST to investigate major structural failures.

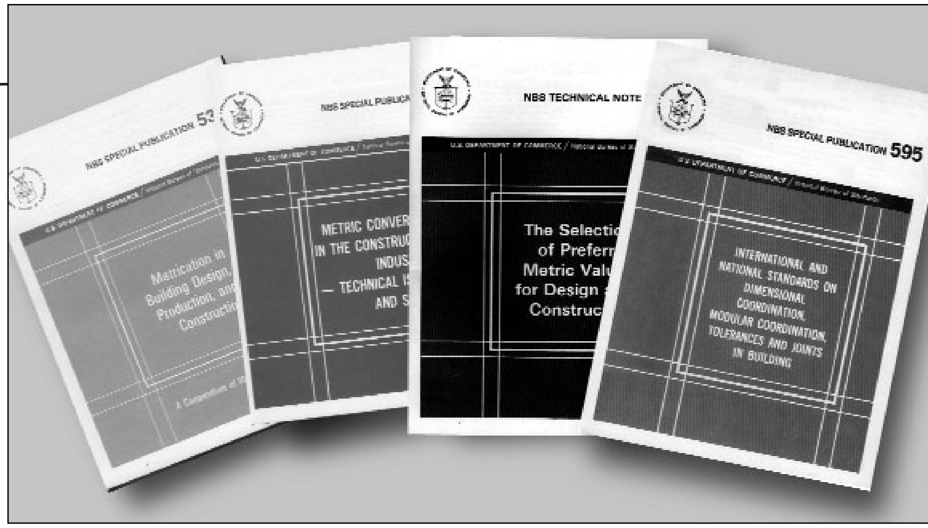
In 1996 NIST and NCSBCS signed an agreement under which the Parties seek to assist the U.S. construction industry in major markets to avoid technical barriers to trade and to promote the application of U.S. technology through the development of appropriate building and construction practices, codes, specifications and standards. It is intended that these efforts will assist in bringing about the establishment of U.S. building and construction codes and standards in international markets. Major projects were undertaken to assist Saudi Arabia and the Caribbean region. The project with Saudi Arabia produced a draft building code for Saudi Arabia based upon the Uniform Building Code produced with the administrative and technical support of ICBO. A Caribbean Region Conference was held in 1997 during which numerous recommendations were put forth to improve building regulations in the region. Some of the recommendations have been acted upon, particularly those recommending revision of regulations and practices to provide greater hurricane resistance in buildings.

In 1996 NCSBCS, with support from NIST and the cooperation of over 50 public and private organizations, embarked upon the Building Regulatory Streamlining project. The project's mission is to enhance public safety, environmental quality, and economic development in states and localities by helping each level of government (federal, state, and local) adopt and implement streamlined administrative procedures, processes, rules, and regulations. The project is intended to eliminate existing areas of regulatory overlap and inefficiency, which have created barriers to safe, affordable, and environmentally sound construction. Through this effort, the project also is designed to support U.S. international economic competitiveness in the construction industry.

Among the goals of the 5 year project are a 60 percent reduction of the regulatory processing time for construction projects and support for the fulfillment of the National Partners in Homeownership Goals and the National Construction Goals for the National Science and Technology Council. The project examined over 200 building regulatory processes and procedures. Fifty-nine models for improvement have been approved by the project participants for implementation. Several states are using the approved models.

14.6 METRICATION FOR CONSTRUCTION

The Metric Conversion Act of 1975 (Public Law 94-168) established a United States Metric Board to provide planning, coordination and public education for the voluntary conversion to metric measurement from U.S. customary units of measurement. At that time there was considerable enthusiasm



A series of CBT reports on metric conversions for the construction sector.

in the building industry for conversion to the Metric (SI) system of measurement. The building industry and the States as represented by the National Conference of States on Building Codes and Standards requested NBS to develop a program to assist in the conversion.

Early it was recognized that one benefit of metrication was the opportunity to select new sizes and dimensions so that products would fit in a coordinated way to reduce job site cutting and fitting which would reduce waste and save time and money. In 1975 CBT started a project "Coordinated Metric Dimensions for Building" to develop information to help industry select new product sizes in a systematic coordinated manner so as to foster efficiency in the building process. Also, the CBT accepted the role of secretariat for the Design, Codes and Standards and the Products Sectors of the Construction Industries Coordinating Committee of the American National Metric Council (ANMC).

Although the U.S. was the first nation to go to the decimal monetary system, it is the last major nation to go to the metric system of measurement. Thus, there was opportunity to learn from others such as England, Australia and Canada. Hans Milton was Chairman of the Government Construction Sector Committee on Metric Conversion in Australia from 1970 to 1975. Australia completed its metric conversion problem in a most effective manner. Milton was recognized as the prime mover in Australia's conversion. In late 1976, CBT arranged a contractual agreement with the Australian government to have Mr. Milton serve as a guest worker in the CBT Building Economics and Regulatory Technology Division to assist the U.S. in metric conversion. This arrangement continued for three years during which Mr. Milton provided technical studies on dimensional coordination and planning for metric conversion to assist the building community.

The first effort was to identify potential conversion problems in the construction codes and standards sector. The results of this study, conducted by Charles T. Mahaffey, were published as NBS Technical Note 915[1].

In response to a request by ASTM Committee E6-Performance of Building Constructions and the American National Metric Council, Hans Milton prepared a Recommended Practice for the Use of Metric (SI) Units in Building Design and Construction [2]. The study results were widely circulated for comment and were processed by ASTM Committee E6 to become an ASTM standard that is widely used and referenced through 2000.

To assist the building community to locate definitive information on metrication and dimensional coordination, a bibliography was prepared and published as a NBS Special Publication [3].

In 1977 at the American Institute of Architects headquarters, the AMNC Design and Construction Products Sectors (CBT held secretariats) sponsored a joint conference to develop background and information on building standards in the metric building world and to examine the opportunity for an industry-wide system of dimensional coordination. Three international speakers were featured. The conference proceedings were published at the request of the attendees' [4]. Many nations recognized the unique opportunities presented by a common measurement system (SI). A study was conducted to identify developments which would impact the U.S. construction community, particularly those related to international trade and competitiveness. Of much interest were European activities and standards development through ISO Technical

Committee TC-59-Building Construction. The identified international trends and developments were distributed to the building community and presented to the National Institute of Building Sciences (NIBS) [5].

During 1977 and 1978, Hans Milton was in high demand as a speaker at national building community meetings. Ten of his papers, each prepared for a different audience, were edited into an authoritative compendium of information on various aspects of metrication from managing the change to training and specific product format [6].

The Naval Facilities Engineering Command (NAVFAC) requested and partially funded a study to provide a rational basis for the evaluation and selection of preferred numerical values associated with metric sizes and quantities. This study was published as a NBS Technical Note [7].

To aid decision making relative to U.S. standards on dimensional coordination, a study was conducted of related standards from other countries, regions and ISO. Standards from over 50 countries were identified. The study showed widespread adoption of 100 mm as a basic building module. Fortunately, this dimension is close to the U.S. accepted building module of 4 inches. The study was sponsored by the Office of Policy Development and Research of the Department of Housing and Urban Renewal and was published as a NBS Special Publication [8].

The National Institute of Building Sciences requested a comprehensive report to provide information on then current technical issues and status of metric conversion in the construction industries as background for a December 1980 national conference "Metric Conversion in the Construction Community." This report was given to all attendees and widely circulated in the construction community [9].

Although metrication was not widely embraced by the construction community, some progress continued. In 1988 Congress amended the Metric Conversion Act of 1975 by the Omnibus Trade and Competitiveness Act (P.L. 100-408). This act made the metric system the preferred system of measurement for the United States. The subsequent issue of the Presidential Order 12770, required the federal agencies to convert federal procurement to the metric system. This led to the formation of the Construction Metric Council of the National Institute of Building Sciences. James G. Gross, who had managed the Metrication for Construction Program as Chief of the CBT Office of Building Standards and Codes and Chief of the Building Economics and Regulatory Technology Division, was named to the Board of Directors. The Construction Metric Council continues to lead metrication for construction. It publishes the "Construction Metrication" quarterly newsletter. This newsletter is available free to interested parties. The documents referenced herein continue to serve as a valuable resource.

In response to requests from ASTM Committee E6-Performance of Building Construction, CBT prepared two draft standards addressing recommended practice for use of metric units in building design and construction [10] and guidance for scales used in building drawings [11] which, after going through the consensus process, became ASTM standards. These standards are still promulgated by ASTM and are widely referenced. Also, CBT led the revision of two standards to include metric dimensions [12,13].

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14.7 MODELING STANDARDS

A standard should be complete (deal explicitly with all instances within its intended scope), clear (unambiguous in each instance as to whether the standard is complied with or not), correct (provide the outcome intended by the standard's writers), and well organized (guide the user to all provisions applicable to the instance). Moreover, standards should be correctly incorporated in computer-aided design software, and the difficulties in incorporating revisions of standards in such software should not be a barrier to the updating of standards. From the mid 70s throughout the 80s, CBT conducted and sponsored research on methods to assist standards writers in the formulation and expression of standards and to assist developers of computer-aided design software in the correct implementation of relevant standards.

Steven Fenves pioneered research on the formulation, expression and application of standards while at the University of Illinois in the 60s. Richard Wright had collaborated in some of this research and involved CBT in the work when he became director in 1974. The content of a standard was examined at four levels: the organizational network relating the requirements to be satisfied, the information network connecting interrelated provisions, the detailed level representing individual provisions in the form of decision logic tables, and the lowest level consisting of the input data for use of the standard [1]. As a guest researcher at CBT, 1975-76, Fenves studied the application of these techniques to the formulation of performance standards [2], mentored colleagues in the use of these techniques in CBT's work and was co-investigator in the application of the techniques to the development of a next-generation standard for the seismic design of buildings [3]. James Robert Harris joined BFRL in 1975 to conduct these studies and received the Ph.D. from the University of Illinois in 1980 for applying the sciences of classification and linguistics to develop a systematic method for outlining and indexing standards [4].

Harris worked closely with the team developing the tentative seismic provisions to assist in achieving a complete, clear, correct and well organized document. The experience gained in this effort was shared with the standards community through a cover story in ASTM's Standardization News [5]. When Harris left CBT in 1981 to start his own consulting engineering practice in Denver, the work on modeling standards was continued by Frederick Stahl and Kent Reed. A computer software system and tutorial was developed and published for Standards Analysis, Synthesis and Expression (SASE) [6] to make the techniques available to standards developers.

Cooperative research with Professor Leonard Lopez of the University of Illinois explored interfacing machine representations of standards with computer-aided design programs. This was called the Standards Interface for Computer-Aided Design (SICAD). The objective was to separate programming of the standard, which would best be done by the standard's developer, from programming of the computer-aided design system. Then the machine representations of standards would represent the standards correctly (a CAD programmer less familiar with the standard would be quite likely to misinterpret it). Also, a standard would not be "hard wired" into the computer-aided design system so that it could readily be used with different standards (such as for different countries) or updated as the standard was improved. Moreover, the standards development organizations could market the machine representations of their standards rather than ceding this market to CAD software developers. Lopez and colleagues developed and demonstrated the SICAD capability [7]. An important lesson learned in this research was the desirability of standard representations of the information contained in computer-aided design systems for buildings, which greatly reduced the amount of work required to develop SICAD implementation. This need resonated with the emerging national and international efforts to develop information interchange protocols in the mechanical and electronics manufacturing sectors.

CBT work on modeling standards dropped to a very low level as the Computer Integrated Construction Group focused its work on information interface protocols for exchange of data in architecture, engineering and construction in the late 80s. Fenves and colleagues summarized the work at CBT and elsewhere and assessed its impact [8]. CBT tried without success in the 80s to interest a major standards developing organization to conduct a pilot application of SASE in the development or revision of a major standard, but Fenves did apply the techniques with the American Institute of Steel Construction in the development of its standard for load and resistance factor design of steel structures. The American Association of State Highway and Transportation Officials applied the SICAD methods in its bridge design system. However, the principles and techniques are not yet widely implemented. They are well documented and available to assist those involved in development of standards and computer aided design systems.

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14.8 FIRE STANDARDS

Advancement of fire standards has been a continuing effort of CFR and BFRL. Research results are delivered to practice through improvements in standards of ASTM; the National Fire Protection Association; the American Society of Heating, Refrigerating, and Air Conditioning Engineers; the International Standards Organization; etc. Need for improvement of standards have been major drivers of the NBS/NIST fire research program. Department of Commerce Awards for advances in fire standards include the Gold Medal to Alexander Robertson in 1976 for career contributions, and the Bronze Medal to Richard Peacock in 1987 for safety of solid fuel heating appliances. Daniel Gross received the NBS Rosa Award in 1987 for his career contributions to fire hazard test method standards.

15. STRUCTURES

15.1 STRUCTURAL FAILURE INVESTIGATIONS

15.1.1 INTRODUCTION

Investigations of the causes of structural failures were a particularly important part of the CBT program from 1975 to 1990. Failure investigations are distinguished from disaster investigations, which also were important for CBT and BRFL and are described in the next section, by their focus on a particular structure and by the absence of an extreme loading. The importance of failure investigations has both technical and pubic policy dimensions. Technically, it is important to understand the physical causes of a failure, determine whether existing standards are adequate to prevent such failures or whether the standards require revision, and disseminate these findings to the profession to avoid repetitions of the failure. Public policy attention is characteristic for major failures as the press, political leaders, concerned groups such as construction labor unions, and the general public become concerned about the safety of the class of structure involved in the failure.

Failure investigations generally do not involve structural research, though they may show needs for research when loadings or mechanisms of failure are found to be inadequately understood. Why then should NBS/NIST do failure investigations? There is a substantial sub-discipline of forensic engineering and architectural firms available to conduct failure investigations for a fee. Congressional hearings [1] made it very clear why NBS/NIST should investigate technically or politically important structural failures. Private investigations generally were funded by a party involved in legal action related to the failure, and therefore viewed as biased. Also, the reports of private investigations generally are sealed by the court as part of the resolution of the case and become unavailable to those not directly involved in the case, but who wish to understand causes in order to avoid repetitions.

As a result of important, successful structural failure investigations conducted by CBT, in cooperation with the Department of Labor's Occupational Safety and Health Administration (OSHA), and at the request of local government authorities, NBS was given a legislative mandate for structural failure investigations in its authorization legislation for fiscal year 1986 [2].

> *The National Bureau of Standards, on its own initiative, but only after consultation with local authorities, may initiate and conduct investigations to determine the causes of structural failures in structures which are used or occupied by the general public.*

Even with this legislation, NBS/NIST lacked authority to demand access to a failure site and information about the structure. Thus for effective investigations of private buildings, local governmental authorities would need to use their regulatory powers to provide access for NBS to the site and data. For federal facilities, NBS/NIST would need the authorities of the responsible federal agency. For failures during construction that injure or kill workers, OSHA has the necessary authority for access and often engaged CBT to investigate on its behalf.

To implement its authorization for structural failures investigations, CBT worked with the National Conference of States for Building Codes and Standards (NCSBCS) to develop a model agreement for a local government and NBS to collaborate in an investigation [3]. However, in the period of this history, through 2000, this agreement was not used.

The building community, Congress and the general public were highly appreciative of the structural failure investigations conducted by CBT. This awareness of the quality and importance of CBT's work were significant in Congressional rejection of the Reagan Administration's proposals for each and every fiscal year from 1984 through 1990 to eliminate or cut in half CBT.

15.1.2 SKYLINE PLAZA APARTMENT TOWER AND PARKING GARAGE

The progressive collapse of this apartment building under construction was triggered by the failure of an upper story floor as a result of premature removal of formwork.

At 2:30 pm on Friday, March 2, 1973, a portion of the apartment tower collapsed for its full height while concreting was underway on its 24th floor and shoring removal was underway on its 22nd floor, and the impact of the debris caused a horizontal progressive collapse of the entire parking garage under construction adjacent to the tower [4]. Fourteen construction workers were killed, four in the garage and ten in the tower, and another 34 were injured.

Initiative is important in failure investigations. Upon learning of the accident from the news, staff of CBT's Structures Division went to the nearby site in the Division's van, gained access for initial reconnaissance, and made contact with OSHA's inspection team. On Monday, March 5, 1973, OSHA requested NBS to ascertain the cause of the collapse and to determine whether non-compliance with OSHA standards had contributed to the collapse. A rapid investigation was required since OSHA had only six months in which to file charges related to violations.

The tower was of reinforced concrete flat plate construction and planned for 26 stories. The parking garage planned for four levels was of unbonded, post tensioned flat plate concrete construction with construction underway for slab B-2, the second level from the top.

The investigation of the tower collapse included studies of the status and condition of the shoring, the properties of the concrete and reinforcing steel, and finite element analyses of the flexural and shearing stresses in the slab. It was determined that premature removal of shoring on the 22nd floor caused punching shear failure of the slab around one or more columns at the

23rd floor. The weight of the debris resulted in failures of the lower floors for the full height of the building. Numerous violations of OSHA standards had contributed to the collapse. E.V. Leyendecker and George Fattal produced a very complete report that became a model for subsequent failure investigations and stimulated study of the maturity (strength gain with time and temperature) of concrete and shoring practices to improve safety of concrete construction.

Understanding of the horizontal progressive collapse in the parking garage was more challenging. The nominal panel dimension was 9 m x 8 m (spacing between columns in the two principal directions) and the garage had a total plan area of 12 by 11 panels 104 m x 91 m. The falling debris impacted only two or so of the 132 panels, but all collapsed by shearing about the columns, which remained standing with the slabs pancaked at the column bases. Because of the importance of this failure, NBS funded a detailed, near full scale, laboratory investigation of the performance of the unbonded post tensioned slab and columns. However, the laboratory testing did not reproduce the failure observed in the field.

15.1.3 Cooling Tower at Willow Island, WV

Shortly after 10 am on April 27, 1978, 51 workers were killed when the top portion of a reinforced concrete hyperbolic cooling tower, being constructed at the Pleasants power station, collapsed with the formwork and scaffolding it supported. CBT investigators arrived at the site on April 29, 1978, in response to a request by OSHA to assist in the investigation of the collapse and determine its most probable cause. CBT conducted field, laboratory and analytical studies [5] and had access to data from OSHA and the constructor.

Collapse of a portion of a reinforced concrete hyperbolic cooling tower.

The tower had reached a height of 61 m of its planned 131 m. Construction was underway on the 29th lift using scaffolding supported only by the concrete of the 28th lift which had been placed the previous day. Detailed studies were made of the patented construction system, site operations, properties of the concrete and other materials, components of the concrete hoisting and scaffolding system, loads acting at the time of collapse, and of the forces generated in the reinforced concrete shell in comparison to its strength. The conclusion was that the most probable cause of the collapse was imposition of the construction loads on the concrete of the 28th lift before it had gained sufficient strength to support these loads. This failure demonstrated dramatically the importance of measuring in-place concrete strengths before initiating a critical construction operation. H.S. Lew received the Bronze Medal Award of the Department of Commerce in 1980 for his leadership of the investigation, and the Silver Medal Award in 1982 for his development of construction safety guidelines to reduce risks of future failures due to immature concrete.

15.1.4 Harbour Cay Condominium

The Harbour Cay Condominium, a five-story flat-plate reinforced concrete building under construction, collapsed shortly after 3 pm on March 27, 1981, killing 11 workers and injuring another 23. The collapse occurred during placement of the roof

Post disaster investigation report of Harbour Cay Condominium collapse.

slab. OSHA requested NBS assistance in investigation of the most probable cause of the collapse. The NBS investigators arrived on site on March 28, 1981, but were limited to general observations of the site until search and rescue operations, which substantially modified the debris, were completed.

The investigation [6] included review of contract drawings and specifications, observations of the site and debris, review of OSHA's interviews with witnesses to the collapse, tests of the strength of concrete and reinforcing steel, and analyses of the loads acting at the time of collapse, forces induced in the structure and the resistance of the structure. The most probable cause of collapse was a combination of design and construction errors: the design did not consider the possibility of punching shear failure and therefore specified a slab thickness of 203 mm when 277 mm was required; top reinforcing steel in the slab at the column was placed lower than specified further reducing the punching shear resistance.

While the slab thickness was less than the building code specified, the slab thickness and reinforcement placement specified in the structural drawings would have provided sufficient punching shear resistance to withstand the construction loads. A careful analysis of the reinforcement shop drawings by George Fattal and Nicholas Carino revealed that incorrect bar support chairs were used in critical portions of the slab.

15.1.5 KANSAS CITY HYATT REGENCY WALKWAYS COLLAPSE

On Friday July 17, 1981, at 7:05 pm two suspended walkways within the atrium area of the Hyatt Regency Hotel in Kansas City, MO collapsed during a dance. One hundred thirteen people died and 186 were injured. In terms of loss of life and injuries, this was the most devastating structural collapse to have taken place in the United States. On Monday July 20, 1981, Senator Thomas Eagleton on Missouri contacted Ernest Ambler, director of NBS, to request that technical assistance be provided to Kansas City. Ambler agreed, and later in the day Kansas City Mayor Richard Berkley requested technical assistance. Two NBS structural research engineers, Edward Pfrang and Richard Marshall, visited Kansas City on July 21 and met with the Mayor and other City officials. On July 22, Mayor Berkley formally requested that NBS independently ascertain the probable cause of the collapse of the walkways.

However, access to the site and data relevant to the failure were not easily attained. Kansas City provided access to its regulatory data, but did not use its authority to provide access to private data. Edward Pfrang, chief of CBT's Structures Division, worked forcefully and skillfully with the press, attorneys for plaintiffs and defendants, and the courts to obtain access to the site, the remnants of the skywalks and debris, and construction documentation. However, access never was gained to structural calculations and change orders involving the skywalk structural system.

The skywalks that fell had crossed the atrium at the fourth and second floor levels [7]. The fourth floor skywalk was suspended by hanger rods connecting the skywalk's crossbeams to the trusses supporting the atrium roof. The second floor skywalk was immediately beneath the fourth floor skywalk and suspended by hanger rods connected to the crossbeams in the fourth floor skywalk. Evidence from observers and debris revealed that the bolts and washers transferring the loads of the second and fourth floor skywalks to the hanger rods had deformed the fourth floor crossbeams and pulled through the crossbeams allowing the fourth floor skywalk to fall with its sus-

Collapsed walkways in the Hyatt Regency Hotel atrium.

pended second floor skywalk to the atrium floor below.

CBT, with support from the NBS Center for Materials Science, inspected the atrium area and the debris stored in a warehouse, weighed debris to ascertain the weights of the walkways, removed selected materials for laboratory testing, reviewed documents from design and construction, videos made just before and after the collapse, and photographs from the accident site. Laboratory studies were conducted of mockups to represent conditions at the time of failure, and of actual specimens from the debris. Analytical studies determined the response of the skywalks to the loads at the time of collapse.

The investigation revealed that the original design for connection of the crossbeams to the hanger rods, which had the hanger rods running continuously through the fourth floor crossbeams to the second floor crossbeams, was not in accord with applicable codes and standards and had only 53 percent of the required capacity. The design had been changed to suspend the second floor skywalk from the fourth floor skywalk, rather than on continuous hanger rods, resulting in a doubling of the forces that had to be transferred from the fourth floor crossbeams to the hanger rods. This doubling of the force on an already inadequate connection was the cause of the collapse.

The investigation received much public attention and CBT's work was highly commended (sidebar). CBT staff, notably Richard Marshall and E.V. Leyendecker, worked very effectively under intense scrutiny by the press and attorneys. Matt Heyman, chief of NBS's Public Information Division, was very helpful in dealing with the press and guiding CBT's staff in their interactions.

Editorial from the Kansas City Times on February 27, 1982

On July 18, 1981, no one in this area was prepared mentally or technically to investigate the causes or causes of Kansas City's worst disaster. Two days later, Sen. Thomas F. Eagleton, followed by Mayor Richard L. Berkly, Sen. John C. Danforth and Rep. Richard Bolling, called on the National Bureau of Standards in Gaithersburg, Md., to investigate the collapse of the Hyatt Regency sky walks.

For those politicians it was second nature to turn to the unique resources of the federal government for a thorough and impartial study that no party involved - not the city, the hotel owner, the builder or anyone else - could have provided. The mandate of the NBS is "to strengthen and advance the nation's science and technology and to facilitate their effective application for the public benefit." The NBS is singularly suited to investigate such complex disasters as the Hyatt.

In the Hyatt investigation, the client is the public of the entire country, the people who use buildings in the course of their lives. The NBS study is paid for with taxpayers' money and the results are matters of public record, for all interested parties to see and learn from.

Ultimately, the results of the study could revolutionize building design and inspection procedures. Such a move would start from a broader base of public acceptance because of the impartial manner in which the NBS team worked to meet its primary obligation to satisfy the public's right to know what happened and why.

Imagine how different the results of the Hyatt study might have been had no pool of experts existed at the NBS headquarters. Imagine where the public would be had there been no such specialized federal agency for this confused, bewildered city to turn to in its time of great need.

Collapse of a concrete highway ramp under construction.

The building community was greatly interested in the investigation for both the physical causes of the failure and for the failures in the building process that had allowed the severe deficiencies in design and construction to have escaped attention. Edward Pfrang's effectiveness in the investigation and dissemination of its results was a significant factor in his being offered and accepting the position of Executive Director of the American Society of Civil Engineers (ASCE) in 1983. In 1982, he and Richard Marshall received the Gold Medal of the U.S. Department of Commerce for their leadership of the investigation. The building community's concern to improve its processes to avoid such defects and accidents in the future led to ASCE's development of a Manual of Professional Practice [8].

15.1.6 RILEY ROAD INTERCHANGE RAMP, EAST CHICAGO, INDIANA

On April 15, 1982, thirteen workers were killed and fifteen injured in the collapse of a highway ramp under construction in East Chicago, Indiana. OSHA requested technical assistance from NBS to determine the cause of the failure. CBT structural engineers arrived on the site on April 17. The investigation [9] included site investigation, experimental and analytical studies.

The ramp was being built by the method known as cast-in-place, prestressed, post-tensioned concrete. At the time of the collapse, the ramp was unable to support its own weight and was supported by a temporary support system know as "falsework." The conclusion was that cracking of a concrete pad supporting a falsework tower was the triggering mechanism of the collapse. Deficiencies contributing to the collapse were: omission of wedges between falsework stringers and crossbeams, inadequate strength of the concrete pads, lack of stabilization of falsework towers against longitudinal movement, and poor weld quality in U-heads supporting cross beams at the top of the falsework towers. This investigation highlighted the importance of careful consideration of the design of all components of the temporary support system used in concrete construction.

15.1.7 STRUCTURAL ASSESSMENT OF THE NEW U.S. EMBASSY OFFICE BUILDING IN MOSCOW

On September 24, 1986, CBT director Richard Wright was called by staff of the Senate Appropriations Committee. "Could you assess the structural integrity of the new U.S. Embassy Office Building in Moscow?" The answer was "yes." "Could you do it in six months for $500,000?" The answer was "we do not yet know enough about the situation to make an estimate." Anyhow, a few days later The Continuing Appropriations Act for Fiscal Year 1987, Public Law 99-591, directed the NBS to conduct an independent assessment of the new U.S. Embassy Office Building in Moscow, in six months and for $500,000. The assessment was to include "an assessment of the current structure and recommendations and cost estimates for correcting any structural flaws and construction defects." Though no structural failure occurred, this study is included here because of its similarity to a failure investigation in both the technical work and the high visibility and priority given the investigation [10].

Under terms of a 1972 agreement between the U.S. and the Soviet Union, the Soviets were responsible for the detailed design and construction of the Embassy Office Building with a Soviet building system widely used in Moscow. This system is comprised mostly of precast reinforced concrete structural elements. The general design was prepared by U.S. firms from 1973 to 1976, construction at the site began in 1979, structural framing was in place in June 1982, exterior walls were substantially complete in November 1983, but construction was suspended in August 1985, except for placement of a temporary roof in November 1986. Construction was suspended because of concern for electronic security in the building (but NBS investigators were instructed to observe nothing related to electronic security). However, official U.S. inspections of the building had observed apparent structural defects so NBS was instructed to provide "an assessment of the current structure and recommendations and cost estimates for correcting any structural flaws and construction defects."

Access to the site and data were difficult to attain. The U.S. and Soviet Union were in a process of expelling each other's diplomats, Soviet workers had been withdrawn from the Embassy making it difficult to support NBS investigators on the site, the U.S. State Department was restricting official visitors to Moscow, and the Soviet Union was not eager to permit entries. NBS management realized the importance of the assignment and assigned Samuel Kramer, deputy director of the National Engineering Laboratory, widely acquainted with Congress and federal agencies, and an inspired expediter, to arrange for access to data on the building available in the U.S. and for access to supplies in Moscow. Kramer skillfully used the Congressional priority to obtain the permissions and resources needed for success of the investigation.

Security and logistical restrictions limited the number of CBT staff who could visit the site and have full access to data on the building. Nicholas Carino was the leader of the project, and William Stone, whose rock climbing expertise provided important access to the structure, also was fully involved in the investigation. Mary Sansalone provided detailed review of the structural plans and calculations and prepared summaries for use at the site. Alexander Rosenbaum, an émigré well informed on Soviet design and construction practices, was engaged to assist in studying the calculations, plans and characteristics of the building system. Because management involvement was needed in the project and site work, Richard Wright participated with technical emphasis on structural steel aspects, and James Gross, deputy director of CBT, participated with technical emphasis on masonry aspects.

With a tight deadline and a Moscow winter approaching, it was frustrating to be unable to visit the site until December 17-19, 1986, but there was much useful work to be done in studying the calculations, plans and information available in the U.S. Fortunately, the building was heated. The initial visit provided an overview of the condition of the structure and building. This information provided insights for planning the investigations during the second site visit from February 17 to March 6, 1987, and for laboratory studies of typical details prior to the second site visit. Carino, Stone and the rest of the project team put in long hours in the field and laboratory to meet the project deadline with a well-received report.

CBT investigator Nicholas Carino, research structural engineer, uses a borescope to examine the condition of the joint between segments of precast columns in the U.S. Embassy Office Building in Moscow. The investigation revealed many cases where large voids were present in the joints between precast structural members.

The investigation found that structural materials and components used in the building were of generally good quality, but important deficiencies existed that should be corrected before the building would be occupied. It had been hard to find a properly grouted connection between pre-cast concrete columns, or a properly completed connection between pre-cast concrete shear wall panels and adjacent panels or columns. All such connections required inspection and completion. The design had not considered resistance to progressive collapse; recommendations were made for enhancing this resistance. The costs for the remedial measures were estimated to be less than $2 million and to take less than a year to accomplish, if the work were done in the Washington, DC area.

Some critics felt that progressive collapse should not be an issue, but subsequent U.S. experience with terrorist attacks has shown its importance. The building has been modified for electronic security, repaired and placed in service. Nicholas Carino received the Silver Medal Award of the Department of Commerce in 1987 for his leadership of the investigation.

Appearance of the L'Ambiance Plaza apartment building that collapsed during construction.

15.1.8 L'AMBIANCE PLAZA BUILDING COLLAPSE

The L'Ambiance Plaza apartment building under construction in Bridgeport, Connecticut collapsed at about 1:30 pm on April 23, 1987, killing 28 construction workers. The building was being constructed by the lift slab method. Two-way reinforced and post-tensioned concrete slabs for floors and roof were cast on the ground, and then lifted by jacks on the steel columns to their final positions. At the time of the collapse, three levels of parking garage slabs and six levels of floor slabs were in place in the east tower, three levels of parking garage slabs and three levels of floor slabs were in place in the west tower, and a package of three slabs was being placed in a temporary position in the west tower. In the collapse, all of the slabs fell.

OSHA requested technical assistance from NBS in determining the most probable cause of the failure on April 24, 1987; CBT engineers led by Charles Culver, chief of the Structures Division, arrived on site at 6:00 pm that same day. While priority was given to rescue efforts, CBT collected data on the nature of the failure of various structural elements. In its investigation [11], CBT used: information on the construction procedures and collapse from interviews of survivors and witnesses conducted by OSHA; project documentation including design specifications, plans, shop drawings, construction records, testing laboratory reports, and project correspondence; laboratory tests of samples removed from the collapsed structure; data from a subsurface investigation of the site after the collapse; and analytical studies of the stability of the columns and forces induced in the slabs and connections during the lifting operations.

The most probable cause was determined to be excessive deformation of a shearhead that connected the jacking rods to the package of three slabs, which led to the slipping off of a jacking rod, which increased loads on adjacent jacking rods causing them to slip off or fracture, which led to failure of the slabs, whose debris caused lower slabs to also fall, which led to general collapse of the west tower, which led to collapse of the adjacent east tower, probably as a result of impacts of debris or pulling action from the west tower. The mechanism of shearhead deformation and slipping off of the jacking rod was reproduced in the laboratory within the range of loadings used in the lifting operations.

Much controversy arose about the cause of this failure. A number of papers were published in the American Society of Civil Engineers' Journal of Performance of Constructed Facilities (12) and alternative hypotheses discussed [13]. OSHA showed its confidence in the investigation by engaging Culver to become director of its Office of Construction and Engineering in 1988. However, this did become the final CBT construction failure investigation for OSHA because, under Culver's leadership, OSHA subsequently conducted its own investigations. As a result of the failure and the lessons learned in its investigations, the American Society of Civil Engineers established a Task Committee on Lift Slab Construction to develop guidelines for successful lift slab construction and OSHA published new rules on this construction method.

15.1.9 ASHLAND OIL STORAGE TANK COLLAPSE

On January 2, 1988, a 15.6 million liter capacity oil storage tank at the Ashland Petroleum Company Floreffe Terminal near West Elizabeth, Pennsylvania collapsed as it was being filled to capacity for the first time since it was reconstructed at the site after more than 40 years of service in Cleveland Ohio. The contents flowed into the Monongahela River approximately 40 km upstream from Pittsburgh and contaminated the water supplies of many communities on the Monongahela and Ohio rivers. Congressman Doug Walgren, the Fire Marshall of Allegheny County and the Governor of Pennsylvania requested NBS to conduct an independent technical investigation into the cause of the collapse. The Ashland Petroleum Company provided full access to the site and its data on the tank and its use to NBS's and others' investigations.


Brittle fracture propagation occurring in tank caused it to rupture and spill its full contents into the neighboring Monongahela River.

Data were obtained from NBS field observations, laboratory and analytical studies [14], from the investigation of the Pennsylvania Tank Collapse Task Force appointed by the Governor, and from the Battelle Columbus Division investigation sponsored by Ashland. The cause of the failure was determined to be brittle fracture initiating from a flaw existing prior to the reconstruction of the tank. Complete rupture of the tank occurred because its steel was of inadequate toughness at the operating temperature to prevent brittle fracture propagation. The steel did not meet the standards of the American Petroleum Institute which were effective at the time of reconstruction of the tank. Concern was expressed for the risk that other tanks might be in service with steels of inadequate fracture toughness for their conditions of use.

John Gross of CBT led the investigation for NBS and John Smith of the Institute for Materials Science and Engineering led its metallurgical aspects.

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15.2 DISASTER INVESTIGATIONS

15.2.1 INTRODUCTION

Post disaster investigations were important to BFRL and its predecessor organizations for both technical and public policy reasons. Technically, an extreme wind, earthquake or conflagration would test the performance of structures and fire protection systems at a scale impossible in the laboratory. Investigations allow confirmation of engineering knowledge and practice or identification of unanticipated mechanisms of failure and needs for research. Politically, a disaster would focus public and policy makers attention on the importance of good structural performance to gain impetus for implementation of improved practices, such as up to date wind or seismic design and construction practices, or for research and development of improved practices when the best available were shown not to prevent unacceptable losses. Thus, disaster investigations have been the impetus for sustained program funding, such as the National Earthquake Hazards Reduction Program, for significant one-time funding to respond to needs for improvements of practice revealed by the disaster, and for public policies such as executive orders for implementation of seismic design and construction practices.

The disaster investigations cited here did not include research or in-depth technical studies needed to develop technical bases for improvements in practice. Rather, they cited evidence of the harmful consequences of not using up-to-date wind or seismic design and construction practices, and identified opportunities to learn from the performance of structures in the extreme environment. They did lead to much research, by CBR/BFRL and others, to address issues identified in the investigations. From the 1989 Loma Prieta and the 1994 Northridge earthquakes substantial supplemental appropriations from Congress were received to address the research needs identified.

Post disaster investigations by NBS began in 1969 with the investigation of Hurricane Camille and continued with investigation of tornado damage in Lubbock, Texas in 1970, the San Fernando Earthquake in 1971, and the flooding from Hurricane Agnes in 1972. These are covered in earlier histories of building research at NBS. Under the leadership of Edward Pfrang for the San Fernando Earthquake, NBS showed the advantages in private and public policy attention of being the first to publish a substantive report. However, subsequent managers and staff were unwilling to devote the necessary energy and resources, and break commitments to other deadlines, to maintain this advantage.

Structural damages to low-rise commercial and residential constructions caused by the 1997 Jarrel, Texas tornado included the partial collapse of the roof of a supermarket. The roof was supported by open-web steel trusses.

15.2.2 WIND INVESTIGATIONS

Richard Marshall joined NBS in 1968 and devoted his career, until retirement in 1996, to field and laboratory studies of wind forces and effects on structures. He led many important wind disaster investigations. Following the December 25, 1974 Cyclone Tracy in Darwin, Australia, he collaborated with Australian authorities in investigation of the loads on damages to buildings [1]. Findings for residential buildings were very applicable to U.S. practice: wall sheathing must be strong and well attached to function in transmittal of lateral forces, and roofs must be firmly connected to walls and walls to foundations in order to hold structures together. Although about 80 percent of the city's houses were severely damaged by winds estimated to range from 49 m/s to 76 m/s (3 s gust at 10 m above ground) well constructed buildings were observed to have performed well. Sound design and construction can minimize damages.

Marshall participated in the National Academies' investigation of the effects of Hurricane Hugo in 1989 on Puerto Rico, the Virgin Islands and Charleston, SC [2, 3]. Hugo was the costliest hurricane to date to impact the United States. Marshall's investigation focused on the Virgin Islands and Puerto Rico and on estimation of the wind forces from limited meteorological measurements and from assessments of damages based on the qualities of construction. It showed that wind velocities in Puerto Rico were less than specified in the building code. Properly designed and constructed buildings indeed showed minimal damages. Wind velocities in the Virgin Islands exceeded code levels, but the code levels were grossly inadequate for the wind hazard and should be increased.

Hurricane Andrew struck south Florida on August 24, 1992, to cause an estimated $25 billion in damage. Marshall was co-leader of a joint investigation by the Wind Engineering Research Council (WERC) and NIST. Walter Rossiter of NIST also participated in the studies of damages to roofing. The investigation concluded that wind speeds, related to engineering design conditions, were between 49 m/s and 56 m/s , while the current engineering standards and codes called for between 51 m/s and 53 m/s. These findings led to disagreements with the National Oceanic and Atmospheric Administration (NOAA) authorities who estimated peak wind velocities of 89 m/s. Actually, both were correct. The engineering design wind was the velocity averaged over the time required for a particle to travel 1.6 km, about 30 seconds, and measured at a height of 10 m above the ground. The NOAA figure was for a short duration gust in a very localized "microburst" area of high intensity wind. Most of the damages and losses were due to structures not being built in accord with the existing building codes. NIST's review requirements did not allow Marshall and Rossiter to be authors of the WERC report, but Marshall did conduct follow-up studies for the Department of Housing and Urban Development (HUD) to recommend improved wind resistant standards for manufactured ("mobile") homes [4]. After much controversy, these standards were adopted in HUD's mandatory standard for manufactured homes and have substantially reduced wind vulnerability at modest cost.

Tornado wind velocities also tend to be estimated at very high levels by the National Weather Service giving the impression that extensive damages are inevitable "acts of God." Indeed wind velocities at the edge of the funnel can be very high and impractical to resist in small buildings, but funnels are narrow and velocities drop off rapidly beyond the funnel so that well constructed small buildings can survive something less than a direct hit. Long Phan and Emil Simiu investigated damages in the Jarrell, Texas tornado of May 27, 1997 [5] to assess the wind speeds and Fujita (F) Class of the tornado. The area had no building code and the destroyed buildings had connections of roofs to walls and walls to foundations that would not meet an appropriate building code. The damages were consistent with an F3 tornado with speeds ranging from 71 m/s to 92 m/s rather than the F5 of 117 m/s to 142 m/s tornado identified by the National Weather Service.

On May 30, 1998, at 8:38pm (CDT), a violent tornado struck the town of Spencer, South Dakota, a small farm community approximately 72 km west of Sioux Falls, leaving 6 dead, more than 150 injured, and nearly 90 percent of a total 195 structures in the six-by-seven blocks community destroyed. Following the passage of this tornado, BFRL researchers visited Spencer and conducted aerial and ground surveys to document structural damage. Post disaster investigations provide valuable information on the responses of structures to extreme loads. Complete documentation of instances of successful or poor performance can yield valuable lessons that can be used to improve construction practices. The picture shows the complete collapse of a water tower in Spencer.

Collapsed steel water tower in Spencer, South Dakota due to the May 30, 1998 Spencer tornado.

15.2.3 EARTHQUAKE INVESTIGATIONS

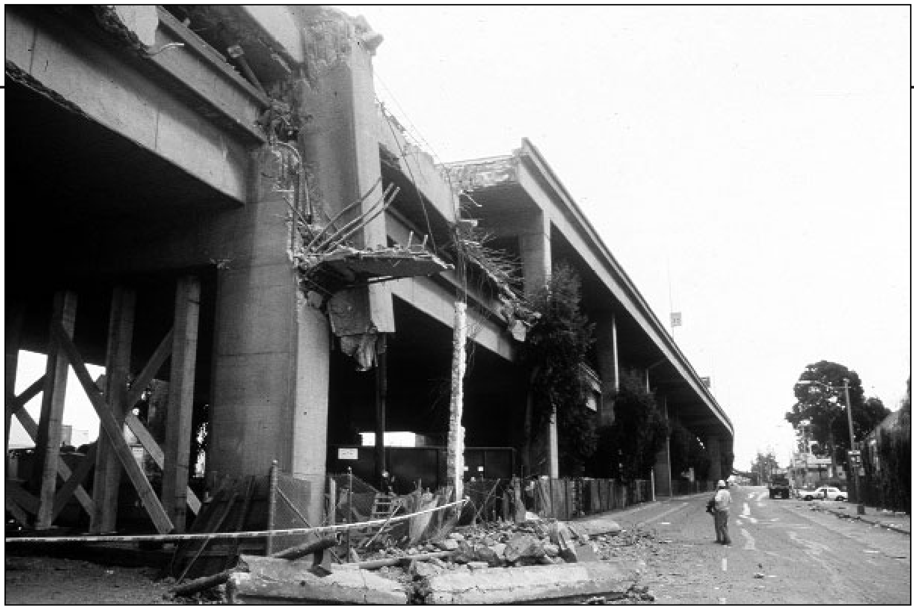
The Miyagi-ken-oki, Japan, Earthquake of June 12, 1978, was of great interest to the U.S. because the earthquake was large, Richter magnitude 7.4, provided design level shaking to many modern structures including an operating nuclear power reactor, and was well instrumented to allow good comparison of structural performance to the actual ground shaking. Because of CBT's leadership in the creation and operation of the U.S-Japan Panel on Wind and Seismic Effects, a multi-disciplinary, multi-agency, U.S. team received access and Japanese government support in investigating the earthquake [6]. Structural performance was generally good, for instance the nuclear reactor was similar to U.S. designs and was undamaged. Damages were concentrated where deep, soft soil conditions amplified motions, suggesting that design criteria consider these effects, where structural asymmetry concentrated distortions, or where bridge piers were non-ductile.

The Mexico earthquake of September 19, 1985, was of great interest to the U.S. because severe damages occurred to modern buildings located at a large distance of 386 km from a great earthquake of Richter magnitude 8.1. Such conditions could occur in the United States: for Chicago from a repeat of the great 1811-12 New Madrid, MO earthquakes, for California cities in response to a great earthquake on the San Andreas fault, or for the Pacific Northwest from a great earthquake in the subduction zone off shore. Therefore, the CBT-led Interagency Committee on Seismic Safety in Construction (ICSSC) organized a multi-agency, multii-disciplinary team to investigate the earthquake [7]. The investigation showed that amplifications of motion in areas of deep, soft soil deposits were responsible for the most severe damages. Standards and codes for the U.S. needed updating to account for such foundation conditions. William Stone received the

Bronze Medal Award of the Department of Commerce in 1987 for his leadership of the investigation.

The magnitude 7.1 Loma Prieta, California earthquake of October 17, 1989, which caused extensive damages in the San Francisco Bay area at a distance of 96 km from the epicenter, showed the relevance of the Mexico City experience. Again, damages were concentrated in areas of deep, soft soil deposits as shown by the investigation of the CBT-led ICSSC [8] and others. Severe damages occurred to bridge structures and loss of water supplies exposed San Francisco to the threat of conflagration like that of 1906. Fortunately, winds were light and the fires did not spread. Congress and the Administration proved much more sensitive to U.S. experience than to warnings from foreign earthquakes and provided substantial supplemental funding to study seismological aspects and building performance to develop recommendations for improvements of standards for new and existing structures. The President also issued an Executive Order, which had been drafted years before by the ICSSC, to call for application of up-to-date seismic standards in the design and construction of federal and federally leased, assisted or regulated new building construction.

H.S. Lew led the investigations of the Loma Prieta earthquake and the subsequent Northridge and Kobe earthquakes. In addition to his good sense for structural behavior he showed remarkable capabilities to elicit the cooperation of emergency management authorities, team members, other investigators and the representatives of the organizations responsible for the facilities being studied.



A failure of supporting columns resulted in the collapse of the bi-level I-880 Viaduct during the 1989 Loma Prieta Earthquake in the San Francisco area.

The magnitude 6.8 Northridge, California earthquake of January 17, 1994, caused severe damages. The investigation of the BFRL-led ICSSC [9] and others showed that most damages occurred to structures already known to be inadequate. However, there was a big surprise in the brittle behavior of modern welded steel frame buildings, and a demonstrated need to improve standards for deformation compatibility of structural members. Major supplemental funding was provided for studies of design criteria for new welded steel frames and for retrofit criteria for existing welded steel frames, and for improvement of the performance of new and existing bridges. (BFRL's work on welded steel frames is described in section 15.12.) Again the risk of conflagration following an earthquake was demonstrated; a BFRL-led workshop [10] developed recommendations for research and improvement of practices. The President issued another ICSSC-developed Executive Order to assess the seismic risks produced by existing hazardous federal or federally leased buildings.

The magnitude 6.9 Kobe, Japan earthquake of January 17, 1995 took 6,000 lives and caused economic losses estimated at over $200 billion. Because the earthquake was exemplary of what a close in earthquake could do to a modern city, the BFRL-led U.S. side of the U.S.-Japan Panel on Wind and Seismic Effects conducted an investigation of the performance of structures, lifelines and fire protection systems in the earthquake [11]. The findings and recommendations of the study identified research and improvements in practice to reduce urban earthquake disasters, and are being addressed in ongoing U.S. and Japanese earthquake risk reduction programs.

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15.3 STRUCTURAL RELIABILITY

Structural codes and standards provide the foundation of good engineering practice and a framework for addressing safety and serviceability issues in structural design. They identify natural and man-made forces that must be considered, define magnitudes of these forces for design, and prescribe methods for determining structural resistance to these forces. The framers of these documents on which the structural engineer places so much reliance must address the question: "How safe is safe enough?" on behalf of society as a whole. Code development is a grave responsibility and, for the most part, has been done well since failures of constructed facilities are rare. On the other hand, such failures, when they do occur, are highly visible and their consequences are severe in human and economic terms for all involved.

At the root of the structural safety problem is the uncertain nature of the man-made and environmental forces that act on structures, of material strengths, and of structural analysis procedures that, even in this computer age, are no more than models of reality. The natural consequence of uncertainty is risk. Structural engineering, as applied to civil construction and in contrast to other engineering fields, relies heavily on analysis and computation rather than on testing because of the scale and uniqueness of typical civil projects in both public and private sectors. Structural codes are linked to computational methods of safety assessment, and their primary purpose is to manage risk and maintain safety of buildings, bridges and other facilities at socially acceptable levels.

Until the 1960s, the safety criteria in structural codes were based on allowable stress principles. The structural system being designed was analyzed under the assumption that it behaved elastically (the fact that structures seldom behave elastically to failure was disregarded). Uncertainties were addressed by requiring that the computed stresses did not exceed a limiting stress (at yielding, rupture, instability) divided by a factor of safety. These factors of safety were selected subjectively; one might, for example, identify the load acting on a structure and then design the structure so that the elastic stresses due to that load remain below 60 percent of the stress at yield (implying a factor of safety of 5/3). Of course, no one knew what the risk of failure was for such a structure. The factor of safety of 5/3 simply represented a value judgment on the part of the standard-writers, based on past experience. During the past century, with the advent of formal structural calculations, the trend in the factor of safety generally has been downward.

This judgmental approach to safety works well as long as the technology being dealt with is stable or evolves slowly and there is opportunity to learn from experience in the standard development process. Occasionally, of course, engineers become overconfident, ignorance catches up or construction practice overreaches the state of the art, and failures occur. More than in most other engineering disciplines, the profession of structural engineering seems to have progressed by learning from its mistakes. To the discomfort of many structural engineers, this learning process usually takes place in the public arena.

The late 1960s also witnessed the beginnings of the move toward a new philosophy toward structural design in the United States, Canada and Western Europe. The shortcomings of allowable stress design were recognized in many quarters, and a search was underway for more rational approaches to distinguish between conditions (termed limit states) directly related to acceptable structural performance, to ensure safety under rare but high-hazard conditions, and to maintain function under day-to-day conditions. Concurrently, the new field of structural reliability was developing around the notion that many of the uncertainties in loads and strengths could be modeled probabilistically. Advances were being made in first-order reliability analysis, stochastic load modeling and supporting statistical databases. Several probabilistic code formats were suggested, including an early version of Load and Resistance Factor Design (LRFD) for steel buildings. However, these early proposals were relatively narrow in scope, and dealt with single construction technologies in isolation from one another. With this lack of coordination, there was a risk that as different standard-writing groups moved toward probability-based limit states design, each would develop load requirements independently, and that these load requirements would be mutually incompatible in structural engineering practice, where construction technologies usually are mixed. Leaders of the profession agreed that structural load requirements must be independent of construction technology to facilitate design with different construction materials.

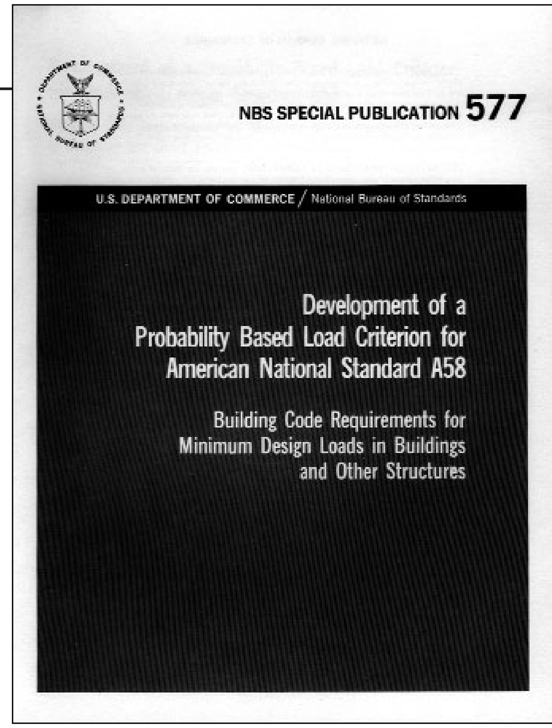
At this time, the Secretariat for American National Standard Committee A58 on Minimum Design Loads for Buildings and Other Structures was administered in the Structures Division of the Center for Building Technology. The antecedents at NBS for this standard dated back to 1924, when the Building and Materials Division published a report under the auspices of the Department of Commerce Building Code Committee on Minimum Live Loads. Research on probabilistic methods in structural standards and codes was a central thrust in the CBT throughout the 1970s, with the work of Charles Culver and Bruce Ellingwood in probabilistic analysis of live and fire loads [1,2], of E.V. Leyendecker and Ellingwood on provisions for general structural integrity to reduce risks of progressive collapse [3], of Ellingwood on wind and snow loads [4] and load combinations for reinforced concrete design [5], and of Emil Simiu, Richard Marshall, James Filliben and in wind loads [6]. This work stood at the intersection of research and practice; its products were internationally recognized in both research and professional communities and incorporated in the A58 standard.

Various standard-writing groups in the United States agreed that the A58 Standard was the logical place for material-independent load criteria to appear. In 1978, Ellingwood accepted the challenge of leading the development of a set of common probability-based load requirements for limit states design that would be compatible with all common construction technologies. He arranged for three other leaders in reliability-based structural codes, Professors Theodore Galambos, James MacGregor, and C. Allin Cornell (father of NIST's 2001 Nobel Prize winner, Eric Cornell), to join him at NBS during the summer of 1979 to develop a set of load requirements using advanced structural reliability analysis methods and statistical databases. The objectives of this joint effort were to:

- recommend a set of load factors and load combinations for inclusion in the A58 Standard that would be appropriate for all types of building construction (e.g., structural steel, reinforced and prestressed concrete, engineered wood, masonry, cold-formed steel and aluminum), and
- provide a methodology for various material specification groups to select resistance criteria consistent with the A58 load requirements and their own specific performance objectives.

The product of this collaboration was, Development of a Probability-based Load Criterion for American National Standard A58, NBS Special Publication 577 [7], which was published in June, 1980. Subsequent developmental work on probability-based codes in the United States in such diverse applications as buildings, bridges, offshore structures, navigation facilities, and nuclear power plants in the intervening two decades all can be traced back to this one seminal document.

The probability-based load criteria in NBS Special Publication 577 were first implemented through the voluntary consensus process in the 1982 edition of American National Standard A58. They have appeared in all editions of that Standard (the standard has been published as American Society of Civil Engineers (ASCE) Standard 7 since 1985) since then, most recently ASCE Standard 7-98, and have remained essentially unchanged since 1982.They have been adopted by reference in all standards and specifications for limit states design in the United States, including the American Institute of Steel Construction's LRFD Specification for Steel Structures (1986, 1994 and 2000 editions), ASCE Standard 16-95 on LRFD for Engineered Wood Construction, and American Concrete Institute Standard 318-96 (Appendix B). They also have been adopted in the International Building Code 2000, the new single model code in the United States. In retrospect, the move toward probability-based limit states design may seem like a small step, but in fact it was not.


NBS SPECIAL PUBLICATION 577

U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

Development of a Probability Based Load Criterion for American National Standard A58

Building Code Requirements for Minimum Design Loads in Buildings and Other Structures

NBS SP 577 joint authored by Bruce Ellingwood, research structural engineer, CBT on probability based load criterion for A58[7].

It required a thorough re-examination of the philosophical and technical underpinnings of the current bases for structural design, as well as the development of supporting statistical databases. Much of this supporting research is still utilized in code development and improvement activities worldwide. It has become the basis for structural design as it is now practiced by professional engineers in the United States.

It is unlikely that these probability-based load criteria efforts would have been completed and implemented in professional practice successfully had they been managed by any other than CBT/NBS. CBT was viewed as representing the structural engineering community at large rather than any one special interest group. The load criteria were completed successfully because they were developed by engineering researchers who were familiar, first of all, with the structural engineering issues involved, as well as with the reliability tools necessary for analyzing uncertainty and safety.

In a more general sense, the load criteria that were developed in this study and reported in NBS Special Publication 577 have had a profound influence on structural codes used worldwide in design of buildings and other structures. The approach taken - developing supporting statistical databases, calibrating to existing practice, and calculating load and resistance factors to achieve desired reliability levels - was followed in a subsequent National Cooperative Highway Research Program study to develop limit states design procedures for highway bridges, now published as an American Association of State Highway and Transportation Officials standard. The National Building Code of Canada will adopt a similar approach to combining loads in its 2000 edition.

Standard development organizations in other countries, including Australia, New Zealand, South Africa, Japan, and Western Europe (through the Eurocodes) have adopted similar load combination requirements for structural design. The NBS Special Publication 577 load combinations have been recognized internationally as the first developed using modern probability-based load combination analysis techniques. They have stood the test of time, and only minor changes have been required as a result of additional research and advances in other areas of structural load modeling during the past two decades.

The probabilistic approach to structural safety embodied in this groundbreaking activity continues to resonate in the structural engineering community. The aftermath of natural and man-made disasters during the past two decades, rapid evolution of design and construction methods, introduction of new technologies, and heightened expectations on the part of the public, all have made judgmental approaches to ensuring safety of the built environment increasingly difficult to defend. The traditional practice of setting safety factors and revising codes solely based on experience does not work in this environment, where such trial and error approaches to managing uncertainty and safety may have unacceptable consequences. In an era in which standards for public safety are set in an increasingly public forum, more systematic and quantitative approaches to engineering for public safety are essential. The probabilistic approach addresses this need, and in the past two decades has been widely accepted worldwide as a new paradigm, for design of new structures and evaluation of existing facilities. NBS Special Publication 577 was the pathbreaking study in this area.

A number of archival publications were prepared from the NBS study. Most notably, references 8 and 9 were awarded the American Society of Civil Engineers' Norman Medal in 1983. The Norman Medal is the oldest and most prestigious of ASCE's prizes, and is awarded annually to the paper(s) that the ASCE Awards Committee and the Board of Directors judge most significant and meritorious for the advancement of the civil engineering profession. Also, in 1980, Ellingwood received the Silver Medal of the Department of Commerce for his work on common load factors for structural design. For an application of the approach to the punching shear resistance of lightweight concrete structures exposed to ice loadings, Long Phan received the Department of Commerce Bronze Medal Award in 1990.

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15.4 The Maturity Method

On March 2, 1973, portions of a multi-story apparent building, under construction in Fairfax County, Va., suffered a progressive collapse (see section 15.1.2 above and [1]). The Occupational Safety and Health Administration requested the assistance of NBS in determining the technical cause of the collapse. The report prepared by the CBT investigators concluded that the most probable cause of the failure was premature removal of formwork that resulted in stresses exceeding the capacity of the relatively young concrete [1].

CBT researchers recognized the need for a simple field method to estimate in-place concrete strength to allow critical construction operations to be done safely. In 1975, H. S. Lew of the Building Safety Section and Thomas Reichard of the Structures Section embarked on a study of a relatively new approach known as the maturity method. The maturity method relies on the measured temperature history of the concrete to estimate strength development during the curing period. The temperature history is used to calculate a quantity called the maturity index. For each concrete mixture, the relationship between strength and the maturity index is established beforehand. The strength relationship and the measured in-place maturity index are used to estimate the in-place strength. The method originated in England in the early 1950s, but was not used in U.S. practice.

The initial CBT research confirmed that the maturity method could be used to represent the development of concrete strength (and other mechanical properties) under different curing temperatures [2,3]. One of the publications [3] reported on a rigorous analysis of the relationships between the water-cement ratio of the concrete and the parameters in a proposed equation for the strength-maturity relationship. In 1980, the American Concrete Institute recognized the significance of the CBT research and awarded Lew and Reichard the prestigious Wason Medal for Materials Research.

In the early CBT work, the initial concrete temperature was the same for all specimens, and the specimens were moved into different constant-temperature chambers after molding. In a subsequent study, Lew and Charles Volz, a student at The University of Texas at Austin, examined the applicability of the maturity method under simulated field conditions [4]. In this case, specimens were stored outdoors and companion specimens were placed in a standard curing chamber. The objective was to determine whether the strength-maturity relationships for the field-cured specimens were the same as those for the companion laboratory-cured specimens. The results revealed that this was not the case. In the CBT research, a traditional equation was used to compute the maturity index from the temperature history.

On April 27, 1978, there was a major construction failure of a cooling tower being constructed in Willow Island, WV. OSHA again requested NBS to assist in determining the technical cause of the failure (see section 15.1.3 above). The CBT investigators concluded that the most likely cause of the collapse was insufficient concrete strength to support the applied construction loads [5]. This failure convinced CBT researchers of the urgent need for standards on estimating in-place concrete strength during construction. Thus the Structures Division began an in-depth study of the maturity method and other applicable methods. The objective of the work on the maturity method was to gain an understanding of the cause of the discrepancies in the earlier work [5]. Nicholas J. Carino, a new member of the Structures Division staff, led this work. He approached the problem from a point of view more theoretical than that of the previous work. By making use of new data analysis tools, Carino established a deeper understanding of the maturity method and explained the cause of the previous discrepancies [6-9]. In 1983, NBS recognized his contributions and awarded Carino the Bronze Medal of the Department of Commerce. In 1984, armed with this new understanding, Carino proposed a draft standard practice on the use of the maturity method. In 1987, ASTM Practice C 1074 was adopted [10].

In 1986, Rajesh C. Tank, a PhD student at Polytechnic University (Brooklyn, N.Y.), joined NBS as a guest worker and collaborated with Carino on further developing the maturity method. The work resulted in two publications [11,12]. One of these [12] reported on the temperature dependence of strength development of different concrete mixtures. The American Concrete Institute recognized the significance of their work and awarded Tank and Carino the 1994 Wason Medal for Materials Research.

In 1991, Carino published a book chapter [13] that provided a comprehensive review of the maturity method. This chapter is regarded as the "bible" for any new student of the maturity method. The latest BFRL research effort was published in 1992 [14], and it demonstrated that the method could be applied to mixtures with low water-cement ratios, which are typical of high-performance concrete.

In the late 1990s, the Federal Highway Administration publicized the maturity method, along with other technologies for testing concrete, to state highway departments throughout the U.S. As a result, in 2000 many state highway departments were adopting ASTM C 1074 into their standard specifications. Widespread use of in-place test methods, such as the maturity method, will result in safer and more economical concrete construction.

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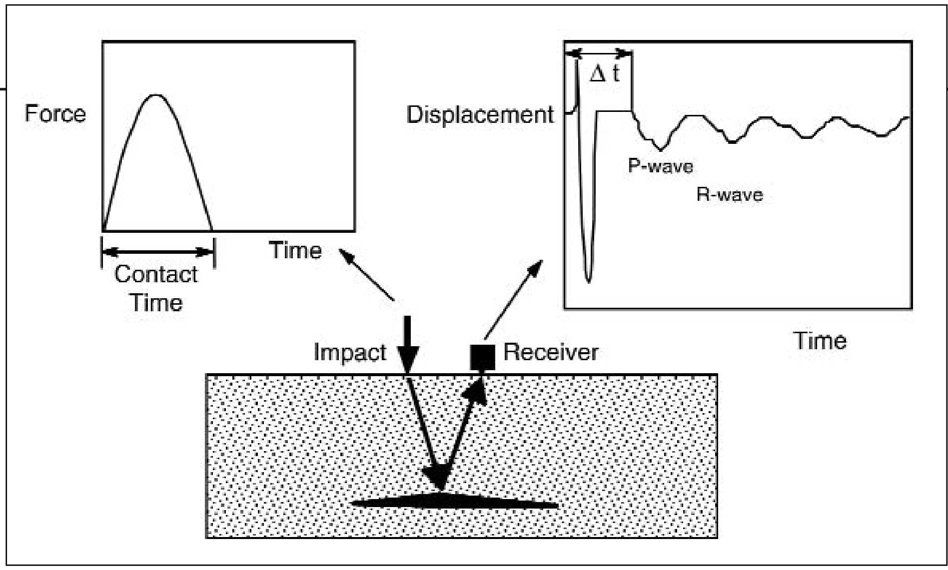
15.5 THE IMPACT-ECHO METHOD

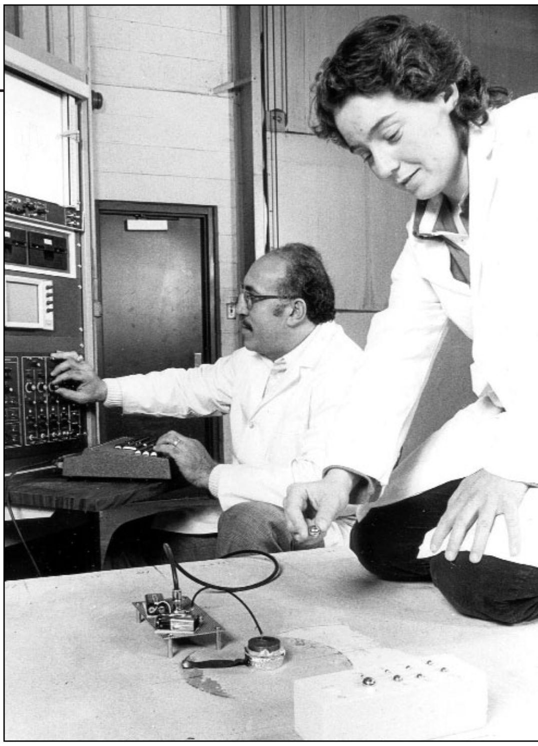
In 1983, the focus of CBT research on in-place testing of concrete shifted toward the detection of internal defects. Despite the advances in non-destructive testing of metals, there was no simple reliable method for locating flaws in concrete. Based on a review of available techniques, it was decided to pursue a test method based on stress waves because their propagation in a solid is affected directly by mechanical properties [1]. The technique that was developed became known as the impact-echo method [2], and its principle is illustrated in the figure below. Mechanical impact on the surface is used to generate a high-energy stress pulse that travels into the concrete. The pulse is reflected by an internal defect and travels back toward the surface where a receiver close to the impact point monitors its arrival. The pulse continues to undergo multiple reflections between the defect and the surface. Thus a resonant condition is created and the frequency of arrival of the pulse is determined. Knowing the stress wave speed in the concrete, the measured frequency can be used to calculate the flaw depth.



The impact-echo method: mechanical impact is used to generate stress waves and a receiver next to the impact point measures the resulting surface motion. Analysis of the measured surface motion permits detection of subsurface defect.

This research effort was highly successful due to a combination of factors. First, the research team was composed of individuals with different capabilities and backgrounds. Nicholas J. Carino, the team leader from the Structures Division, provided expertise in concrete technology and test methods; Mary Sansalone, a PhD student from Cornell University, provided expertise in finite element modeling; and Nelson N. Hsu, of the Manufacturing Engineering Laboratory (MEL), provided expertise in wave propagation. Second, the availability of numerical modeling tools permitted the researchers to simulate stress wave propagation under different test conditions. The numerical simulations established the scientific basis for the impact-echo method and permitted the development of optimum testing configurations. Third, a new point-displacement transducer, which was developed by Thomas Proctor of MEL as a reference for calibrating acoustic emission transducers, turned out to be ideal for impact-echo testing. Fourth, the researchers took advantage of developments in signal processing and used frequency analysis of the recorded signals. Finally, the basic capabilities of the method were established by a combination of numerical studies and companion controlled-flaw studies.

The initial success was the result of using Proctor's point transducer in combination with steel balls to produce the required short duration impacts. The American Concrete Institute (ACI) recognized quickly the significance of the new approach underlying the CBT research. In 1986, Carino was awarded the ACI Wason Medal for Materials Research for a paper that reviewed the fundamentals of wave propagation in concrete and summarized the first series of controlled-flaw studies [3]. The next significant development was the use of the fast Fourier transform technique to convert the recorded time domain waveforms [4] into the frequency domain [5]. This development simplified signal interpretation. Next, extensive simulations of different test conditions were carried out by using a state-of-the-art stress-wave propagation code developed at the Lawrence Livermore National Laboratory. In 1987, Sansalone and Carino received the CBT Communicator Award for a series of papers that summarized the results of these simulations [6-9]. At the same time, Stephen Pessiki, a graduate student from Cornell University, demonstrated the feasibility of using



Nicholas J. Carino, research structural engineer, and Mary Sansalone, graduate student, are shown performing some of the initial tests that led to the development of the impact-echo. Sansalone is about to create an impact by dropping a steel ball next to the point displacement transducer and Carino is ready to observe the resulting surface motion displayed on a waveform analyzer.

the impact-echo method to monitor setting and early-age strength development of concrete [10].

Another key aspect of the CBT research was a series of laboratory controlled-flaw studies that verified the results of the numerical simulations and demonstrated the breadth of applicability of the impact-echo method [11-14]. One of the studies dealt with the detection of delaminations in concrete slabs, such as bridge decks, that result from corrosion of the reinforcement. In 1991, the American Concrete Institute awarded Sansalone and Carino the Wason Medal for Materials Research for their paper on the delamination study [11].

At the conclusion of the CBT effort in the late 1980s, Sansalone continued the research at Cornell University. Advances resulting from the Cornell work included developing a PC-based field test system, extending the application to more complex structures, and establishing a technology transfer program to train new users. Eventually, Sansalone published a book to document, in one place, the theory and capabilities of the impact-echo method [15].

In 1996, Carino and Sansalone collaborated on the development of a draft standard on the use of the impact-echo method to measure the thickness of plate-like concrete structures. Carino championed the draft standard through the ASTM standardization process, and in 1998, Test Method C 1383 was approved [16].

The CBT research leading to the impact-echo method is an excellent example of how a multi-disciplinary team can solve a difficult problem. The combination of theory, simulation, and experimental verification provided a solid foundation for what is being recognized worldwide as a powerful tool for "seeing" into concrete.

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15.6 WIND ENGINEERING

Since the late 1960s to the 1990s wind engineering technology has been advanced by NIST through theoretical, experimental, and computational research.

15.6.1 ENGINEERING MICROMETEOROLOGY

NIST has initiated the use in wind engineering of consistent descriptions of the atmospheric boundary layer, based on first fluid dynamics principles and state-of-the-art meteorological research. Those descriptions pertain to: the mean wind speed profile in the surface layer and the dependence of the surface layer height upon wind speed and terrain roughness; the dependence on elevation of the spectrum of the longitudinal turbulent wind speed fluctuations, which affects tall building design; the shape of the spectrum for the very low frequencies of interest in deep-water offshore platform applications; and the dependence of the mean wind profile upon the centripetal accelerations inherent in cyclostrophic flows modeling hurricane winds [1].

15.6.2 EXTREME WIND CLIMATOLOGY

The reliability of structures subjected to strong wind loads depends upon the ratio between the design wind speeds specified in standards - usually wind speeds with a 50 year mean recurrence interval - and the extreme wind speeds causing structural damage or failure. This ratio depends upon the length of the upper tail of the extreme wind distribution. Using advanced statistical techniques, NIST (a) showed that extreme wind speed distributions used in the ANSI A58-1972 Standard were unrealistic, and (b) helped to introduce an improved distributional model in subsequent versions of the standard [2]. Following the development in the 1970s of novel approaches to extreme value estimation, NIST showed that, at most locations, extreme wind speeds have finite, rather than infinite upper tails. This finding allowed the development of structural reliability models resulting for the first time in realistic estimates of safety margins and failure probabilities for structures subjected to strong winds.

15.6.3 BLUFF BODY AERODYNAMICS AND WIND TUNNEL TESTING CRITERIA DEVELOPMENT

NIST has developed full-scale measurement techniques and obtained full-scale wind pressure measurements used all over the world for the calibration of wind tunnel measurements and the development of standard provisions on wind pressures [3, 4]. NIST has also contributed to the development of performance criteria for wind tunnels simulating the turbulent atmospheric boundary layers.

15.6.4 WIND LOADS ON LOW-RISE BUILDINGS

During 1973-1976, under an Agency for International Development contract, NIST developed information on design pressure coefficients for low-rise buildings used to improve the

Richard D. Marshall, research structural engineer, with Philippine Weather Bureau technician installing a pressure transducer to one of the wind test houses at the Quezon City, Philippines field test site.

A58.1 Standard (now ASCE 7). Richard D. Marshall served as principal investigator and Noel Raufaste as program coordinator. The research findings resulted in improvements to basic design data concerning the effects of extreme winds on low-rise, low-cost housing and other public service buildings in developing countries. It developed improved design criteria for building details. And it developed and demonstrated a methodology to assist suburban and rural building design for local wind climate. A variety of reports were published on this project [5]. Among the products of this project noteworthy was the film High Wind Study [6] that was awarded 2nd place in the 1976 Rome Film Festival for documentaries.

Raufaste and Marshall created an advisory committee of Philippine officials from 15 public and private sector organizations who collaborated with NBS to improve the wind-resistance of low-rise structures. They donated four test buildings at three field sites. The Philippine Weather Bureau and the University of Philippines were two key contributors. In addition, representatives from two of the four geographic wind prone areas contributed to this work. Jamilur Choudhury of the Bangladesh University of Engineering and Technology represented the Bay of Bengal countries and Alfrico Adams, a private civil engineering practitioner, heavily involved in codes and standards of the Caribbean, represented the Caribbean Countries. They contributed to the research and transferred findings to their respective parts of the world. The other two wind prone geographic areas: Southeast Asia and the US east and gulf coasts were represented by the Philippines and the US through the NBS study.

15.6.5 STRUCTURAL DYNAMICS

NIST developed linear models of the resonant and non-resonant effects of wind loading on high-rise structures that account for the imperfect spatial correlation of the wind pressures and their stochastic variability in time. Because wind speed fluctuations have large energies at frequencies close to the fundamental frequencies of vibration of compliant deep-water offshore platforms, it was widely believed for such platforms resonant effects due to the wind loading are prohibitively large. NIST developed a time-domain analysis used in conjunction with nonlinear hydrodynamic damping models, which showed that resonant amplification effects due to wind loading are in fact relatively small [7]. NIST's approach was adopted for use by the American Petroleum Institute.

15.6.6 STRUCTURAL RELIABILITY AND POST-DISASTER INVESTIGATIONS

Owing primarily to inadequate extreme wind modeling, early reliability models yielded the unrealistic result that the estimated failure probability of structures subjected to wind loads is one if not two orders of magnitude lower under wind than under gravity loads. NIST's later results on extreme wind distribution tails made it possible to show that this is not the case and to develop realistic estimates of wind load factors and of probabilities of failure due to wind loads [8]. NIST has also shown that standard wind loading provisions for the design of structures in hurricane-prone regions were inadequate, and led the effort to improve standard provisions accordingly. Structural reliability and performance models have been scrutinized by using observations of damage obtained during numerous, highly effective post-disaster investigations.

15.6.7 GLASS BEHAVIOR UNDER FLUCTUATING WIND LOADS

Using state-of-the art fracture models in conjunction with nonlinear analyses of stresses induced by fluctuating wind loads on glass panels, as well as innovative approaches to experimental glass strength characterization [9], NIST research was influential in the development of new standard provisions for glass panels subjected to wind loads.

15.6.8 DEVELOPMENT OF CRITERIA ON TORNADO WIND SPEEDS AND TORNADO-BORNE MISSILES SPEEDS

NIST developed criteria on tornado-borne missile speeds adopted by the Nuclear Regulatory Commission for the design of nuclear power plants [10]. NIST also initiated on-going research to modify the Fujita tornado intensity scale so observations of tornado-induced damage can lead to more realistic estimates of tornado speeds than had been previously the case.

15.6.9 DEVELOPMENT OF PERFORMANCE CRITERIA ASSURING HIGHER SAFETY LEVELS AND LOWER COSTS FOR STRUCTURES SUBJECTED TO WIND LOADING

Conventional standard provisions are based on wind loading simplified representations designed to accommodate slide-rule or pocket calculator capabilities. NIST has developed an IT-based methodology for the direct and practical use in design of unadulterated wind tunnel records of fluctuating wind pressures measured simultaneously at hundreds of points on the building surface [11]. By helping to eliminate material where it is superfluous and add it where it is needed, this methodology makes possible risk-consistent designs resulting in safer structures at lower costs. NIST also used this methodology in conjunction with time-domain nonlinear approaches to obtain for the first time in the history of structural engineering realistic ultimate capacities of structures subjected to fluctuating wind loads.

15.6.10 EDUCATION AND PRACTICE

Simiu and Professor Robert Scanlan have synthesized wind engineering knowledge and practice for use in graduate education and by practicing engineers in a world-recognized book [12].

15.6.11 AWARDS

In addition to the awards noted above for individual papers and activities, the National Society of Professional Engineers named Emil Simiu Federal Engineer of the year 1984 for his contributions to knowledge and practice in wind engineering. In 1999, the American Society of Civil Engineers named Richard Marshall the first recipient of the Walter J. Moore, Jr. Award for excellence in and dedication to the development of structural engineering codes and standards. In 2001, the Americas Conference on Wind Engineering created the Outstanding Wind Engineering Ph.D. Award in memory of Richard Marshall.

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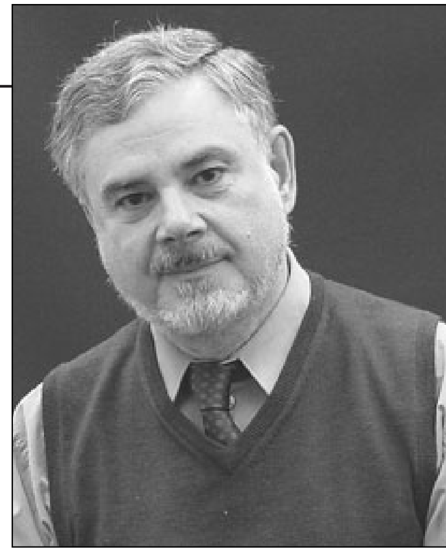
15.7 CHAOTIC DYNAMICS

Chaotic dynamics research at BFRL benefited at various stages from NIST work on the behavior of nonlinear electronics and mechanical engineering systems. It was motivated primarily by structural engineering and hydroelasticity modeling problems related to the design of deep water compliant offshore platforms.

R. L. Kautz of the Electronics and Electrical Engineering Laboratory (Boulder) performed a series of studies of the dynamics of the Josephson junction, a multistable system that can exhibit chaotic behavior. The studies were supported mathematically and computationally by H. Fowler of the Information Technology Laboratory (ITL), who also helped BFRL chaotic dynamics research efforts. M. A. Davies and C. J. Evans of the Center for Manufacturing Engineering, with T. J. Burns of ITL, studied the dynamics of chip formation in machining hard metals, and D. G. Sterling of ITL/Boulder studied the hitherto unknown phenomenon of the synchronization of the motions of chaotic systems. BFRL benefited from interactions with most of these authors.

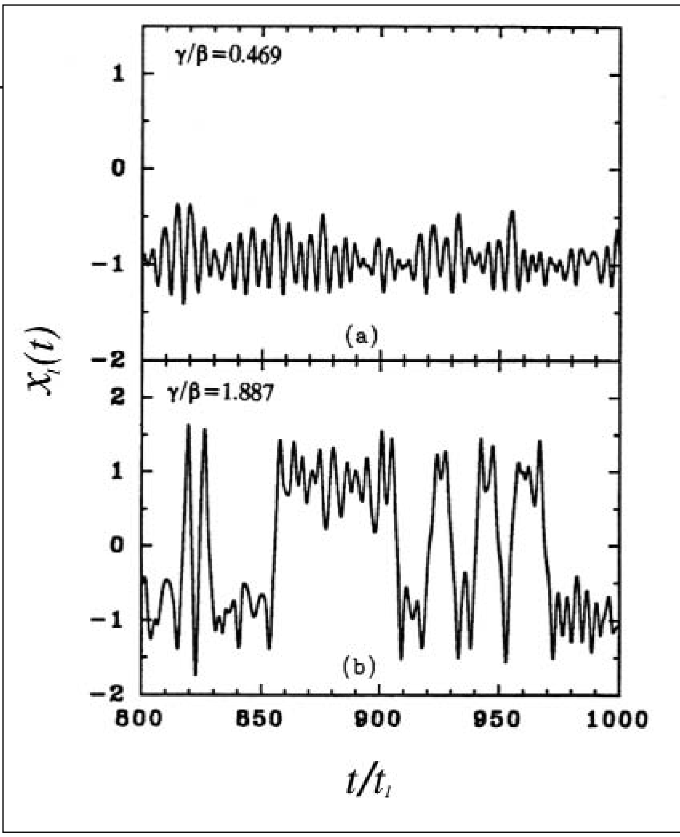
In particular, Emil Simiu and G. R. Cook of BFRL and T. J. Burns of ITL collaborated within the framework of a NIST competence building project on computational and mathematical aspects of the chaotic behavior of a deterministic model of a galloping



Emil Simiu, leader in wind research and chaotic structural dynamics.

oscillator [1]. The competence project subsequently focused on the effect of stochastic excitation on the behavior of systems whose deterministic counterparts can exhibit chaotic behavior.

Experimental work on hydroelastic systems, conducted by BFRL at the David Taylor Research Center showed that stochastic excitation of multistable systems can promote dynamics indistinguishable in practice from chaotic behavior. Theoretical research by BFRL with M. R. Frey of the Statistical Engineering Division, ITL, confirmed the validity of this finding for a wide class of physically realizable multistable stochastic systems whose deterministic counterparts possess a Melnikov function [2]. The research made use of classical approximations of stochastic processes by finite periodic or quasiperiodic sums of harmonic terms with random parameters, which allow the application of the Melnikov approach -- originally devised for periodically or quasiperiodically excited systems -- to physically realizable systems with stochastic excitation. This work led to the development of a unified Melnikov-based approach to the study



(a) Non-chaotic and (b) chaotic time histories induced in a bistable dynamical system by dichotomous noise excitation.

of the dynamics of both deterministic and stochastic dynamical systems, and the conclusion that deterministic and stochastic excitations play similar roles in the promotion of chaos.

To the Melnikov function defined for the deterministic systems there corresponds in their stochastic counterparts a Melnikov process. Melnikov processes were subsequently used in studies of the chaotic behavior of systems with additive Gaussian noise, non-Gaussian infinitely-tailed noise, state-dependent (parametric) noise, and dichotomous noise.

The spectral density of the Melnikov process was shown to be equal to the spectral density of the excitation times the square of a system-specific transfer function. This relation can be used to assess the effect of the noise color upon the propensity of the system to experience jumps over its potential barrier(s).

With Office of Naval Research support, the stochastic Melnikov approach was used in a wide variety of applications, including: the generation by turbulent wind of along-shore currents in ocean flow over a corrugated bottom, open-loop control, buckled column snap-through, stochastic resonance, acceptable cut-off frequencies for experimentally generated colored noise excitation, and the chaotic behavior of auditory nerve fiber dynamics [3, 4, 5, 6, 7].

The BFRL research provided basic material for what is believed to be the first monograph in the literature on the study of transitions in stochastic systems from a chaotic dynamics point of view [8]. The monograph is designed for use by engineering, physics, and life sciences researchers whose primary interest is in applications. It covers the basic requisite material on the chaotic and stochastic dynamics of a wide class of nonlinear planar multistable systems, and provides detailed examples of applications in naval architecture, oceanography, structural/mechanical engineering, control theory, physics, and neurophysiology.

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15.8 THE NATIONAL EARTHQUAKE HAZARDS REDUCTION PROGRAM

The National Earthquake Hazards Reduction Program (NEHRP) was authorized by the Earthquake Hazards Reduction Act of 1977, Public Law 95-124, to "reduce the risks of life and property from future earthquakes in the United States through the establishment and maintenance of an effective earthquake hazards reduction program." Its implementation plan was issued by the Executive Office of the President on June 22, 1978. CBT and BFRL have played significant roles in the development and accomplishments of NEHRP. NEHRP has been an extraordinary, and often exemplary, collaboration between federal agencies, state and local governments and the private sector.

15.8.1 BACKGROUND

CBT's predecessor, the Division of Building Research, began work in earthquake hazard reduction with its organization in 1969 of the U.S./Japan Panel on Wind and Seismic Effects under the U.S./Japan Program on Natural Resources, and its investigation of the performance of structures in the 1971 San Fernando, California earthquake. Both of these activities were led by Edward Pfrang. Later in 1971, Richard Wright and Samuel Kramer represented NBS in the Disaster Preparedness study of the Office of Emergency Preparedness (OEP) of the Executive Office of the President [1]. They worked with Ugo Morelli of OEP, Charles Thiel of NSF and Arthur Zeizel of HUD on needs for collaborative efforts to research, develop and implement building practices for disaster mitigation.

Charles Thiel was able to exploit the flexibility of the Research Applied to National Needs (RANN) program of NSF to fund private sector and university participants through NBS to prepare improved seismic design and construction provisions. NSF and NBS proceeded to convene and fund a national workshop to define a cooperative program on Building Practices for Disaster Mitigation (OEP was being eliminated as President Nixon streamlined his Executive Office and HUD was unable to provide co-sponsorship). The Structural Engineers Association of California organized the Applied Technology Council (ATC) to provide a mechanism to conduct studies for the improvement of building practices; its first such study was an input to the workshop on procedures and criteria for earthquake resistant design. The workshop [2] evaluated current practices, defined opportunities to improve practices based on documented research findings, recommended professional and public policy actions for implementation of improved practices and identified gaps in knowledge requiring further research.

Seismic design and construction provisions for buildings needed to use consistent loadings and resistance expressions for all types of buildings and all building materials to achieve consistent levels of safety. Since national standards were and are generally materials specific, a comprehensive program, involving all professional and materials interests, was needed to achieve nationally applicable provisions for all types of buildings and building materials.

NSF and NBS continued in 1973 to sponsor a study by ATC of a two-level seismic design approach based in principle on that used for the seismic design of nuclear facilities: a damage threshold spectrum representing earthquake motions having a moderate probability (50 percent) of being exceeded during the design life (70 years) of the structure, and a collapse threshold spectrum having a low probability (10 percent) of being exceeded during the design life. An engineering panel developed design provisions adapted from the 1973 Uniform Building Code, and each of eleven buildings was redesigned according to the design provisions by the one of ten firms that originally designed it. The study [3] found the approach workable but challenging for designers to grasp.

In 1974, NSF and NBS funded ATC to present the current state of knowledge in the fields of engineering seismology and engineering practice for seismic design and construction of buildings. ATC convened 85 recognized experts led by Roland Sharpe, project director, who had extensive experience in seismic design and in development of seismic design provisions, and Nathan Newmark, chairman of the project steering group, who was head of Civil Engineering at the University of Illinois and a leader in earthquake engineering research. Charles Culver of CBT oversaw the project for NBS. The provisions were intended to enable new and existing buildings to:

1. Resist minor earthquakes without damage,
2. Resist moderate earthquakes without significant structural damage, but with some non-structural damage,
3. Resist major or severe earthquakes without failure of the structural framework of the building or its component members and equipment, and to maintain life safety.

The resulting provisions [4] were a significant advance on existing provisions and were not recommended for adoption in building codes until a detailed evaluation was made of their workability, practicability and potential economic impact. Charles Culver received the Silver Medal of the Department of Commerce in 1977 for his leadership of the project.

15.8.2 ESTABLISHMENT OF NEHRP

Congressman George Brown and Senator Alan Cranston, both of California, led the Congressional efforts to produce the Earthquake Hazard Reduction Act of 1977. Karl Steinbrugge, an insurance industry expert in seismic damages, led a working group in the Executive Office of the President to develop the National Earthquake Hazards Reduction Program (NEHRP) in response to the Act. Charles Thiel represented NSF and Charles Culver represented NBS on the working group. The memorandum of transmittal and program document [5] are somewhat incoherent reflecting the conflict between the working group's desire for an effective program and the Administration's concern for controlling costs.

In the NEHRP, NBS was assigned:

- Development of seismic design and construction standards for consideration and subsequent adoption in Federal construction, and encouragement for the adoption of improved seismic provisions in State and local building codes.
- Assist and cooperate with the Department of Housing and Urban Development, other federal agencies (particularly those involved in research), National Institute of Building Sciences, professional organizations, model code groups, and State and local building departments, in continuing the development, testing, and improvement of model seismic design and construction provisions suitable for incorporation in local codes, standards, and practices.
- Research on performance criteria and supporting measurement technology for earthquake resistant construction.

The Federal Emergency Management Agency (FEMA) was formed by combining the Defense Civil Preparedness Agency, the Federal Insurance Agency, the Federal Disaster Assistance Administration, and the U.S. Fire Administration, and designated as the lead agency for NEHRP. Its role was to provide leadership in coordinating earthquake hazards reduction activities in the appropriate federal agencies and to assist State and local governments in planning and implementing their own programs. The other principal agencies were the U.S. Geological Survey (USGS), charged to conduct research on the nature of earthquakes, earthquake prediction, hazards evaluation and delineation, and induced seismicity, to evaluate earthquake predictions, and prepare national seismic risk maps; the National Science Foundation (NSF), charged to support fundamental research studies on earthquakes, and basic and applied research on earthquake engineering and policy; and NBS with the role cited above.

FEMA, USGS, and NSF requested and received budget increases to support their roles. NBS requested FEMA to fund through the FEMA budget the development, testing and adoption of seismic design and construction standards.

15.8.3 SEISMIC STANDARDS FOR BUILDINGS

Efforts to develop nationally applicable seismic design and construction provisions suitable for adoption by model building codes and state and local governments continued while NEHRP was being planned. With funding from

NSF, NBS consulted 30 private sector organizations to develop a plan for assessment and implementation of the tentative provisions [7]. Charles Thiel transferred to FEMA to lead its earthquake hazard mitigation activities and supported the organization in 1979 of the Building Seismic Safety Council (BSSC), under the auspices of the National Institute of Building Sciences (NIBS), to convene the expertise and interests needed to develop nationally applicable and acceptable seismic design and construction provisions. Ugo Morelli joined FEMA to become the program officer for the effort, and James Smith became executive director of BSSC. As BSSC came up to speed, and working with private sector and other agency experts convened by BSSC, CBT provided technical support for review and refinement of the tentative provisions [8], planning the trial design program for the tentative provisions [9], and preparing amendments to the tentative provisions for use in the trial designs [10].

E.V. Leyendecker led the Structures Division's Earthquake Engineering Group through the exciting initial years of NEHRP working effectively with colleagues in other federal agencies and the private sector and leading both earthquake engineering research and participation in the development of seismic design and construction provisions for buildings. In recognition of these efforts, Leyendecker received the Bronze Medal of the Department of Commerce in 1981, and the Silver Medal of the Department of Commerce in 1986. The review of the tentative seismic provisions provided an excellent opportunity for CBT staff to become familiar with the state of the art of knowledge and practice, their peers in research and practice, and priority needs for research. CBT participants included: Louis Cattaneo, Robert Chapman, Riley Chung, Patrick Cooke, Bruce Ellingwood, Thomas Faison, H.S. Lew, Richard Marshall, James Pielert, Timothy Reinhold, Lawrence Salamone, James Shaver, Stephen Weber, Kyle Woodward, and Charles Yancey. Weber's study, revealing the modest cost implications of the recommended provisions [11] as determined by the trial designs, was crucial to the subsequent issuance of the Executive Order requiring use of the provisions in federal construction and in adoption of the provisions in national standards and model building codes.

Since NBS had relinquished the funding of seismic standards studies to FEMA, and FEMA came to consider it more cost effective to fund BSSC to provide the technical secretariats for the various technical committees developing the provisions, CBT participation declined. James Harris, who left CBT in 1981 for private practice in structural engineering, continued to be active in BSSC and ASCE standardization activities and has become a nationally recognized leader. E.V. Leyendecker, who left CBT in 1986 to join the USGS, continued throughout the 1990s to play a lead role in development of the seismic hazard maps referenced by seismic design and construction standards.

BSSC completed The NEHRP Recommended Provisions for Seismic Regulations for New Buildings in 1985, and was funded by FEMA to continue their evolution in subsequent editions of 1988, 1991, 1994, 1997, and 2000. There was no immediate movement, following their issuance in 1985, towards adoption of the Recommended Provisions by national standards and model building codes. As described in the following section on ICSSC, CBT/BFRL was influential in achieving adoption of the Recommended Provisions.

15.8.4 INTERAGENCY COMMITTEE ON SEISMIC SAFETY IN CONSTRUCTION

At the start of NEHRP the White House directed FEMA to form an Interagency Committee on Seismic Safety in Construction (ICSSC) to assist the more than 30 federal agencies involved in construction in implementing earthquake hazards reduction elements in their ongoing programs. ICSSC was assigned the only output milestone for the program: to develop seismic design standards for federal construction and initiate their testing by federal construction agencies by 1980. ICSSC, with FEMA funding CBT to provide its technical secretariat, met this milestone [6]. Charles Thiel of FEMA chaired ICSSC from its inception in 1978 until he left federal service in 1982. Richard Wright of

CBT then chaired ICSSC until he retired from federal service in 1999. Subsequently, Shyam Sunder of NIST has chaired ICSSC and Steven Cauffman has provided its secretariat.

The federal agencies wished (by federal policy and for efficiency and economy) to use the same seismic design and construction practices for its construction as were generally used in the private sector and referenced by state and local building codes. However, legislation and Administration policy also required the federal agencies to use up to date seismic design and construction practices, and private sector consensus procedures for voluntary standards and model codes could be slowed by proprietary concerns. Therefore, ICSSC worked with the private sector in the BSSC and simultaneously developed and tested its own provisions [6, 12] to have a viable alternative if the BSSC effort failed. For his leadership in this work, James Harris received the Department of Commerce Bronze Medal Award in 1981 for this accomplishment.

In accord with the direction of the NEHRP Program Plan [5], ICSSC proceeded to develop a proposed Executive Order [13] requiring use of up to date seismic provisions in federal construction. The original proposed Executive Order, developed through many ballots by ICSSC agencies, covered new and existing buildings and lifelines. As consideration proceeded in the White House, its scope was reduced to new federal and federally assisted or regulated buildings for which up to date standards had been prepared (by BSSC and ICSSC) and for which the cost implications had been shown to be modest by trial designs.

The October 17, 1989, Loma Prieta earthquake in California renewed public, Administration, and Congressional interest in seismic safety. Using the ICSSC-developed proposal at hand, the President issued Executive Order 12699, Seismic Safety of Federal and Federally Assisted or Regulated New Building Construction, on January 5, 1990. Federal agencies were able to proceed immediately to use ICSSC or BSSC provisions for their own buildings. Broader effect on seismic safety was achieved by the requirement that federally assisted construction, such as new homes with FHA or VA mortgages, be designed and constructed using standards considered appropriate by ICSSC. This federal mandate actually was welcomed by the national standards organizations and model building codes since it provided incentive for state and local governments to adopt and enforce up to date standards and codes to be eligible for federally assisted construction. ICSSC, BSSC and its member standards and model code organizations, collaborated to show equivalence of the 1991 Uniform Building Code to the 1988 BSSC Provisions and to develop and adopt changes based on the 1988 BSSC Provisions in the 1992 supplements to the SBCC Standard and BOCA National Building Codes. The NEHRP goal of making adequate seismic resistance available for all new U.S. building construction was achieved.

Diana Todd joined the CBT staff in 1990 to provide dynamic leadership for the ISCSC secretariat. ICSSC was much involved in support to federal agencies in implementation of EO 12699 for new buildings [14], support for the assessment of the equivalency of model building codes to the BSSC provisions [15] and the development of proposals for changes to the model codes, and in developing standards [16], and a proposal for an implementing executive order, for the seismic safety of existing federal buildings. FEMA provided sustained support for BSSC in developing guidelines for seismic evaluation and strengthening of existing buildings and for ICSSC in developing policies and practices for evaluation and strengthening of existing federal buildings.

Following the January 17, 1994, Northridge Earthquake, the President issued Executive Order 12941, Seismic Safety of Existing Federally Owned or Leased Buildings, on December 1, 1994. It adopted the standards [16] and called for agencies to inventory their owned and leased buildings and estimate the costs of mitigating unacceptable seismic risks. ICSSC developed guidance to the federal agencies on implementation of the executive order [17] and collaborated with BSSC in a trial design program, using federal buildings, of the costs implementing the BSSC-produced NEHRP

Guidelines for the Seismic Rehabilitation of Buildings.

In September 2000, FEMA submitted, A Report to the Congress: Toward Earthquake Resistant Federal Buildings, to the Office of Management and Budget. This report included an inventory of Federal Buildings, compiled by John Hayes and Steve Sweeney of the U.S. Army Civil Engineering Research Laboratory. The report, prepared by Degenkolb Engineers under the leadership of Ugo Morelli of FEMA and Chris Poland of Degenkolb Engineers. During its preparation, the report was extensively reviewed and commented on by the ICSSC.

ICSSC Subcommittee 1 (Standards for New and Existing Buildings), under the leadership of H. S. Lew drafted an Executive Order entitled, Seismic Rehabilitation of Federal Buildings, to implement the recommendations of the Report to Congress. Ugo Morelli of FEMA and Charles Gutberlet of the U. S. Army Corps of Engineers prepared the draft Executive Order. The Executive Order was approved by the ICSSC Full Committee and submitted by FEMA to the Office of Management and Budget with the Report to Congress in September 2000.

ICSSC organized federal teams to investigate performance of buildings and lifelines in important earthquakes [18, 19, 20] and developed recommendations for ICSSC activities to mitigate effects of future earthquakes.

15.8.5 EARTHQUAKE ENGINEERING EXPERIMENTAL FACILITIES

At the request of the White House Office of Technology Policy, the National Research Council (NRC) in 1984 organized a committee led by H. Norman Abramson and published a report on Earthquake Engineering Facilities and Instrumentation [21]. It concluded:

> *The irreducible need for full-scale data on the behavior of earthquake-impacted multistory structures requires that the nation have experimental facilities able to test such structures across a range from damage initiation to collapse.*

It recommended:

> *The federal government should undertake, on an accelerated basis, planning aimed at developing a major national earthquake engineering experimental/test facility.*

FEMA, NSF and NBS funded CBT in 1985 to conduct the planning. CBT defined a four year, four phase study covering research needs, facility characteristics, siting and management. The first phase, research needs, included collecting background data, commissioning research needs recommendations from six expert consultants, a workshop of researchers, professionals and industry representatives to define research needs, and commissioning another NRC Panel, chaired by James Beavers, to advise in the study. The CBT report [22] presented a five year research program for a National Earthquake Engineering Experimental Facility (NEEEF).

The report of the NRC Panel [23] concluded;
. . . it is now clear to the panel that the National Bureau of Standards' current approach, which focuses on a particular facility, cannot be continued because of broader issues and needs that must first be considered in such a feasibility study.

Essentially, the Beavers panel disagreed with the Abramson panel that there should be a plan for a single, major, national facility. Apparently, the principal research universities objected that at most one of their number (the facility might go to a national laboratory instead of a university) would monopolize the state of the art earthquake engineering experimental facilities. While the NEEEF study did not need to focus on a single facility, NEHRP was not hearing good support from the earthquake community for its continuation by CBT; hence, it was terminated.

The need for improvement of U.S. earthquake engineering experimental facilities remained and was highlighted by uncertainties in understanding of structures performance in the 1989 Loma Prieta and 1994 Northridge earthquakes. The 1994 reauthorization of NEHRP (PL 103-374) called for the President to "conduct an assessment of earthquake engineering research and testing capabilities in the United States." Informed by the experience ten years before, NSF and NIST commissioned the Earthquake Engineering Research Institute to perform the assessment [24], which was chaired by Daniel Abrams with James Beavers as project manager. It gave highest priority to modernizing existing laboratories and led to the $84 million George W. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) that NSF began in 2000.

15.8.6 STANDARDS FOR LIFELINES

Lifelines are the transportation (highways, airports, railways, waterways, ports and harbors) and utility systems (electric power, gas and liquid fuels, telecommunication, water, and sewer) that support most human activities. Lifeline failures during earthquakes cause losses of life, property, and income as well as environmental damages. Lifeline failures also result in post-earthquake fires, hinder emergency and rescue operations, and delay recovery and reconstruction. While by 1990, there were up to date seismic provisions available for building codes, there were no nationally accepted standards or guidelines for lifelines except for highway structures and nuclear facilities. Public Law 101-614, the 1990 National Earthquake Hazards Reduction Program Reauthorization Act stated:

> *The Director of the Agency (FEMA), in consultation with the Director of the National Institute of Standards and Technology, shall submit to Congress, not later than June 30, 1992, a plan, including precise timetables and budget estimates, for developing and adopting, in consultation with appropriate private sector organizations, design and construction standards for lifelines. The plan shall include recommendations of ways Federal regulatory authority could be used to expedite the implementation of such standards.*

In response to the mandate, FEMA funded NIST/BFRL to conduct the planning. FEMA organized a Steering Group chaired by Ronald Eguchi, then chairman of the Technical Council on Lifeline Earthquake Engineering, to advise on the planning. The Steering Group approved the process for planning which included commissioning drafts for the various lifeline types from private sector experts and holding a planning workshop from September 25-27, 1991, of over 50 experts predominantly from the private sector and academia. The resulting plan [25] called for an 8 year program totaling $54.7 million dollars. Implementation would be primarily through the existing voluntary standards system with an Executive Order requiring federal agencies to adopt and use seismic standards for federal and federally assisted or regulated new and existing lifelines.

A draft plan, based on the workshop report, was reviewed by the NEHRP Advisory Committee in January 1992, and was not supported by the Advisory Committee or FEMA. FEMA and NIST worked with a subgroup of the Advisory Committee to develop a revised plan that was approved by the White House and submitted to Congress [26]. It called for working with the private sector to develop guidelines and standards for lifelines, but did not give a schedule or estimate funding required. Then, under the auspices of the Interagency Committee on Seismic Safety in Construction (ICSSC) a Lifeline Policymakers Workshop was held by the American Society of Civil Engineers (ASCE) (27) which estimated that a five year program amounting $16 million was required. FEMA has supported the formation by ASCE of the American Lifeline Alliance to work on the development of guidelines and standards for lifelines.

15.8.7 NEHRP MANAGEMENT

CBT/BFRL as a principal agency in NEHRP was fully involved in its planning and management activities. These included several cycles of strategic planning and planning for special supplementary research funding following the 1989 Loma Prieta and 1994 Northridge earthquakes to assure exploitation of the opportunities to improve knowledge and practice from lessons that could be learned by studying earthquake mechanisms, performance of structures, societal behavior and emergency management procedures in the earthquakes. CBT/BFRL's influence on plans and public policies was proportionally much greater than its two percent share in NEHRP appropriations because its representatives for planning and Congressional testimony were knowledgeable in earthquake engineering.

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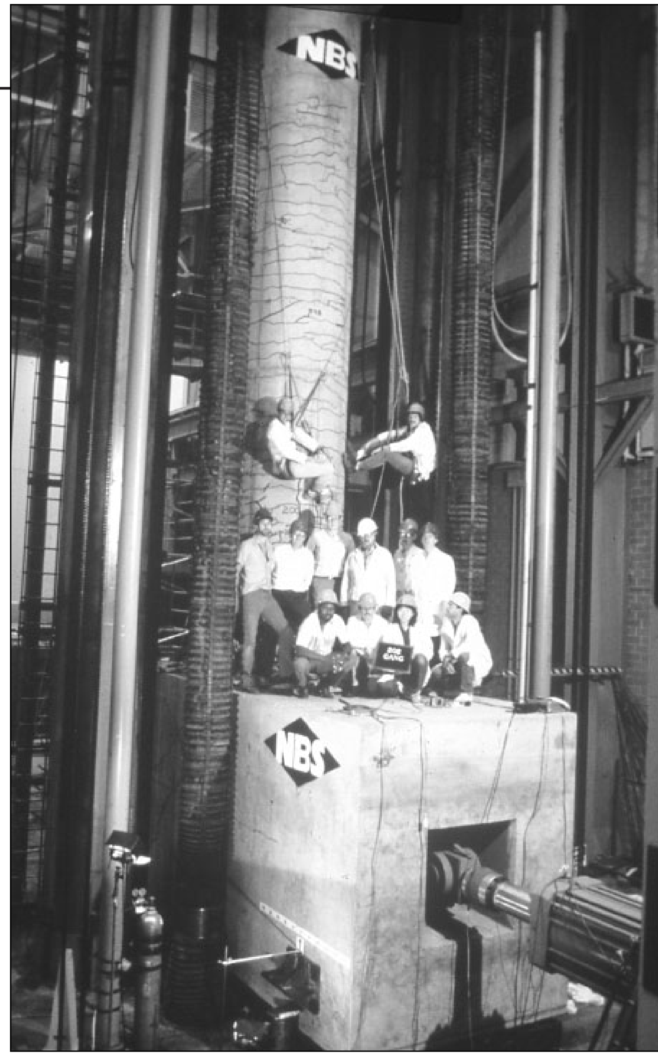
15.9 EARTHQUAKE RESEARCH

15.9.1 SOIL LIQUEFACTION

CBT formed a Geotechnical section led by Felix Yokel in the mid 70s as part of the Structures and Materials Division. One of it major focuses was the prediction of soil liquefaction under strong ground shaking which had been shown to be a major factor in damages to buildings and lifelines. Yokel recruited William Kovacs, Riley Chung, and Larry Salomone to join CBT and involved external experts such as Ricardo Dobry in the section's research. The widely used Standard Penetration Test (SPT) had been shown to correlate with liquefaction potential, but variability in the test procedures made predictions unreliable. A thorough study of the test procedures and the energy delivered to the sampling device [1] led to recommendations to improve ASTM Standard D1586 for the test and reduced variability of results. Cooperation with Japanese researchers through the US/Japan Panel of Wind and Seismic Effects led to joint studies of US and Japanese testing procedures [2] so that Japanese data on liquefaction in earthquakes could be used with U.S. data and test methods for prediction of seismic liquefaction potential of soil deposits. Laboratory and field studies of pore water pressure build up in shaken soils led to identification of the critical cyclic strain as the mechanism leading to liquefaction [3].

Threats to the existence of CBT and cuts in its funding in the 80s led to the departure of most of its geotechnical engineers and the end of the section. With increased funding for earthquake engineering at NIST following the 1989 Loma Prieta and 1994 Northridge earthquakes, Riley Chung returned to BFRL to lead its Earthquake Group and recruited Ronald Andrus to resume geotechnical research. Andrus and Chung performed important work to develop the shear wave velocity method [4] for predicting liquefaction potential. However, restricted funding in the late 90s caused BFRL again to terminate geotechnical research since it could not support a world class program. In spite of limited resources and work that started and stopped, twice, CBT's and BFRL's researchers succeeded in making major contributions to reliable and economical methods for identifying liquefaction susceptible soil deposits.



Full-scale test of bridge column performed in BFRL's large-scale structural test facility with its 53 MN universal structural testing machine that can test structural components up to 17.7 m in height.

15.9.2 BRIDGE COLUMN REINFORCING REQUIREMENTS

As a result of the 1971 San Fernando earthquake, design requirements for bridge columns in seismic zones were modified. This included new requirements for the anchorage of longitudinal reinforcing steel into foundations. However, the adequacy of these design modifications was not verified. The Large Scale Bridge Column Project was initiated by the Center for Building in the early 1980s to provide the necessary verification. This project, led by William Stone, consisted of two full-scale bridge column tests; one column was designed to fail in flexure and the other was designed to fail in shear. The columns were designed to the CALTRANS (California Department of Transportation) specifications. The challenges arose from the size of the test specimens and the need to apply lateral (seismic) loads in addition to vertical (gravity) loads. The tests were designed to use the existing 53 MN universal testing machine to apply the vertical load to simulate the mass of the bridge superstructure. A 14 m high post-tensioned reaction wall and rail system had to be constructed for the application of the lateral loads. The series of column tests was the first of its kind and as such, provided important benchmark data [5]. The tests verified the adequacy of the revised CALTRANS design specifications. In addition, Geraldine Cheok tested companion 1/6-scale bridge columns and the results indicated that the behavior of full-scale bridge columns could be extrapolated from small-scale bridge column tests. This finding suggests that the high costs associated with full-scale tests are not always necessary and less expensive small-scale tests may be sufficient.

15.9.3 PRECAST CONCRETE FRAMES

Precast concrete frame construction has not been used extensively in high seismic regions of the United States, despite its potential benefits in construction speed and quality control. This is because building code requirements (e.g., Uniform Building Code, UBC) have been based on past experience with cast-in-place construction and regard precast construction as an "undefined structural system" which must be shown to be equivalent to cast-in-place systems and to provide sufficient lateral force resistance and energy absorption capacity. Also, a precast concrete framed structure collapsed in the 1964 Anchorage, Alaska earthquake.

Therefore, in 1987, CBT initiated a project to study the performance and development of moment-resisting precast beam-column connections. The challenge was to develop a connection that was economical, easy to construct, and capable of resisting the cyclic inelastic deformation caused by earthquake loadings. Based on initial tests in the study, a post-tensioned precast connection appeared to be viable. These early results caught the interest of Charles Pankow Builders, which provided funding through the American Concrete Institute Concrete Research Foundation to further develop the post-tensioned concept. Close collaboration between William C. Stone, Geraldine S. Cheok, and H. S. Lew of NIST, Dean Stephan and David Seagren of Pankow Builders, and John Stanton of the University of Washington, resulted in three different designs. The most viable design combined the use of low strength reinforcing steel and high strength prestressing steel - a hybrid connection. Based on tests conducted by NIST [6], design guidelines for precast hybrid connections were developed. These guidelines and results were used to obtain approval from the International Conference of Building Officials Evaluation Service for the construction of hybrid connections in seismic zones.

Thirty-nine-story precast concrete building in San Francisco.

In addition, the American Concrete Institute (ACI), which is responsible for the national standard for reinforced concrete structures, developed a provisional standard for this system. Several structures using the hybrid connections have been constructed and several more are under consideration. The hybrid connection allowed for construction of a $128-million, 39-story building in San Francisco (see drawing). This building will be the tallest concrete frame building to be built in a high seismic region. Recognition of the innovation of the work was reflected in the awards received - ACI Structural Research Award for Cheok and Stone in 1997, Department of Commerce Bronze Medal for Cheok in 1997, Finalist in Civil Engineering Research Foundation Charles Pankow Award for Innovation in 1998, Maryland Young Engineer Award for Cheok in 1997, and Department of Commerce Silver Medal for Cheok, Lew and Stone in 2001.

15.9.4 REHABILITATION OF WELDED STEEL MOMENT FRAME CONNECTIONS

Steel framed buildings traditionally have been considered to be among the most seismic resistant structural systems. The January 17, 1994 Northridge earthquake, however, caused unexpected damage to many welded steel moment frame buildings. In general, the damage was confined to beam-to-column connections that suffered brittle fracture in the flange welds. In response to these failures, NIST initiated research into methods to modify existing buildings to improve their seismic performance. A collaborative research effort led by John Gross was undertaken and involved Nestor Iwankiw of AISC, Michael Engelhardt of The University of Texas, Chia-Ming Uang of the University of California, San Diego, and Kazuhiko Kasai of Lehigh University. Three methods to reduce the stresses at the beam-to-column connection were studied: 1) welded haunch, 2) reduced beam section, and 3) bolted bracket. Eighteen full-scale tests were conducted on subassemblages representing interior joints, both with and without a concrete floor slab. The result of this multi-year effort was the publication of comprehensive guidelines for the seismic rehabilitation of existing welded steel frame buildings - AISC Design Guide No. 12 [7]. The guidelines provide experimentally-validated response prediction models and design equations for the three connection modification concepts that shift loading from the weld joints into the beams, thus enabling the structure to absorb the earthquake's energy in a non-brittle manner. AISC Design Guide No. 12 has been cited by the FEMA document, Recommended Seismic Evaluation and Upgrade Criteria for Existing Welded Steel Moment Frame Buildings. John Gross received the Bronze Medal Award of the Department of Commerce in 2001 for his leadership of this study.

15.9.5 TEST METHODS FOR PASSIVE AND ACTIVE SEISMIC ENERGY ABSORPTION

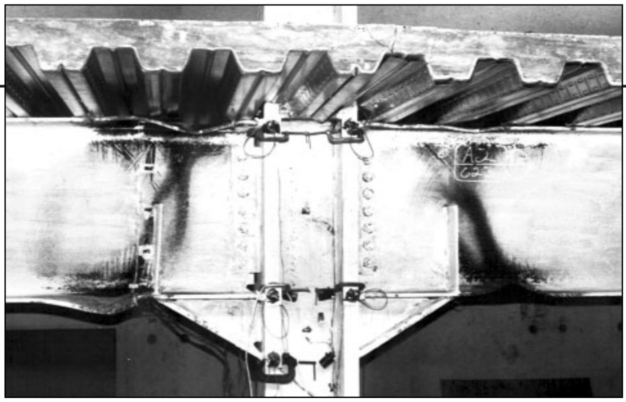
Structural control devices, such as seismic isolation and passive energy dissipators, have been installed in numerous structures throughout the world and have proven to be effective in reducing both motions and forces during earthquakes and strong winds. Still these devices are generally produced in small quantities, specifically for each application. To guarantee that the devices will perform as the designer expected, many building codes and guidelines recommend that the devices be tested before installation. While some of these standards describe a limited number of specific tests, widely accepted test standards do not yet exist. Before his untimely death in 1993, Albert Lin recognized the need for comprehensive and consistent test standards. Such standards are useful to designers, manufactures, and contractors, since they will make the process of validating these devices consistent. To address the issue, BFRL developed two sets of testing guidelines and has worked to experimentally verify the guidelines completeness.

BFRL researchers began the effort with the development of guidelines for testing seismic isolation systems [(8] entitled: Guidelines for Pre-Qualification, Prototype, and Quality Control Testing of Seismic Isolation Systems. Harry W. Shenton, III, developed this set of guidelines, in consultation with a technical review committee that consisted of designers, manufactures, and academicians who are experts in the field. A draft of the guidelines was reviewed by a broader group of seismic isolation experts, and their comments were incorporated into the final version of the guidelines. The American Society of Civil Engineers (ASCE) is in the process of developing a national consensus standard based on the NIST-developed isolation device testing guidelines. The consensus standard is currently (2002) in the balloting phase.

To verify the completeness of the isolation testing guidelines, Andrew Taylor, working with Gregory Bradley and Peter Chang, both from the University of Maryland, began experimental tests on elastomeric isolators. They performed a series of tests to determine the bearing's ultimate compressive strength, failure mode, and the effects of model scale on the response [9]. The experimental results were compared with numerical simulations, and used to improve the accuracy of the numerical models. The effort is continuing with a series of tests that will be performed on isolators with known manufacturing flaws. These tests will also investigate how accurately such flaws can be numerically modeled and how adversely they affect the performance of the isolators. The results of these tests are expected to expose any inconsistencies, omissions, or other unforeseen problems with the testing procedures, and will provide useful data for the development of performance-based seismic design.

While seismic isolation is generally accepted by earthquake engineering profession and recognized in the building codes in high-seismic areas, passive structural dampers are still gaining acceptance and semi-active devices are still in the development phase. To address the needs related to these newer technologies, BFRL research is continuing with efforts to develop and improve test methods, design procedures, and analytical tools for passive and semi-active structural dampers. Fahim Sadek and Michael A. Riley followed a procedure similar to that used to develop the isolation device testing process of developing these guidelines. Analytical results led to better methods for determining the number of equivalent cycles necessary for testing structural control devices.

In addition to the development of testing guidelines, this program has produced a wide variety of other structural control related documents. Work by Fahim Sadek, Riley Chung, Andrew Taylor, and Bijan Mohraz of SMU led to publication of an innovative, simplified method for designing tuned mass dampers. BFRL researchers have also developed improved design procedures for passive dampers [10], which are intended to replace current procedures that may produce non-conservative designs in some cases. Research on semi-active control devices and the on-going collaboration with researchers at the Polytechnic School of Tunisia is leading to advancements in non-linear control laws and control of non-linear structures [11]. Andrew Taylor received the Bronze Medal Award of the Department of Commerce in 1996 for his contributions to development of the testing guidelines.



Full-scale test of welded haunch modification to steel moment frame connection

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A APPENDIX

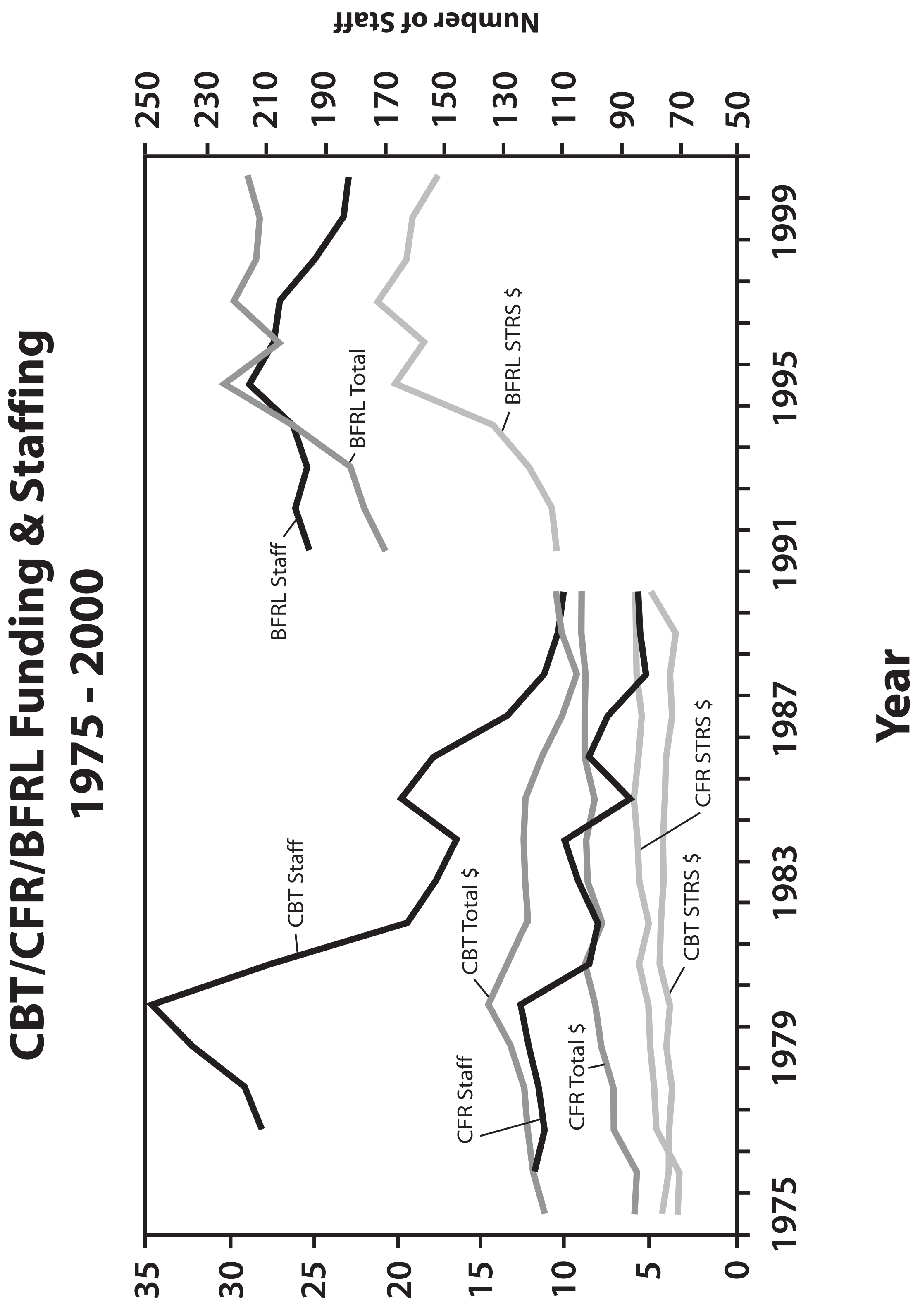
CBT/CFR/BFRL Data **RNW 12/20/02**

	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
CBT																
Direct $M	4.2	3.8	3.8	3.6	3.9	3.8	4.4	4.4	4.3	4.4	4.3	4.1	3.8	3.9	3.6	5.1
Total $M	11.2	11.9	12.2	12.4	13.2	14.7	13.6	12.4	12.5	12.6	12.6	11.6	10.4	9.5	10.3	10.8
WY	205	229	209	180	189	199	182	138	146	139	134	128	102	89	84	89
Staff			211	217	235	249	208	162	152	145	164	153	128	115	111	109
CFR																
Direct $M	3.3	3.2	4.6	4.7	5	5.1	5.7	5.1	5.7	5.8	6.1	5.8	5.6	5.9	6	6
Total $M	5.8	5.7	7.1	7.1	7.8	8.2	8.8	7.9	8.7	8.9	8.4	8.9	8.9	8.9	9.2	9.2
WY								91	92	95	94	89	87	83	78	77
Staff		118	114	116	120	123	100	97	103	108	86	100	94	81	83	84

1976 data adjusted to represent four quarters rather than the five quarters of the transition to the new fiscal year.

	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
BFRL										
Direct $M	10.7	11	12.3	14.6	20.3	18.6	21.5	19.8	19.4	17.9
Total $M	20.9	22.2	23	26.5	30.5	27.2	30	28.7	28.5	29.1
WY	177	179	179	184	192	185	180	173	174	164
Staff	195	200	196	200	216	208	206	194	184	182

Staff data do not include research associates from industry and guest workers from universities and other laboratories. Generally, these professionals amounted to some 60 additional work years.



CBT/CFR/BFRL Funding & Staffing
1975 - 2000
Funding ($M)
Number of Staff
Year
35
30
25
20
15
10
5
0
250
230
210
190
170
150
130
110
90
70
50
1975
1979
1983
1987
1991
1995
1999
CBT Staff
CBT Total $
CFR Staff
CFR Total $
CBT STRS $
CFR STRS $
BFRL Staff
BFRL Total
BFRL STRS $

APPENDIX B

CBT/CFR/BFRL NBS/NIST/DoC Awards

Names	Award	Year	Reason
Ryan, John	Bronze	1975	Total Energy
Snell, Jack	Silver	1975	Energy Conservation
Mathey, Robert	Silver, jt	1975	Coated Rebars
Clifton, James	Silver, jt	1975	Coated Rebars
Achenbach, Paul	Gold	1975	Energy Document
Anderson, Erik	Bronze	1976	Concrete Durability
Berger, Harvey	Bronze	1976	Lead Paint
Castle, L. Jocelyn	Bronze	1976	Administration
Parker, William	Bronze	1976	Laboratory Scale Fire Tests
Quintiere, James	Bronze	1976	Room Fire Growth
Bright, Richard	Silver	1976	Smoke Detectors
Hill, James	Silver	1976	Solar Test Methods
Petersen, Stephen	Silver	1976	Energy Dollars
Robertson, Alexander	Gold	1976	Fire Standards
Cattaneo, Louis	Bronze	1977	Guard Rail Safety Standards
Embree, Edward	Bronze	1977	Electrical Connections Overheating
Fattal, S. George	Bronze	1977	Guard Rail Safety Standards
Hunt, Charles	Bronze	1977	Air Exchange Measurement
Jason, Nora	Bronze	1977	FRIS - Fire Research Information Service
Berry, Sandra	Crittenden	1977	NCSBCS Conferences
Culver, Charles	Silver	1977	Seismic Standards
Rockett, John	Silver	1977	Fire Modeling
Ruegg, Rosalie	Silver	1977	Solar Economics
Pielert, James	Silver, jt	1977	Mobile Home Performance
Gross, James	Silver, jt	1977	Mobile Home Performance
Lyons, John	Gold	1977	CFR creation
Bailey, William	Bronze	1978	Laboratory Support

Names	Award	Year	Reason
Robertson, Alexander	Rosa	1978	Flammability Test Method
Huggett, Clayton	Silver	1978	Flame Inhibition
Kelly, George	Silver	1978	Energy labeling of AC and HP
Marshall, Harold	Silver	1978	Economics research leadership
Winger, James	Silver	1978	Furniture and Fabric Flammability Standards
Buchbinder, Benjamin	Bronze	1979	Decision analysis for fire safety
Lee, Thomas	Bronze	1979	Smoke Chamber Test Method
Nelson, Harold	Safety	1979	CFR safety program
Pierman, Brian	Safety	1979	CBT safety program
Benjamin, Irwin	Silver	1979	FSES and adoption of fire standards in codes
Dikkers, Robert	Silver	1979	Solar performance criteria
Burch, Douglas	Bronze	1980	Attic insulation and ventilation
Grot, Richard	Bronze	1980	Weatherization field measurements
Kaetzel, Lawrence	Bronze	1980	Laboratory automation
Lew, Hai-Sang	Bronze	1980	Willow Island investigation
Masters, Larry	Bronze	1980	Service Live Prediction standard
Raufaste, Noel	Bronze	1980	CBT information publications
Roberts, Willard	Bronze	1980	Solar materials tests
Streed, Elmer	Bronze	1980	Solar collector test methods
Waksman, David	Bronze	1980	Solar performance standards for durability
Krasny, John	Bronze	1980	Self extinguishing cigarettes
Loftness, Joseph	Bronze	1980	Cigarette ignition resistance of mattresses
Clark, Elizabeth	Safety	1980	Materials laboratory safety
Ellingwood, Bruce	Silver	1980	Probability-based load criteria
Cullen, William	Gold	1980	Roofing Standards
Kusuda, Tamami	Gold	1980	NBSLD - National Bureau of Standards Load Detection Program
Cherry, Sonya	Bronze	1981	Grants administration
Harris, James R.	Bronze	1981	Seismic standards for federal buidings
Jones, Robert	Bronze	1981	Guarded Hot Plate management
Leyendecker, EV	Bronze	1981	Seismic provisions review and refinement
Simiu, Emil	Bronze	1981	Wind load research and book
Trechsel, Heinz	Bronze	1981	Residential energy conservation installation standards
Jones, Robert	Meas.Services	1981	Guarded Hot Plate management
Didion, David	Silver	1981	Seasonal performance of heating and cooling systems
Pfrang, Edward	Silver	1981	Performance criteria for housing
Chapman, Robert	Bronze	1982	FSES software
Hurley, Warren	Bronze	1982	Appliance test method data acquisition

Names	Award	Year	Reason
Kashiwagi, Takashi	Bronze	1982	Radiative ignition
Raines, James	Bronze	1982	Laboratory automation
Frohnsdorff, Geoffrey	Silver	1982	Blended cements standards
Lew, Hai-Sang	Silver	1982	Construction safety guidelines
Nelson, Harold	Silver	1982	FSES
Quintiere, James	Silver	1982	Fire growth modeling
Wright, Richard	Gold	1982	CBT restructuring
Marshall, Richard	Gold, jt	1982	Hyatt investigation
Pfrang, Edward	Gold, jt	1982	Hyatt investigation
Brown, Paul	Bronze	1983	Cement hydration data
Carino, Nicholas	Bronze	1983	Concrete Maturity method
McCaffrey, Bernard	Bronze	1983	Large plume experiment and theory
Rankin, Frank	Bronze	1983	3D testing facility
Walton, George	Bronze	1983	Thermal Analysis computer program
Collins, Belinda	Bronze	1984	Color rendering for safety symbols
Twilley, William	Bronze	1984	Cone calorimeter design and construction
Woodward, Kyle	Bronze	1984	3D testing facility
Simiu, Emil	Silver	1984	Wind research
Horner, Barbara	Bronze	1985	Secretarial service
Mulholland, George	Bronze	1985	Smoke particle generation and growth
Yancey, Charles	EEO	1985	Recruiting minority students
Baum, Howard	Gold, jt	1985	LES room model
Rehm, Ronald	Gold, jt	1985	LES room model
Babrauskas, Vytenis	Bronze	1986	Cone calorimeter and heat release rate
Ohlemiller, Thomas	Bronze	1986	Smoldering combustion
Yaniv, Simone	Bronze	1986	Characterization of semi-reverberant rooms
Lyons, John	Condon	1986	Scientific American book "Fire"
Lawson, J. Randall	Safety	1986	Gas well blowout studies
Mathey, Robert	Safety	1986	CBT program
Leyendecker, EV	Silver	1986	BSSC recommended seismic provisions
Peacock, Richard	Bronze	1987	Safety of solid fuel heating appliances
Stone, William	Bronze	1987	Mexico earthquake investigation
Gross, Daniel	Rosa	1987	Fire hazard test method standards
Smyth, Kermit	Condon	1987	Chemistry of molecular growth processes in flames
Didion, David	Appl. Res.	1987	Refrigerant mixtures
Levine, Robert	EEO	1987	Recruiting minority engineers and scientists
Carino, Nicholas	Silver	1987	Moscow embassy investigation

Names	Award	Year	Reason
Didion, David	Gold	1987	Refrigerant mixtures
Snell, Jack	Gold	1987	Puerto Rico fire code and Dupont Plaza investigation
Fanney, Hunter	Bronze	1988	Solar hot water test methods
Didion, David	Condon, jt	1988	Quest for alternatives
McLinden, Mark	Condon, jt	1988	Quest for alternatives
Persily, Andrew	Bronze	1989	IAQ measurements
Simiu, Emil	Gold	1989	Wind and wave effects on off shore platforms
Nelson, Harold	Gold	1989	FSES in Life Safety Code
Evans, David	Bronze	1990	Sprinkler response prediction
Phan, Long	Bronze	1990	Punching shear resistance of lightweight concrete
Twilley, William	Safety	1990	Controlled atmosphere cone calorimeter
Braun, Emil	Silver, jt	1990	Hazard I
Bukowski, Richard	Silver, jt	1990	Hazard I
Forney, Lynn	Silver, jt	1990	Hazard I
Jones, Walter	Silver, jt	1990	Hazard I
Peacock, Richard	Silver, jt	1990	Hazard I
Cramer, Deborah	Bronze	1991	Secretarial service
Domanski, Piotr	Bronze	1991	Cycle II for refrigerant combinations
Pitts, William	Bronze	1991	Turbulent combustion measurements
Kashiwagi, Takashi	Appl Res	1991	Thermal degradation of PMMA
Kashiwagi, Takashi	Silver	1991	Characterization of flame spread
Bushby, Steven	Bronze	1992	BACnet
Flood, Carolyn	Bronze	1992	Secretarial service
Babrauskas, Vytenis	Rosa	1992	Cone calorimeter and HRR
Smyth, Kermit	Silver	1992	Measuring chemical structure of flames
Nyden, Marc	Bronze	1993	Computational molecular dynamics
Walton, William	Bronze	1993	Tests of burning oil spills
Danner, William	Bronze, jt	1993	STEP Methodologies
Palmer, Mark	Bronze, jt	1993	STEP Methodologies
Fleegle, Nancy	Bronze	1994	Secretarial service
McKnight, Mary	Bronze	1994	Coatings practices
Nguyen, Tinh	Bronze	1994	Modeling degradation of coatings
Hill, James	Gold	1994	Environmental systems research and management
Reed, Kent	Silver, jt	1994	Initial Release of STEP
Gann, Richard	Silver	1994	Cigarette ignition propensity
Kedzierski, Mark	Bronze	1995	Measurement of refrigerant heat transfer
Didion, David	Slichter, jt	1995	Alternative refrigerants

Names	Award	Year	Reason
Domanski, Piotr	Slichter, jt	1995	Alternative refrigerants
Kedzierski, Mark	Slichter, jt	1995	Alternative refrigerants
Evans, David	Silver	1995	Burning oil spills
Grosshandler, William	Silver	1995	Alternative fire suppressants
Martin, Jonathan	Bronze	1996	Service life prediction methods
Taylor, Andrew	Bronze	1996	Test method for seismic base isolation
Bushby, Steven	Slichter	1996	BACnet
Pitts, William	Silver	1996	CO yields in combustion
Cheok, Geraldine	Bronze	1997	Pankow frame
Roadarmel, Gary	Safety jt	1997	Large scale fire tests
Delauter, Laurean	Safety jt	1997	Large scale fire tests
Bentz, Dale	Bronze	1998	Concrete modeling
Bryner, Sheilda	Bronze	1998	Secretarial service
Dougherty, Brian	Bronze	1999	Test methods for heat pumps and air conditioners
Gilman, Jeffrey	Bronze	1999	Nanotechnology for fire resistant polymers
Jason, Nora	Bronze, jt	1999	Fire on the Web
Forney, Glenn	Bronze, jt	1999	Fire on the Web
Ehlen, Mark	Bronze	2000	Bridge LCC
Yang, Jiann	Bronze	2000	Suppression effectiveness of liquid agents
Butler, Kathryn	EEO, jt	2000	BFRL Diversity Committee
Bryner, Nelson	EEO, jt	2000	BFRL Diversity Committee
Kashiwagi, Takashi	Gold	2000	Flame retardants principles and models
Gross, John	Bronze	2001	Rehabilitation of welded steel frames
Madryzkowski, Daniel	Bronze	2001	Large field fire tests
McGrattin, Kevin	Silver, jt	2001	Fire dynamics simulations
Forney, Glenn	Silver, jt	2001	Fire dynamics simulations
Cheok, Geraldine	Silver, jt	2001	Pankow frame
Stone, William	Silver, jt	2001	Pankow frame
Lew, Hai-Sang	Silver, jt	2001	Pankow frame

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