NISTIR 5207

WATER MIST FIRE SUPPRESSION WORKSHOP, MARCH 1-2, 1993: PROCEEDINGS

Kathy A. Notarianni and Nora H. Jason, Editors

Building and Fire Research Laboratory
Gaithersburg, Maryland 20899

NIST

United States Department of Commerce
Technology Administration
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June 1993
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National Institute of Standards and Technology
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U.S. Department of Commerce
Ronald H. Brown, *Secretary*
National Institute of Standards and Technology
Arati Prabhakar, *Director*

ABSTRACT

The water mist fire suppression workshop was organized to facilitate the commercialization of water mist technology in the United States. The imminent lack of availability of halon fire suppressants has sparked worldwide efforts in developing alternative fire fighting agents and delivery systems. Water mist systems are potential replacements in many industrial uses, as well as in new markets, such as commercial passenger aircraft. Speakers presented state-of-the-art papers on the incentives of using misting sprays, the advances in spray drop size measurement and the engineering criteria for water mist fire suppression systems. Three papers discussed projects demonstrating the use of water mist systems in aircraft, marine, and telecommunications applications. With this background the speakers and attendees were divided into three panels: research needs, end use criteria, and marketing. The purpose of the panel sessions was to identify the areas of concern relating to the commercialization of water mist systems. The proceedings brings together the recommendations of each panel and the individual technical papers.

Key Words: fire suppression; water fog; water mist; water sprays; fire research; droplets; drop sizes; fire extinguishment; sprinklers; aircraft; electronic facilities; marine transportation

PREFACE

The water mist fire suppression workshop was organized to facilitate the commercialization of water mist technology in the United States. The imminent lack of availability of halon fire suppressants has sparked worldwide efforts in developing alternative fire fighting agents and delivery systems. Water mist systems are potential replacements in many industrial uses, as well as in new markets, such as residences and commercial passenger aircraft. The workshop was funded, organized, and conducted by the Building and Fire Research Laboratory (BFRL) and the Advanced Technology Program (ATP) at the National Institute of Standards and Technology (NIST).

NIST, a principal agency of the Department of Commerce's Technology Administration, has as its mission to strengthen U.S. industry's competitiveness, advance science, and improve public health, safety, and the environment. NIST conducts basic and applied research in the physical sciences and engineering, developing measurement techniques, test methods, standards, and related services. NIST does generic and precompetitive research and development work on new advanced technologies. BFRL's mission is to provide performance prediction and measurement technologies and technical advances that improve the quality of constructed facilities.

The Advanced Technology Program funds advanced technologies that have a significant potential for improving the competitiveness of U.S. businesses. The ATP is a federal assistance program, and awards are based on merit as determined through a full and open competition. ATP appropriations for Fiscal Year 1993 are $68 million, and significant increases have been proposed for the next several years.

To facilitate the process of commercializing water mist systems, the workshop brought together approximately 100 people from industrial, academic, governmental, and approval organizations to discuss the issues impeding the commercialization of water mist technology. The workshop included representatives from system suppliers, end users (consumers), researchers, insurance, and approval laboratories. The workshop resulted in uniting the industrial effort by assessing the value of such systems, and identifying the areas of concern for all groups that could form the basis of future ATP projects.

The ATP Director presented an overview of the program and information on application for an ATP award. Speakers presented state-of-the-art papers on the incentives of using misting sprays, the advances in spray drop size measurement and the engineering criteria for water mist fire suppression systems. Three papers discussed projects demonstrating the use of water mist systems in aircraft, marine, and telecommunications applications.

These presentations gave all participants a common background in preparation for participation in the panel discussions. All participants were divided into three panels: research needs, end use criteria, and marketing. Each panel was composed of representatives from various technical and industrial backgrounds or interests. The panel themes were identified prior to the workshop and attendees were asked to identify discussion items within each panel. This list was provided to the panel chairs prior to the workshop, and to each attendee at registration. The sole purpose of the list was to provide a starting point of discussion within each panel. After three to four hours of discussion, each panel chair summarized the conclusions of their panel to all participants. Participants voted on each panel recommendation so that an indication of the priorities evolved. Each participant could cast a total of from one to five votes for the priorities within each panel.

The proceedings contain the recommendations of each panel and the individual technical papers that were presented. It is hoped that the proceedings can serve as a resource to organizations researching, marketing, or employing water mist systems, as well as provide documentation of the thinking of a cross section of individuals representing a broad range of technical expertise, experience, and responsibility in their respective organizations. Further information regarding the ATP program at NIST can be obtained by calling the ATP "hotline" (Recording) at (301) 975-2273 or General Inquiries (301) 975-2636.

I would like to express my gratitude to Ms. Nora H. Jason for her efforts as conference coordinator, attending to every detail of the planning for the conference and publishing the proceedings with great care. I would like to acknowledge the contribution of Dr. David D. Evans, NIST; he encouraged the creation of the workshop and introduced the voting methodology that was employed in this Workshop. It was used earlier at the *First International Conference on Fire Suppression Research*, held in Stockholm, Sweden, in 1992.

Kathy A. Notarianni

Kathy A. Notarianni, P.E.

June 1993

CONTENTS

1.0 AGENDA

WATER MIST FIRE SUPPRESSION WORKSHOP
March 1-2, 1993

National Institute of Standards and Technology
Gaithersburg, MD 20899 USA

March 1

8:00-8:30 AM	Registration
8:30AM	Kathy A. Notarianni, Workshop Chair *Opening Remarks*
	Richard N. Wright, BFRL Director, NIST *Welcome*
8:45	George A. Uriano, National Institute of Standards and Technology. *Advanced Technology Program: A Status Report.*
9:15	Ronald L. Alpert, Factory Mutual Research Corp., *Incentive for Use of Misting Sprays as a Fire Suppression Flooding Agent.*
9:45	William D. Bachalo, Aerometrics, Inc. *Advances in Spray Drop Size and Velocity Measurement Capabilities for the Characterization of Fire Protection Systems.*
10:15	Jack R.Mawhinney, National Research Council, Canada. *Engineering Criteria for Water Mist Fire Suppression Systems.*
10:45	Break
11:15	Constantine P. Sarkos, FAA Technical Center. *Evaluation and Optimization of an On-Board Water Spray Fire Suppression System in Aircraft.*
11:45	Antony R.F. Turner, Marioff Hi-Fog Oy. *Water Mist in Marine Applications.*
12:15	Terence Simpson, Fire and Safety International. *Water Mist Fire Protection Systems for Telecommunication Switch Gear and Other Electronic Facilities.*
12:45	Lunch

2:00 PM	Panel Sessions begin: Research Needs: Thor Eklund, Chair End Use Criteria: Russell P. Fleming, Chair Marketing: Kathy Vernot, Chair
5:00	Panel Sessions adjourn

March 2, 1993

9:00	Panel Sessions reconvene
10:00	Break
10:30	*Research Needs Panel Summary*: Thor Eklund, FAA Technical Center
10:50	*End Use Criteria Panel Summary*: Russell P. Fleming, National Fire Sprinkler Assoc.
11:10	*Marketing Panel Summary*: Kathy Vernot, Reliable Automatic Sprinkler Co.
11:30	Voting
11:45	*Closing Remarks*: Kathy A. Notarianni

2.0 PANEL ACTIVITY

2.1 Methodology

Prior to the Workshop all participants were asked to identify issues impacting upon the implementation of water mist fire suppression technology for the following panels:

A. Research Needs
B. End Use Criteria
C. Marketing

Responses were received from approximately one-eighth of the participants. The responses were collated and forwarded to the panel chairs prior to the Workshop. The responses were edited by the panel chairs and the revised lists were included in each participant's registration information packet. The purpose of the lists was to provide a stimulus to the panel discussions.

The panels met for three hours on the afternoon of the first day of the Workshop and for one hour on the morning of the second day. Three sets of needs were identified during the simultaneous work sessions. Each panel chair gave a summary presentation to all Workshop participants and prepared a written summary of the findings of their panel. The written summaries are included in the next section. After the presentation each participant was asked to vote on the items identified by each panel. For the voting procedure, each participant was given five dots for each panel (each panel had a different color). Each participant could cast all five votes for one item identified by a particular panel or distribute the votes amongst items within that panel.

The voting time was short, approximately twenty minutes, and the results should be viewed as a quick assessment of how the participants felt after the panel presentations. The results are to a large degree a function of the background, expertise, and current interest areas of the participants. The summary of the rankings within each panel is presented below.

2.2 Panel Summaries

A. Research Needs Panel Summary: by Thor Eklund

The overall strategy used in identifying research needs involved definition of the present state of knowledge, identification of potential applications for mist systems, postulation of potential mist system shortcomings, and development of research thrusts that could close the gaps between current capability and future applications.

An issue raised early on was the disparity between sprinkler technology and mist technology. It became evident that sprinkler technology was based on full scale test demonstrations of worst case fire scenarios. As such, the details of the fire suppression physics were not needed for establishment of codes and design criteria.

Mist systems, on the other hand, are most promising as tailored to specific fire protection problems where excess water application rates are either unavailable or unwanted. The obvious current example is the potential use of water mists as substitutes for halons in total flooding applications. The sentiment of the panel was that mist systems should not be targeted at applications currently being satisfied by sprinkler technology.

There were a number of significant observations on what premises can be used as starting points. For one, the thermal requirements for fire suppression are known for mists if it is assumed that the droplets are 100 percent effective. Also, the majority of real life fires do not involve premixed flames. The majority of real fires are diffusion flames with oxidation reactions occurring in the vapor phase, smoldering fires, or Class C fires where combustion energy release is sustained in part by the availability of electrical energy. These are the type fires that mist systems must be tested against.

The panel consensus was that two big technical unknowns were: first, how droplets actually work against fire, and second, how the "right" size droplets are transported to the "right" place to suppress the fire most effectively. There was additional consensus that mist technology was presently primitive enough so that significant progress in the near term required a two-track approach involving basic research along with development and testing of prototype mist systems.

The basic research needs include understanding of droplet dynamics and interaction with fire. Additionally, the capabilities of mists to control fire by both radiation attenuation and fuel surface wetting have to be included in assessing mist system performance. Research also is needed on the effect of additives such as surfactants, soluble powders, and those changing the refractive index. A drawback to mist systems is the poor ability of mists to get behind physical obstacles.

Mist systems were somewhat arbitrarily grouped into four types:

1. High pressure (approximately 7000 kPa or 1,000 psi) systems that produce very fine droplets;

2. intermediate pressure (690 kPa or 100 psi) high flow systems;

3. low flow systems such as are presently being tested for aircraft interiors;

4. pneumatic (gas assisted atomization) systems.

It was suggested that prototypes of these four systems be tested against some generic group of fire scenarios including steady fires with pronounced plumes, spreading fires, and smoldering fires. It was further suggested that some of these test scenarios be the same as those used for testing other systems or agents so as to provide a point of reference.

Intermediate between basic research and prototype system evaluation was the need to identify engineering trade-offs among system pressure, particle size, momentum, and evaporative cooling. Because water mist systems are not envisioned as overkill systems, optimal performance of mist systems will require appropriate engineered fire detection systems that will activate the misting at the proper time. The usefulness of mists as an inerting agent was identified as limited but as yet inadequately quantified. The dynamics of droplet coagulation was an issue of importance because even the fine mists from high pressure systems become more coarse as the distance from the nozzle increases.

Although there was general consensus that modeling should be a part of the overall research, the role of modeling ranged from completely theoretical solutions to the use of models as an aid to generalize experimental results.

Some potential positive and adverse safety effects were identified. In terms of human survivability and escape, mist systems could cool gas temperatures, as well as remove toxicants and soot from the smoke filled atmosphere. On the negative side, acid gases dissolved in small droplets could be transported deep into the lung; evaporation of mist in hot gases could expose occupants to steam-type injuries; mist-induced mixing could upset smoke layer stratification and reduce visibility at locations close to the floor. In so far as toxicity was a concern, the statement was made that carbon monoxide has traditionally been the big killer in building fires. The best way to minimize toxic hazards is to extinguish the fire. All these hazard considerations led to the conclusion that research is needed on the effects of mist on plume gas characteristics.

In terms of goals for development of prototype systems, there emerged a clear need for end users to define applications of interest and acceptable test methods that could show a system's adequacy for a given application.

The panel felt that the area of water mist fire suppression was highly suitable for inclusion in NIST's Advanced Technology Program. There was skepticism among panel members that mist systems could be developed for more than a few applications as halon system replacements before halons are phased out.

The open three-hour discussion leading to the above summary was followed by a one-hour session where each panel member was invited to postulate one specific research need. The final seventeen research projects include a number of consolidations of recommendations from different panel members. All recommended projects identified by a panel member were included in the list.

It is noteworthy that the top six research topics gaining the most votes from Workshop attendees were experimental in nature. Of these, three involved fairly basic research and three involved applied research with either commercially available or prototype misting equipment.

B. End Use Criteria Panel Summary: by Russell P. Fleming

The panel began its deliberations by listing potential uses of water mist systems. Within a fairly short period of time, nearly 60 potential uses had been identified, ranging from vehicle engine compartments to large open office areas. This exercise was helpful in that it allowed panel members to think beyond applications in their own specific fields.

The panel then began compiling a list of user needs. Following the development of a preliminary list, the panel turned its attention back to the potential end uses. An effort was made to categorize the end uses according to the nature of the likely predominating suppression mechanism. In other words, referring to the presentations of the Workshop speakers, it was decided to try to determine if the use of water mist in a specific end use was likely to parallel the use of a total flooding agent, the use of a traditional sprinkler system applied over an area, or some type of intermediate application whereby the agent is discharged on surfaces of equipment or over a process hazard so as to provide a localized protection effect. This would be similar to the manner in which carbon dioxide or water spray systems are sometimes used.

Discussion led to the conclusion that it was impractical to categorize the end uses in this manner, since the potential existed for a variety of design approaches in many uses. For example, the total flooding approach could be used in virtually any type of use or occupancy if practical, based upon the volume of the area to be protected and the degree of confinement. Further development of design approaches may provide system designers and specifiers with a choice of suppression mechanisms to be employed in a specific application.

Refinement of the user needs list led to its presentation in three general categories: user needs from the research and development community, user needs of system information enabling the selection process, and user needs in standards development.

The user needs from the research and development community include those that are oriented toward fundamental research such as an understanding of the basic suppression mechanisms, the sensitivity to ventilation effects, minimum water quality requirements, additive concerns, and enclosure/confinement needs. Also included are development-oriented needs such as design criteria, use limitations, and acceptance test criteria.

Information related to system selection is needed by the end user to evaluate the water mist systems against available alternatives. The panel operated under the general premise that the potential uses of water mist should be limited only by capability, and that factors such as reliability, cost, and maintenance requirements will ultimately determine the degree of acceptance by the fire protection community.

The standards development needs includes two items which were recognized as "umbrella" needs: 1) development of a National Fire Protection Association installation standard and 2) development of standards for third party testing and listing of equipment. It was agreed that many of the other specific user needs will necessarily be met during the development of such standards. The panel also, however, chose to specifically mention the need to develop standardized fire tests and minimum product performance criteria. Standardized terminology and technician certification/training were included in the standards development needs.

In all, the panel identified 39 user needs which must be satisfied to bring water mist technology into proper use in the fire protection community.

C. Marketing Panel Summary: by Kathy A. Vernot

The marketing panel addressed the most viable impediments to the successful marketing of a water mist system by defining the applications for the system, identifying the probable groups which would resist the system, and then discussing the points of resistance.

It was determined that the types of applications would be water-sensitive in nature, with the largest existing replacement market being that of halon 1301. In addition, new markets are represented in transportation, cultural resources (for example, museums, libraries), and locations having limited water supplies.

The panel felt that authorities having jurisdiction (AHJ), end users, equipment manufacturers and other water product manufacturers (for example, sprinkler) would be likely to impede the marketing of water mist systems. Their resistance may be due to misconceptions, cost, system reliability, or simply because the systems represent new technology. Other objections may be related to aesthetics or to the fact that the system does not have an unlimited agent supply.

Recommendations by the marketing panel to overcome these impediments include the conduct of full scale fire tests in laboratories to simulate conditions in a standardized test series, including the end users and equipment manufacturers in an interactive process.

The panel also concluded that it would be important to the development of confidence in the system reliability to continue to develop the technology in end user and equipment manufacturer pilot programs, and updating the technology in target applications. This effort also would be helpful in addressing failures as they occur.

Overall, the panel felt that all impediments could be overcome if the manufacturer of the water mist system included the AHJ, end users, and equipment manufacturers in testing and target installations. This interaction process would be critical to the education of the groups responsible for the development of standards and installation practices and costs.

2.3 Ranking of Panel Ideas

A. Research Needs Panel

Votes	Discussion Item	
62	A2.	Full scale tests where drop size, concentration, and jet momentum are characterized
36	A9.	Relationships among drop size, application rate, fire size, and room geometry
25	A6.	Develop at least one application to the point where standards/ requirements can be set for that application
25	A13.	Test of effects of mists on energized and de-energized electrical equipment of all types to determine damage potential and refurbishment requirements
23	A12.	Comparative evaluations of commercially available existing systems under equivalent fire exposures with measurements of specific engineering parameters
20	A3.	Small scale studies of interaction of characterized sprays in diffusion flames including such details as radiation effects, heat transfer, transport phenomena, etc.
18	A14.	For halon replacement applications, develop mist flooding characteristics, effectiveness and behavior prior to hardware development efforts
16	A1.	Interaction of mist and compartment gases given the presence of fire and effects on occupants
15	A5.	Numerical modeling verified through small scale tests to design large scale tests and to be used to generalize results to develop performance based tests

A. Research Needs Panel (continued)

Votes	Discussion Item	
15	A7.	Development of end-user/standard setting bodies acceptable consensus-based tests for at least one application
14	A8.	Comparative study of mist effectiveness against open vs. hidden fires in enclosed compartments
12	A4.	Testing of additives in water mist formed pneumatically by inert gas
10	A16.	For generalized development of mist technology use a three-track approach of basic research, prototype development, and research coordination
8	A10.	Research on self-contained, self-actuating water mist systems with additives
8	A15.	Develop and test mist total flooding systems for aircraft cargo compartments
7	A17.	Mist optimization for smoldering, spreading, and extinction through testing in already well-analyzed fire test geometries
1	A11.	Analytical model describing interaction of flame flow field and droplets

B. End-Use Criteria Panel

B1. Research and Development Needs
B1A. Research-oriented

Votes	Discussion Items	
10	B1A-3.	Ventilation concerns/sensitivities
8	B1A-2.	Droplet size limits/optimization
6	B1A-1.	Enhanced understanding of operating mechanisms

B. End-Use Criteria Panel (continued)

B1. Research and Development Needs (continued)
B1A. Research-oriented

Votes	Discussion Items	
5	B1A-5.	Additive concerns
2	B1A-4.	Enclosure/confinement needs
1	B1A-6.	Minimum water quality requirements
19	B1B-1.	Confidence in design criteria related to hazards
9	B1B-2.	Use limitations, including environmental temperature ranges

B1. Research and Development Needs (continued)
B1B. Development-oriented

9	B1B-3.	Safety concerns including pressure, steam burns, electric shock, noise, and inhalation
6	B1B-6.	Acceptance test criteria
2	B1B-8.	Corrosion resistance of equipment
0	B1B-4.	Enclosure overpressurization
0	B1B-5.	Earthquake protection/resistance
0	B1B-7.	Standardized equipment

B. End-Use Criteria Panel (continued)

B2. Information Affecting Selection of System

Votes	Discussion Items	
27	B2-5.	Reliability
12	B2-2.	Speed of suppression
9	B2-1.	Cost
7	B2-16.	Availability/market access
6	B2-3.	Weight/space
6	B2-12.	Acceptance by authority having jurisdiction/fire department procedures
5	B2-7.	Maintenance/service requirements and availability
5	B2-8.	Retrofit and expansion potential
5	B2-10.	Postfire cleanup and corrosion effects
4	B2-4.	Environmental effects
3	B2-19.	Water-friendly equipment
2	B2-11.	Restorability
2	B2-13.	Risk management model
2	B2-14.	Standardized equipment
2	B2-15.	Corrosion resistance of equipment
1	B2-9.	Compatibility with other systems/redundancy
1	B2-17.	Vendor network
1	B2-18.	Specifications
0	B2-6.	Inspection procedures

B3. Standards Development Needs

Votes	Discussion Items	
43	B3-1.	Development of NFPA/other standards
42	B3-4.	Develop standardized fire test(s)
34	B3-2.	Third party testing/listing of equipment
25	B3-5.	Develop minimum product performance criteria
6	B3-6.	Technician certification/training
2	B3-3.	Clarify terminology

C. Marketing Panel*

Votes	Discussion Items		
135	C1.		New Technology
(49)		1.	Full scale fire testing in laboratories to simulate conditions and accelerate standards and listing processes
(48)		2.	Test protocol standardization (universal consistency)
(38)**		3.	Include equipment manufacturers in testing cycle and select target applications (unprotected) for facilitation of pilot programs with highly visible end users
75	C5.		Reliability of system effectiveness
(62)		1.	Continue to develop technology to provide greater levels of confidence
(13)		2.	Include end users and equipment manufacturers in pilot program: update their technology as it is developed
(0)		3.	Be prepared to acknowledge and deal with failures

* Six votes withdrawn due to incorrect placement on chart

** It was not possible to separate the voting, so two items were combined

C. Marketing Panel (continued)

Votes		Discussion Items	
31		C6.	Lack of standards and acceptance by authorities having jurisdiction; a part of C1 (new technology impediment): education authorities having jurisdiction and the fire community about mist/fog systems
25		C4.	Costs; existing mist/fog technology is more expensive (on a unit basis) than sprinkler systems; therefore, it is important to emphasize the value of property contents, the cost of business interruption and that the fog/mist systems provide more cost-effective fire protection
16		C3.	Misconceptions - most prominent: water on sensitive equipment; work with equipment manufacturers to educate them about differences between mist/fog and sprinklers (test process inclusion)
8		C2.	Not an unlimited agent supply
	(8)		2. Assurance from testing that unlimited is non-essential
	(0)		1. Standard should acknowledge limited water supply acceptability
4		C7.	Aesthetics Be aware of possible importance of appearance of mist/fog nozzle

3.0 WORKSHOP SUMMARY

The Research Needs panel identified 17 topic areas to be addressed. The end-use criteria panel identified 39 user needs which they broke down into three categories: Research and Development Needs, Information Affecting the System Selection, Standards Development Needs. Research and Development was further subdivided into Research-Oriented Needs and Development-Oriented Needs. The marketing panel identified seven impediments to commercialization of water mist systems.

In the research needs panel, the top four of the 17 needs identified received nearly 50% of the votes. They are: 1) full-scale tests where drop size, concentration, and jet momentum would be characterized; 2) determination of relationships among drop size, application rate, fire size, and room geometry; 3) development of at least one application to the point where standards/requirements can be set for that application; and 4) test to determine the effects of water mist on all types of energized and de-energized electrical equipment.

In the end-use criteria panel, standards development needs received the majority (46%) of the votes including development of NFPA standards, development of standardized fire tests, third party testing, and listing of equipment. Receiving an additional 30% of the votes was information affecting system selection.

In the marketing panel, 46% of the votes were for issues relating to the fact that water mist is a "new technology". Another 26% of the votes related to reliability and/or effectiveness of water mist systems.

The following topics concerned more than one panel:

- water mist and electrical equipment. (A13, B1B-3, B2-19, and C3)
- standards development (A7, B3, C6)
- drop size/system optimization (A2, A9, B1A-2)
- additives (A4, B1A-5)
- confidence in design criteria/system reliability (B1B-1, B3-5, C5)
- cost (B2-1, C4)
- acceptability by authorities having jurisdiction (B2-12, C6)
- water quantity and/or quality (B1A-6, C2)

The above statements reflect areas where the group felt work could be done that would aid in the commercialization of water mist systems. With the availability of ATP funding to sponsor such work, it is hoped that proposals will be generated by industry in the area of water mist fire suppression.

Advanced Technology Program:

A STATUS REPORT

George A. Uriano
Director, ATP

National Institute of Standards and Technology
Technology Administration
Department of Commerce

ATP AUTHORIZING LEGISLATION

1988 Omnibus Trade Act
1992 American Technology Preeminence Act

- Assist U.S. businesses to create and apply generic technology to:
  - Commercialize significant new scientific discoveries and technologies rapidly
  - Refine manufacturing technologies

- Cooperate with Other Agencies

GOAL

Assist U.S. businesses to develop *PRE-COMPETITIVE GENERIC* technologies. These technologies are:

- ENABLING -- offer many potential applications; provide technical basis for process- and product-specific applications

- HIGH VALUE -- offer significant long-term benefits to the economy by enhancing economic growth and increasing productivity

ATP ELIGIBILITY

- Joint ventures
  - No more than 5 years
  - NIST share must be less than 50%

- Individual companies
  - No more than 3 years
  - Up to $2 million total

- No direct funding to universities, government agencies or non-profit independent research institutes

INTELLECTUAL PROPERTY, LICENSING, AND ROYALTY PROVISIONS

- Seek balance between public good and business incentives
- With some exceptions, recipients may generally elect to obtain title to inventions
- Recipients may generally establish claim to copyrights
- Government <u>may</u> obtain nonexclusive royalty-free license for its own use

SYNERGISM BETWEEN ATP AND NIST INTRAMURAL PROGRAMS

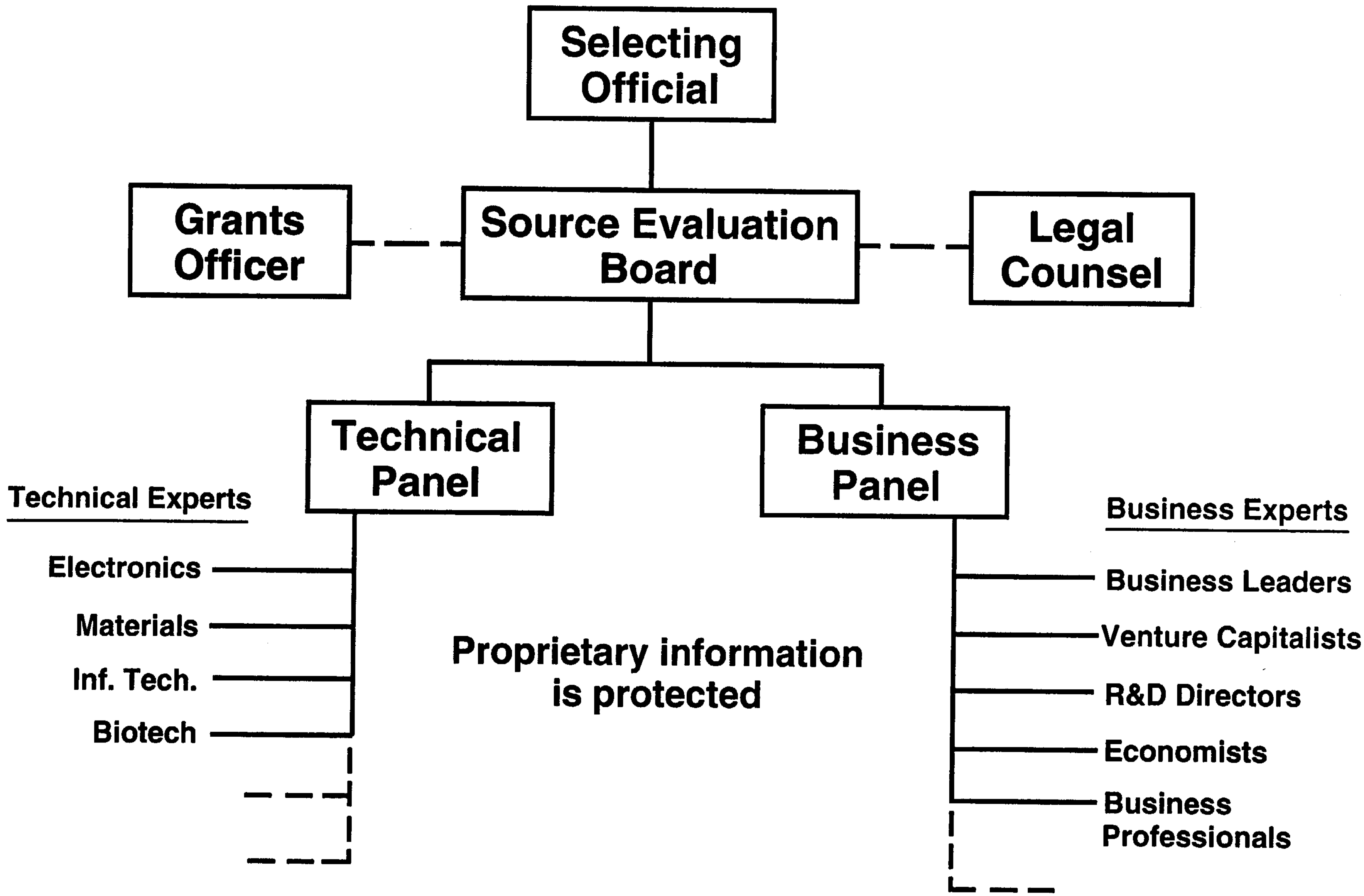
- Unique and Long-Standing NIST Mission - - Technical Assistance to Industry to Develop Commercially Important Technologies - - Reinforces ATP Mission

- Long History of NIST / Industry Cooperation - - Enables Strong Technical Support to ATP Awardees
  - Research Associate Program
  - CRADAS
- Substantial Technology / Assessment Capabilities - - Crucial to ATP Proposal Evaluation

- ATP Serves as Technology Forecasting Sensor and Driver for NIST Intramural Programs

- ATP Uses NIST Administrative Systems at Marginal Cost - - Personnel, Accounting, Contracting, Legal, Security, etc.

SELECTION PROCESS MANAGEMENT



ATP SELECTION CRITERIA (Weight)

- Scientific and technical merit (20%)
- Broad-based benefits (20%)
- Technology transfer benefits (20%)
- Experience and qualifications (20%)
- Level of commitment and organizational structure (20%)

ATP SELECTION PROCESS

ADVANCED TECHNOLOGY PROGRAM

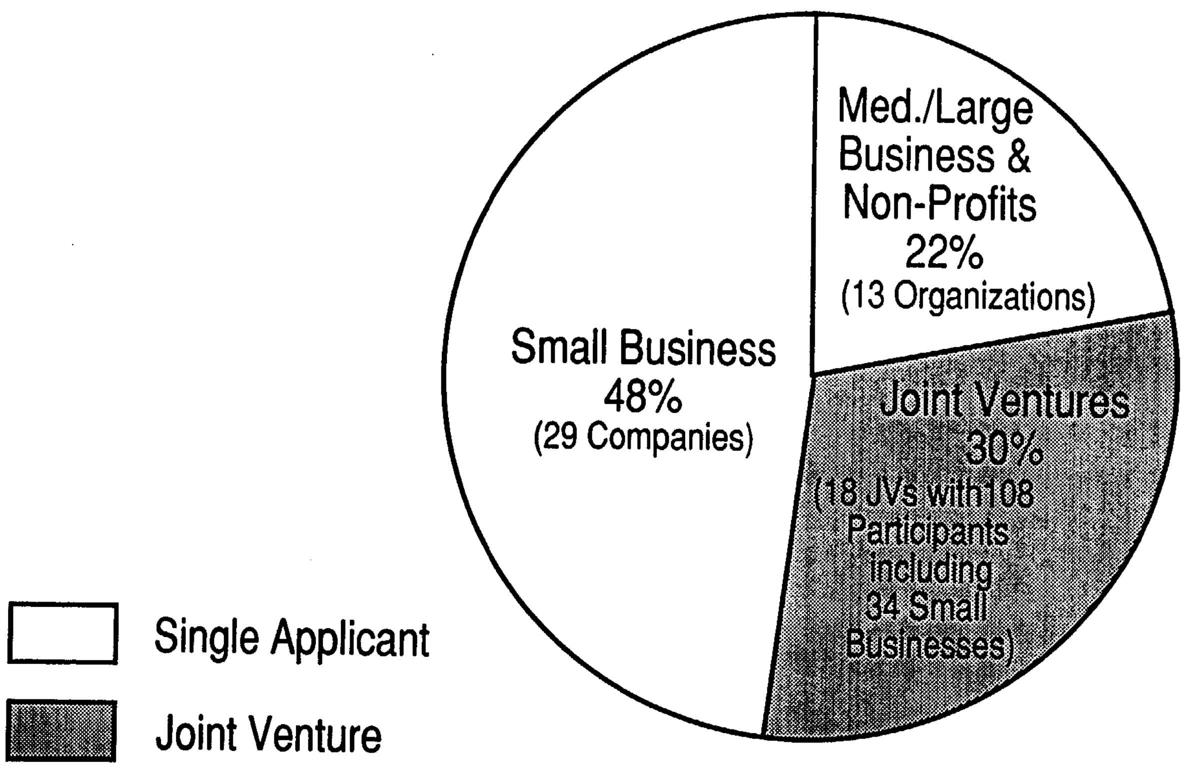
Important Statistics - - 3 Competitions

Proposals Submitted	660
Participating Organizations*	1232
Total ATP Funding Requested	$1 B
Total Estimated Cost-Share	$1 B
Number of Awards	60
(Joint Ventures)	(18)
(Single Applicants)	(42)
Participating Organizations*	150
Total ATP Funds Committed	$187 M
Total Estimated Cost-Sharing	$210 M
Award Size - - Range	$500K - $20 M

* Excludes Subcontractors

ATP COMPETITIONS 90-01, 91-01, & 92-01

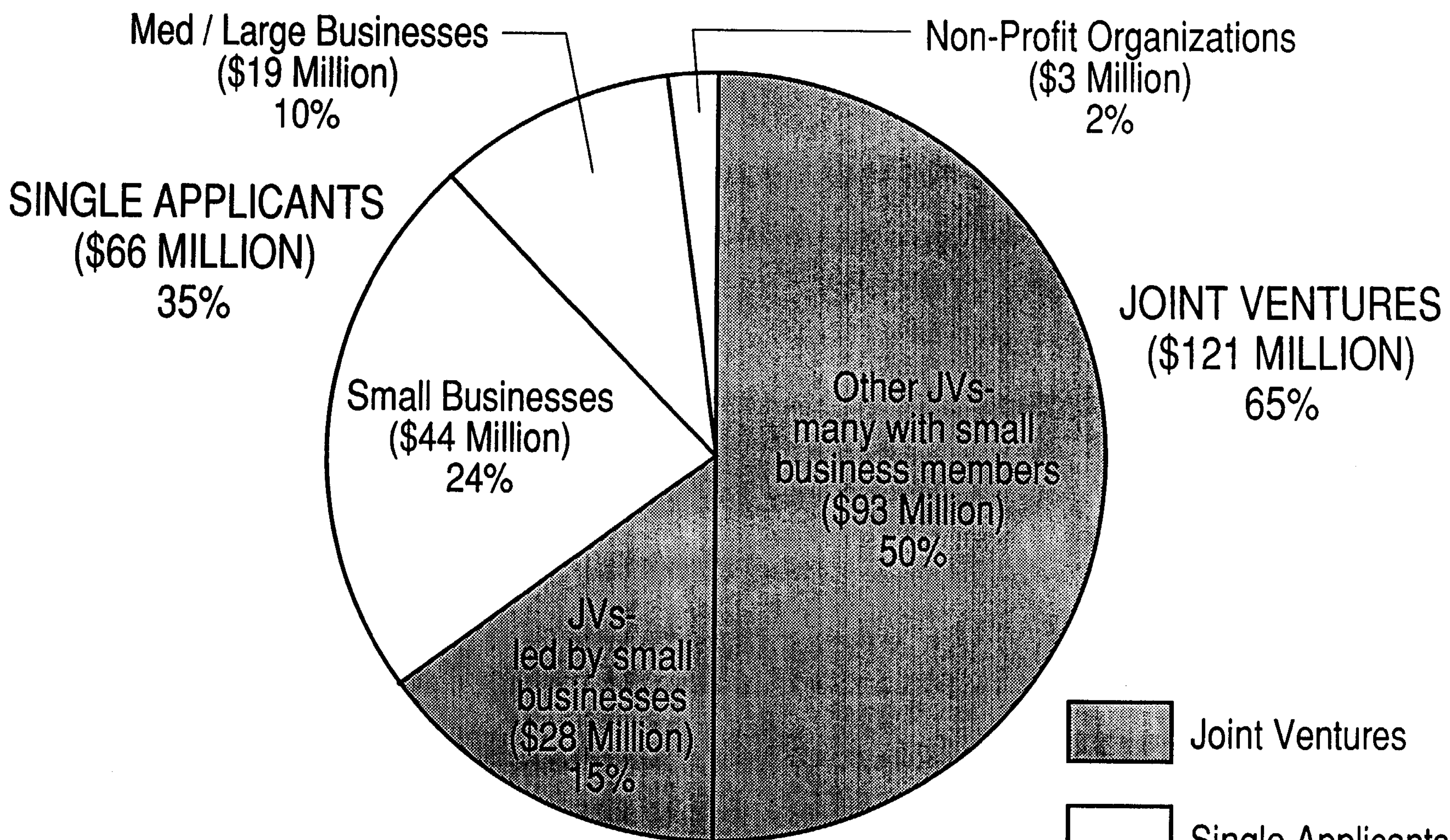
ATP 60 AWARDEES
BY TYPE OF ORGANIZATION



ATP COMPETITIONS 90-01, 91-01, & 92-01

$187 MILLION OF ATP FUNDS AWARDED

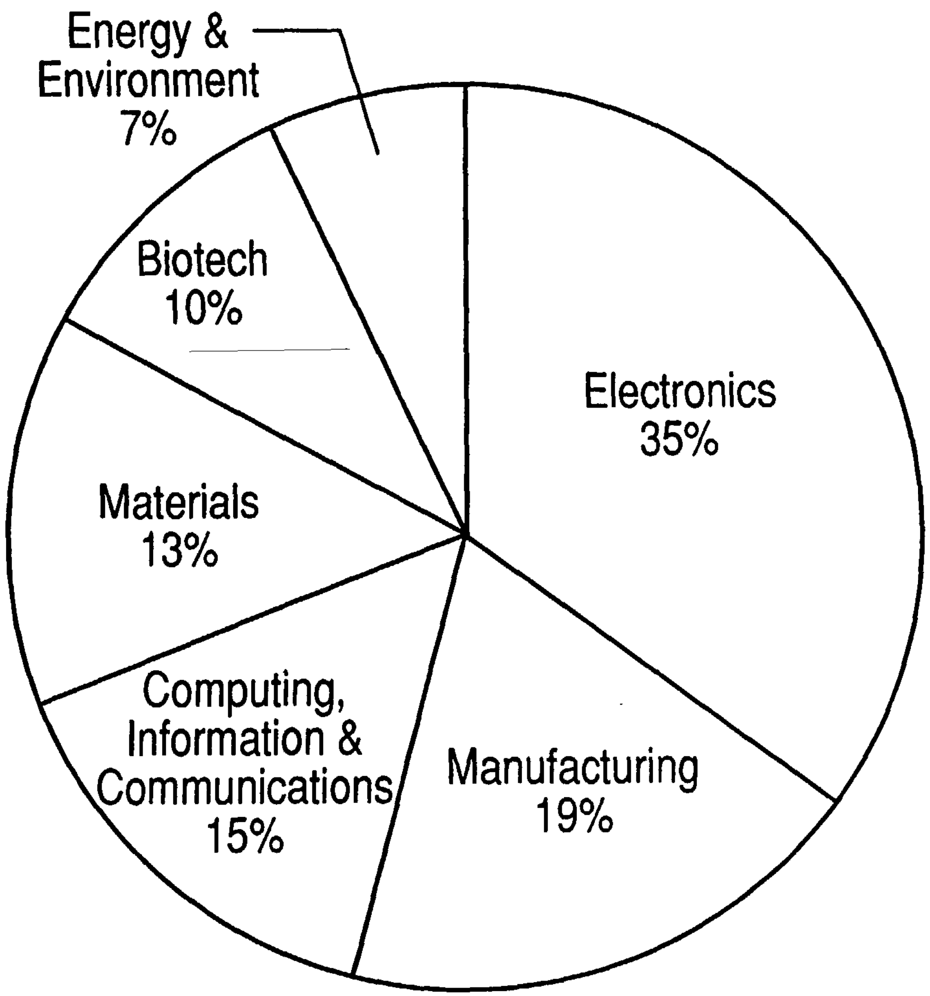
By Type of Organization



ATP COMPETITIONS 90-01, 91-01, & 92-01

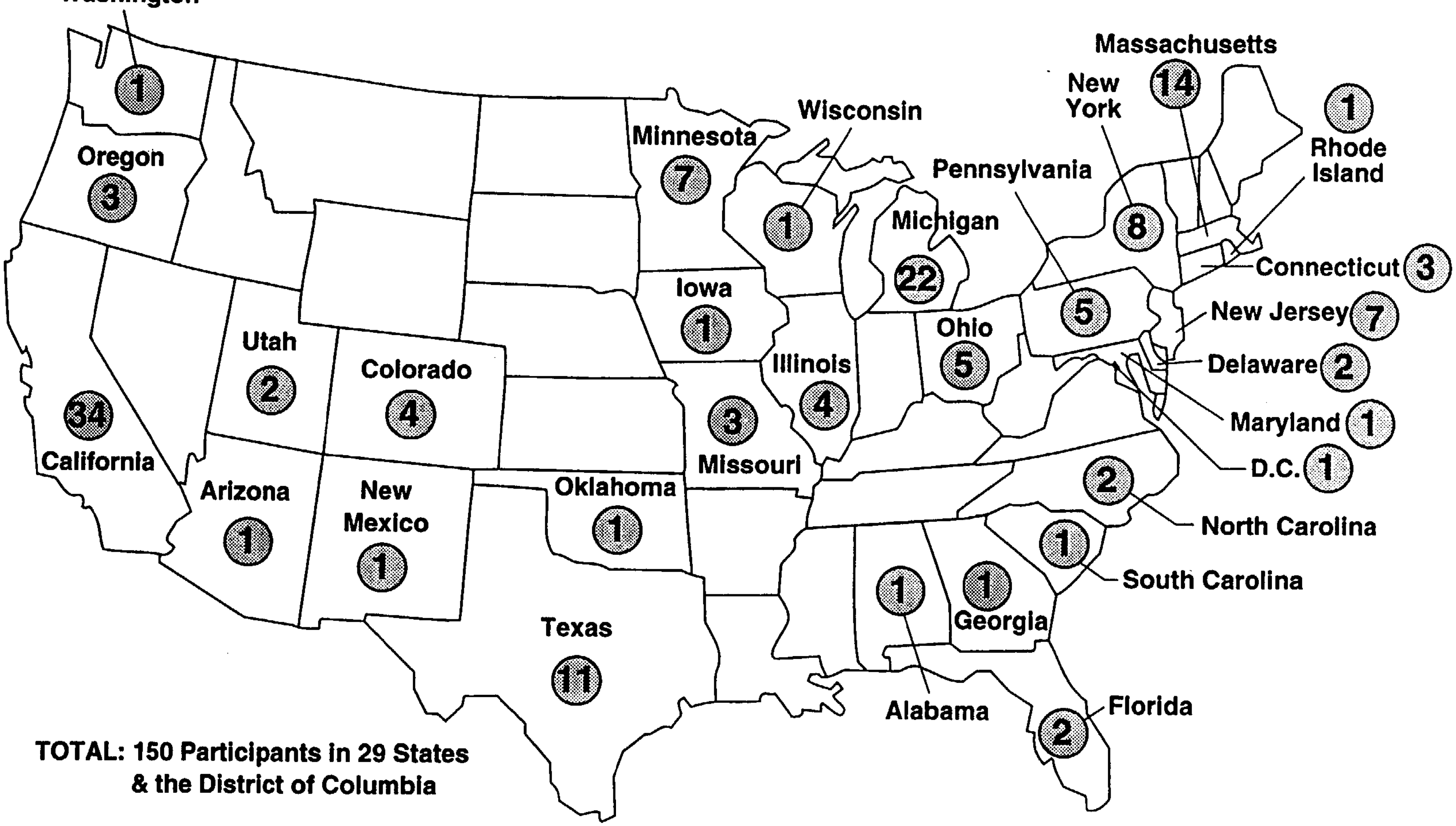
TECHNOLOGIES FUNDED BY ATP

As a percent of $187 M Awarded



ATP COMPETITION 90-01, 91-01, & 92-01

ATP PARTICIPANTS* BY STATE



TOTAL: 150 Participants in 29 States
& the District of Columbia

* "Participants" includes joint venture members, and excludes subcontractors, informal collaborators with joint ventures, and collaborators and strategic partners of single applicants.

ATP TECHNOLOGY AREAS

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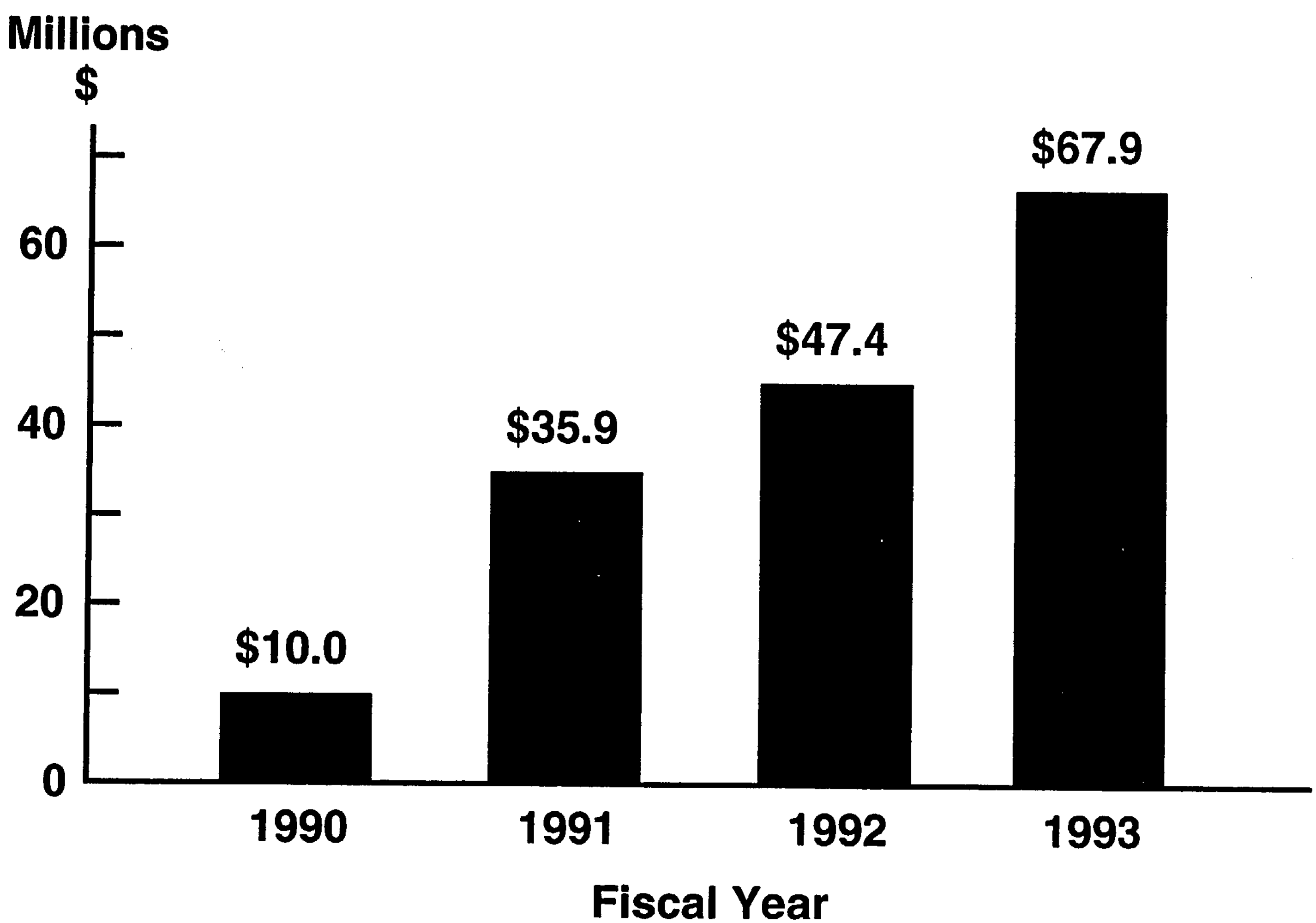
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INCENTIVE FOR USE OF MISTING SPRAYS AS A FIRE SUPPRESSION FLOODING AGENT

Ronald L. Alpert
Factory Mutual Research Corporation
Norwood, MA 02062-5082 USA

SUMMARY

Positive factors favoring the development and introduction of water mist technology for fire suppression are discussed, followed by a brief survey of world-wide activity in this area. Potential problems impeding the use of such a technology are then outlined. The paper concludes with an overview of how water mist technology may fit into the total market for alternative flooding agents.

1. INTRODUCTION

The rapid, even precipitous phaseout of the predominant fire suppression flooding agent, Halon 1301, in the last few years has resulted in a desperate search for alternatives. Whereas Halon 1301 had been recommended and installed previously for many locations without too much thought about other possibilities, now necessity requires fire protection engineers to look at each application critically and decide which technology can best provide satisfactory fire suppression. In this search for new technologies, fine water sprays have become a prominent topic for study as well as commercialization.

I will define misting sprays or fine water sprays for the purpose of the present discussion as the spray from any device which produces a mass-median drop size below the median drop size expected from conventional fire suppression sprinklers at the highest usual operating pressure. In practice, that means devices generating a mass-median drop size below 300 to 400 microns would be designated as misting or fine-spray devices. However, not all such sprays could be considered as true flooding agents, in the sense that the droplets generated would have a residence time or suspension time sufficiently long to be carried by air currents to remote or obstructed parts of an enclosure. True flooding agents probably require drop sizes to be less than some 10 to 30 microns in diameter.

2. ADVANTAGES OF MISTING SPRAY TECHNOLOGY OVER GASEOUS AGENT SYSTEMS.

As alternatives to the traditional flooding agents have been considered in the last few years, various concerns have arisen about the merits of each new agent or suggested strategy. One important concern has been the danger to personnel posed both by new so-called chemical agents and by traditional and newly announced so-called inerting agents, the former because of toxicity and the latter because of asphyxiation dangers. Water misting sprays, of course, are not associated with such dangers to people in occupied areas.

Another concern about agents suggested for replacement of Halon 1301 is that of cost and availability. The use of misting sprays instead of expensive chemicals or patented mixtures would certainly avoid the cost problem and also the lack of adequate agent quantities on the market soon.

As far as effective fire suppression and extinguishment is concerned, misting sprays may have advantages in some situations when compared to the new gaseous flooding agents. These situations include the case of deep-seated fires in charring or glowing materials and fires near high temperature equipment surfaces. In the first case of deep-seated fires, misting sprays will probably be more effective than typical concentrations of gaseous agents due to the higher cooling capacity and penetration of liquid water. For the same reason, misting sprays may be more effective than gaseous agents in a high temperature environment (e.g., machinery spaces, combustion turbine enclosures) where re-ignition would be likely if the gaseous agent concentration can't be maintained for long enough periods.

An important problem with recently identified Halon 1301 replacements is the increased likelihood of corrosion from breakdown products (mainly hydrogen fluoride) compared to the situation for Halon. Here, misting spray technology may offer the advantage of reduced overall corrosion rates due to the relatively small quantities of liquid water being used. Obviously, research will be needed to verify this advantage.

Probably the biggest advantage of a system based on water over a flooding system based on new gaseous chemical agents is the known regulatory environment related to the use of water. Business is seriously concerned about the possibility that any new flooding agent, no matter how apparently benign, may in the future be subject to government regulations similar to those now in effect for the Halons.

3. ADVANTAGES OF MISTING SPRAY TECHNOLOGY OVER CONVENTIONAL SPRINKLER SYSTEMS

It is anticipated that misting sprays will allow significantly reduced water flow rates, and hence less water damage to sensitive equipment or occupancies, compared to conventional sprinkler sprays. Whether water flows are sufficiently low to allow such sensitive equipment to keep operating during spray actuation, which is a requirement for some Halon 1301 installations, is still a question. The low water flows associated with misting sprays may, in fact, permit in-situ testing of the spray system, which would impact on the issue of system reliability discussed below. Certainly, if water supplies are limited due to the type of space or weight requirements found in transportation systems, the low water flows of misting sprays represent a clear incentive for future testing.

Misting sprays used near high temperature surfaces, such as a turbine casing may, in fact, be a better choice than conventional sprinkler sprays because of the potential for damage from too rapid cooling if water fluxes are too high or drop sizes are too large. Our own analysis of heat transfer when droplets impinge on a hot surface has shown that at low water fluxes, droplet diameters characteristic of misting sprays should not "wet" hot surfaces and thus should not cause thermally-induced stresses or deflections to reach damaging values.

Finally, flammable liquid spray fires and some other types of flammable liquid fires cannot readily be controlled with conventional sprinkler sprays but have been extinguished by misting sprays used as a flooding agent in enclosured spaces that have reached flashover conditions.

4. GROUPS INVOLVED IN MISTING SPRAY RESEARCH AND MARKETING

The several potential advantages of misting sprays that have already been enumerated have led to several groups world-wide studying fire suppression applications and marketing new systems, as described in Table 1.

Table 1. Partial list of groups involved in misting spray research and marketing

Group	Location	Contact
Civil Aviation Authority	UK	Mr. N. Povey
Darchem Engineering	UK	Mr. P. Vaughan
FAA Technical Center	Atlantic City, NJ	Mr. C. Sarkos
Factory Mutual Research	Norwood, MA	Dr. R.G. Bill
Fire Research Station	UK	Ms. C. Cousins
GEC Avionics	UK	Mr. D. Silsbey
Greenwich University	UK	Dr. E. Galea
IEI	Australia	Mr. I. Hanson
Kidde-Fenwal	USA	Mr. S. Vaillancourt
Kidde-Graviner	UK	Mr. D. Ball
Marrioff	Finland	Mr. P.K. Marttila
NRC-Canada/NFL	Canada	Dr. J. Mawhinney
NRL	Washington, DC	Dr. R. Scheinson
Securiplex Technology	Canada	Mr. V. Gameiro
SINTEF	Norway	Dr. R. Wighus
Southbank Polytechnic	UK	Prof. P. Nolan
SP	Sweden	Mr. A. Ryderman

5. PROBLEMS IMPEDING THE USE OF WATER MIST TECHNOLOGY

With any new technology in the fire safety engineering field, the most important unknown factor is likely to be reliability. This is especially true for a device which may remain untested and not maintained for extended periods, or even decades before that device is actuated by a fire. Reliability is certainly one obvious advantage of conventional sprinklers and results from their inherent simplicity. Current versions of misting spray devices, on the other hand, are more complicated than conventional sprinklers and may involve the use of components with unproven performance records. Even existing Halon and gaseous flooding systems, which are also more complicated than conventional sprinklers, are known to have reliability problems that are still of concern to fire protection engineers. The introduction of misting spray devices will, therefore, require not only the development of new hardware, but also the development of strategies for maintenance and testing (or self-testing) that will insure acceptable reliability. As a result of the reliability issue, it will probably be easiest to introduce misting spray technology in those niche applications where conventional sprinklers and available inerting agents do not now offer practical alternatives.

A second major problem associated with misting spray technology is the current lack of information needed to specify completely the design of a new suppression system. It will take some time to develop design requirements and design parameters for all the varied potential applications of the technology. For example, how should the system be designed if there is strong building ventilation or frequent air changes, as in computer rooms? If there are intricate obstructions within a compartment, how will this influence the design? Another problem associated with the lack of design parameters is the lack of performance tests for the actual misting spray devices. It is vital that such tests be available to qualify newly developed hardware.

One obvious way to solve these problems is, as soon as possible, to thoroughly understand the mechanism of fire suppression for each particular application of misting spray technology. For example, is fire suppression accomplished by gaseous inerting, by fuel surface cooling or by some other mechanism such as absorption or reduction of the thermal radiation from luminous flames? Once this information is developed, rapid progress can be made in optimizing parameters and developing test methods.

One possible fire suppression mechanism for certain misting sprays is that of flame cooling and so-called inerting by droplets that are 1) small enough to be carried into the flame by air entrainment, yet 2) large enough to survive the radiant flux just outside the flame. For such droplets, rapid evaporative cooling inside the flame leads to a reduction in flame temperature and then the generation of steam dilutes the oxidant for further reductions in the flame temperature. A sufficient reduction in flame temperature then results in extinguishment.

6. NICHE APPLICATIONS FOR POST 1301 FLOODING AGENTS

It appears to me that many of the current uses for Halon 1301 fall into one of the following three flooding agent categories:

A. Unoccupied or rarely occupied moderate-size, sealed spaces very sensitive to long-term corrosive effects from water or agent break-down products, where the principle challenge is a slowly growing Class A or Class C fire (e.g., telecommunications facilities)

B. Occupied moderate-size spaces not sensitive to long-term corrosive effects from water or agent break-down products but requiring large safety factors in agent concentration due to leakage at openings (e.g., transportation facilities).

C. Occupied, very large compartments with heat sources capable of re-igniting fuel vapors, and the presence of deep seated or flammable liquid fires (e.g., combustion turbine enclosures).

Water mist technology may well turn out to be an optimum fire suppression solution for Category C and possibly Category B, where the water misting sprays may compete with so-called chemical agents replacing Halon (these newly proposed "chemical agents" are actually just high molecular weight gases that mainly utilize high specific heat to decrease flame temperatures at moderate to low concentrations). For Category A, so-called inerting gases with specific heats comparable to that of air may be most practical.

CONCLUSION

There appears already to be a clear role for water mist technology in certain niche applications where neither gaseous agents nor conventional sprinklers would be totally satisfactory. To broaden the applicability of this technology to other types of occupancies, additional research will be necessary to establish suppression mechanisms, thereby allowing test methods for device approval and installation guidelines to be developed.

ACKNOWLEDGEMENTS

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ENGINEERING CRITERIA FOR WATER MIST FIRE SUPPRESSION SYSTEMS

J. R. Mawhinney, P. Eng.
National Research Council Canada

ABSTRACT

This paper discusses a number of practical issues relating to the design of water mist fire suppression systems. There is presently considerable interest among fire safety engineers in using water mist systems as an alternative to halon, on the basis that the mist will act like a gaseous suppression agent to fill all recesses of a compartment. Although there is a growing confidence that water mist systems can successfully extinguish flammable liquid pool fires and high pressure jet fires with small amounts of water, engineering criteria are needed to allow designers to match a water mist system to a range of fire scenarios and compartment types. This paper draws a parallel between the long-established practices for design of standard sprinkler systems, which allow any experienced designer to custom-fit a sprinkler system to a wide variety of fuels and buildings, and the need for similar design principles for the design of water mist systems. Research being carried out by various research agencies has just begun to document the information required to establish general design criteria for mist systems.

Starting with the need to define both the fire hazard and the fire safety objective, this paper presents information on characterizing sprays suitable for water mist systems. It points out that macro-scale effects in large volume compartments cause agglomeration of droplets, so that what starts out as a very fine spray ends up as a much coarser spray. It also points out that the types of nozzles available for producing suitable fine sprays have, at best, fairly high pressure demands and, in the case of air-atomizing nozzles, very high compressed-air demands. These factors set a practical limit on the size of compartment that can be protected in a cost-effective way by total flooding systems. An alternative to total-flooding systems for larger compartments would be zoned piping linked to a sophisticated detection system. Much experimental work will be needed to validate such systems.

The matter of determining the spray flux density required for suppression is discussed in depth. Spray flux density is likely to vary by several hundred percent throughout a compartment as a result of removal of spray on the surfaces of obstructions. It is more efficient to achieve high localized densities in the vicinity of the known fire source by strategic location of nozzles, than to attempt to create a single uniform density in the compartment. More than spray density is required to extinguish flames, however. The

spray must have enough kinetic energy to interact turbulently with the flame. In this respect, water mist does not act in the same manner as gaseous suppressants. Finally, the paper discusses some of the factors relating to ventilation of the compartment, and the effects of spray systems on the pressure conditions in the fire room. The feasibility of discharging a number of air-atomizing nozzles into a completely closed compartment is questioned. The effects of sudden contraction or expansion of hot gases or steam upon application of the water spray are also discussed.

This paper does not state conclusive design criteria for particular hazards. Instead, it concentrates on the general principles of defining the hazard, deciding on the objective or desired performance of the system, understanding the practical limitations of the equipment, and preparing for the actual interaction of the system with the fire. It is from this basis that the development of design criteria and procedures for a wide variety of hazards must start. Design criteria for particular hazards will have to be built, case by case, application by application, as they were for standard sprinkler systems. With the strong demand to build a data base for efficient design quickly, however, there is a need to combine the efforts of all agencies working on the problem.

Introduction

This paper will highlight some of the engineering issues that need to be addressed in designing a fire suppression system based on very fine water sprays, i.e., water mist. Considerable international interest has been generated in developing such engineering criteria for the following reasons. The first is an economic interest in reducing the volumetric water requirements for suppression systems – it is understandable that the promise of a fast-acting, low-water-volume fire suppression system should attract considerable attention. A second reason is that many fire safety specialists view the use of a fine mist as a potential replacement for gaseous fire suppressants, assuming that the mist will be drawn by convective air movements into all recesses of the space – therefore, intense international interest in finding an environmentally benign alternative for halon is motivating research into these systems.

Over the last few years, there have been a number of impressive demonstrations of the effectiveness of very fine water mists in extinguishing gas jet fires, flammable liquid spill fires, and even fires involving plastic foam furnishings. Evans and Pfenning (1985) demonstrated how a fine mist injected into a high velocity methane gas jet below the flame front could extinguish a 200 MW flame within seconds. British Petroleum Ventures (BPV) in the UK, among others, has demonstrated similar rapid extinguishment of gas flares on off-shore oil drilling platforms, by injecting water mist directly into the gas stream at the base of the flare. Tests done at the Swedish National Testing and Research Institute at Borås, and at SINTEF, the Norwegian Fire Laboratory, have demonstrated how effective water mist systems can be for diesel fuel and crude oil pool fires in enclosures (Olsson & Ryderman 1990; Wighus 1991). In the petroleum industry, water mist systems have been demonstrated by BPV to extinguish up to 25 MW fires involving spilled fuel and a pressurized hydraulic jet flame. In the aviation sector, much work has been done in the last 7 years in the UK and in the USA to develop water mist fire suppression systems for use on aircraft, to protect the occupants from an external pool fire long enough to provide time to escape. The aviation industry's need for a very low weight system has driven the technology towards making maximum use of a small volume of water to block radiant heat and provide cooling in a relatively large volume space (Hill 1992). There are other examples of where water mist fire suppression systems are already being used to protect special risks, such as on submarines (Soja 1990; Yard 1988).

So, with what appears to be an extensive level of experience, internationally, in the use of fine mists for fire suppression or control, it is interesting to note that there are many fundamental questions still being asked about how to actually design a water mist system for a particular fire hazard. The Canadian, British and American Navies, for example, are aware of the potential benefits of use of water mist for protecting shipboard spaces that are presently protected by gaseous fire suppression agents, such as halon. However, before proceeding to replace all existing halon suppression systems with water mist systems, they would like to have answers to some basic engineering questions, such as:

- What are the characteristics of a "fine spray" that are critical to its effectiveness?
- What technologies exist for producing fine sprays with the desired characteristics, and which are the most reliable and cost effective?
- How does one relate the spray characteristics of drop size and rate of application to the type of fire possible in the space, and the geometry of the space?
- What degree of control should be expected – complete extinguishment? ... or can reduction of heat release rate and room temperature be considered to provide the desired performance? If so, how much reduction?

This list is not exhaustive, but it serves to illustrate the fact that certain engineering principles are required before water mist fire suppression systems can be designed with confidence for critically important facilities. There are numerous compartment conditions which will affect the performance of a fire suppression system, including floor area and ceiling height, obstructions, fuel type and configuration, and ventilation.

It is interesting to compare the engineering information that exists today for the design of automatic sprinkler systems, with that which does not yet exist, but is needed, to standardize the design of water mist fire suppression systems. The designer of a sprinkler system follows well-established practices to match the sprinkler system to the type of fuel and its potential heat release rate, and to take into account ceiling types and heights, sprinkler spacing, sprinkler response time, activation temperatures, and other specific conditions. The design practices have been built-up over many years, sometimes based on full-scale testing, and sometimes validated by many years of fire loss data. The standardized procedures are adequate for most commonly encountered situations, only requiring expert modification for relatively few special circumstances. Technical reference books are available to support the design community. Industries exist to produce reliable equipment and to regulate the manufacture of such equipment. This technical infrastructure does not yet exist for water mist fire suppression systems. Some practical procedures to direct the design of water mist systems for pool fires and jet fires in enclosures are emerging, but much more research is needed to broaden the understanding of the relationship between fuel type, compartment features and spray system performance. Although sprinkler system design practices evolved over many years, there is a demand to produce a similar data base for a wide range of applications for water mist systems as quickly as possible. The best way to build such a technical base quickly is, therefore, to combine the coordinated efforts of all research groups.

A research project at the National Fire Laboratory, presently in progress, is aimed at investigating the engineering factors that must be understood in order to design a water mist fire suppression system for shipboard machinery spaces. This research program, which is jointly funded by the Canadian Navy (National Defence) and the National Fire Laboratory, has involved testing of water mists in obstructed spaces, including fire suppression tests in a mock-up of a shipboard machinery space. A number of practical engineering factors that have been identified as part of the development work necessary to bring these systems into the mainstream of fire suppression design are summarized in this paper. These include: defining the fire hazard and the fire safety objective; specifying the characteristics of fine sprays; exploring cost effective methods of producing suitable sprays and understanding their limitations; determining the spray flux needed to achieve the fire control objective for particular fire scenarios; accounting for the effects of obstructions and ventilation on spray density and distribution. This paper does not attempt to provide solutions to the engineering questions that have been raised. The objective is to sketch out the nature of each problem, and to suggest possible directions for resolution.

Defining the Fire Scenario

As in any fire suppression system design, the fire scenario must be well defined so that factors such as minimum nozzle discharge and spray flux density, nozzle location and spacing, minimum spray duration and probable degree of fire control can be determined. The fire scenario will depend on the fuel type and configuration, and the compartment conditions, such as:

Fuel Type:
- Combustible/flammable liquid – spill and pool fires
- Pressurized liquid jet
- Gas jet
- Class A combustibles, including plastics
- Electrical or electronic equipment

Fuel Configuration:
- Pool fire at floor level
- Jet fire at floor, mid-height, or ceiling level
- Class A combustibles, at floor, mid-height or ceiling level, low or high piled, loose or dense
- Electrical equipment in cabinets, cable trays

Compartment Conditions:
- Compartment dimensions
- Open or closed compartment
- Obstructions, localized or dispersed
- Shielded fire
- Ventilation factors affecting air movement
- Damageability of contents

These three factors of fuel type, configuration and compartment conditions, combine to define the nature of the fire and set the conditions under which it can be extinguished or controlled. For example, the fuel type will determine the heat release rate and potential fire duration. The fuel configuration, i.e., dispersed throughout a space, in piles, on racks, on surfaces, or inside cabinets, will determine how fast the fire grows and spreads. Both the type of fuel and its configuration influence whether it will be a flaming or smouldering fire. Compartment conditions, such as ventilation and size, determine the intensity of heat radiation reflections from surrounding surfaces to the fuel, the velocity of the fire plume, the rate of deepening of the hot gas layer, and the manner in which a fire suppressant can be distributed in the space. The compartment also physically limits the placement of detection and suppression system components. Finally, the vulnerability of the contents of the compartment to fire damage determines how fast the system must operate and the degree of control that must be achieved.

The experience base for mist systems, so far, applies to only a few of the possible fuel types, configurations and compartment conditions. Of the fuels, flammable/combustible liquid pool fires and liquid fuel jet fires and, to a lesser extent, gas flares, have received the most attention. Water mist systems are being suggested for fires in ordinary cellulosic (Class A) combustibles such as bedding and foam mattresses, as has been demonstrated in recent tests conducted in Sweden in conjunction with the Marioff company. Fire in wood and plastics usually develops a char layer which reacts quite differently to spray than an open flame above a pool fire (personal communication, Fire Research Station, UK, 1992). The potential use of water mist systems for smouldering fires in electrical cables and in electronic circuit boards is of interest to many, but not much has been done to test the suitability of water mist for these types of fuels. With respect to the compartment conditions, the experience base is strongest for naturally ventilated compartments of small to moderate size, with a minimum number of obstructions.

It is important to understand how the fuel, its configuration and compartment conditions combine to determine the fire scenario, because those same factors also influence how the water mist system will perform. The mechanism by which water spray acts to extinguish flame appears to be the result of a combination of factors, including heat extraction due to rapid evaporation of fine drops, oxygen displacement due to steam displacement of air, and attenuation of the radiant heat feedback loop between flame and unburned fuel. The relative importance of one or the other factor is influenced by the type of fire (flaming or smouldering), its stage of growth, and the degree of enclosure. For example, it has been demonstrated that water mist can extinguish pool fires in both enclosed and unenclosed conditions. Steam displacement of oxygen may be significant in the case of an enclosed fire, but less so in the case of an enclosed fire. Attenuation of the radiant heat feedback and heat extraction would be of greater significance in the case of the unenclosed fire. In enclosed fires, if the fire is incipient and the compartment temperature is low, there may be very little steam produced when the spray activates, so that steam displacement again will not be the primary mode of extinguishment. If the spray had been discharged into a hotter compartment, steam displacement would dominate the suppression event, however.

These examples serve to illustrate that the performance of the water mist system itself and the expected level of fire control are dictated by the type of fuel, its configuration and the compartment conditions. It is not yet possible to set design criteria that are applicable to the full range of fuels, fuel configurations and compartment conditions for which water mist systems are being considered. Generalizable design criteria will emerge as the experience base grows, case by case, application by application.

Defining the Fire Safety Objective

Having identified the fire scenario, the designer of a water mist system must set realistic criteria by which to judge the success of the system. The expected outcome of operation of a standard sprinkler system is reasonably well defined – either it extinguishes the fire or limits fire size, burning rate and room temperatures to minimize the potential for harm. The expected outcome of operation of a water mist system is similar, with some additional possibilities. For water spray systems used in aircraft post-crash fires, the objective is not to extinguish the fire, but to attenuate radiant heat from an external pool fire and provide cooling, to provide an additional 2 or 3 minutes time for the occupants to escape (Hill 1992). Where it is intended to use a water mist system to replace a halon system, the intended performance of the system will inevitably be compared to the performance of a halon system. It may be that, where the halon would have completely extinguished even a shielded fire, the water mist system might not be able to achieve complete extinguishment. Various compensating factors will affect the final comparison, however, such as more rapid temperature reduction due to the superior cooling effect of water mist, less restriction on compartment tightness, earlier re-entry, and so on. In other words, the fire safety objective of the water mist system should be consistent with the attributes of water mist. The fire scenario, and the fire safety objective, then, define the starting point for effective engineering design of a water mist fire suppression system.

Characteristics of Water Sprays for Fire Suppression

A full discussion of how to characterize atomized sprays in general is beyond the scope of this paper. The reader is referred to the text "Atomization and Sprays" by Arthur H. Lefebvre for an authoritative, comprehensive presentation of the subject. Lefebvre presents the basic science for sprays used in a myriad of applications, from paint sprays to fuel sprays in combustion chambers. For the purpose of developing engineering methods for design of water mist fire suppression systems, however, certain fundamental principles must be discussed. In regard to the characterization of sprays, then, four factors are needed to properly characterize a water mist for fire suppression purposes. These are:

Drop size distribution (diameter and range)
Spray flux density
Spray angle
Spray projection

Drop Size Distribution

Researchers commonly define a spray, for casual comparisons at least, by stating a single statistically-defined mean diameter, typically the Volumetric Mean Diameter (VMD), or the Sauter Mean Diameter (SMD). Representative mean diameters can be defined in terms of simple diameter, droplet surface area or volume. For example, the VMD (also referred to as the Mass Mean Diameter (MMD), and notationally as $D_{V0.5}$), means that 50 percent of the total liquid volume is in drops of smaller diameter. The SMD is the volume/surface area mean diameter. If a single representative diameter is used, the same spray could be described using the SMD as an "80 micron spray," or using the VMD as a "100 micron spray," depending on the speaker's choice. The choice of representative mean diameter depends on the application being studied, and different engineering disciplines have different preferences. The SMD is used for mass transfer and reaction analysis. The VMD, however, is emerging as the preferred representative mean diameter for computer modeling of spray/fire interactions. An agreement to use one or the other for casual comparison should be established for fire safety engineering use.

To provide a better sense of the nature of a spray distribution, it is useful to plot the results of a drop size measurement as "Cumulative % volume" versus drop diameter. The resulting "S" shaped curve reveals the whole story, including the maximum size of drop and the range of drop sizes. If the whole curve cannot be provided, a minimum of three parameters can be used to give the same general information. For example, the three parameters $Dv_{0.1}$, $Dv_{0.5}$ and $Dv_{0.9}$ (i.e., the diameter for which 10%, 50%, or 90%, respectively, of the liquid volume is in drops of lesser diameter), describe the spray drop size distribution reasonably well. The stated range of drop sizes then includes both the SMD and the $Dv_{0.5}$ and gives a sense of the extremes of the spray. Figure 1 shows typical spray cumulative distribution plots for a pressure-type nozzle at different operating pressures and distances from the nozzle.

For modeling the interaction of water mist and fire using computational fluid dynamics, the distribution of drop sizes in the spray is represented as a function of two parameters, one of which is a representative diameter and the other a measure of the range of drop sizes. Various empirical distribution functions are available: a Rosin-Rammler distribution, described in Lefebvre (1989), is used by many modelers at present. It can be computed easily from the data collected by widely used drop sizing instruments.

Although the differences between the VMD and the SMD may appear significant on paper, there are practical aspects of using sprays for fire suppression systems that make it of academic concern. For one thing, at the macro-scale of fire suppression mists, the unavoidable variation in experimental measurements may exceed the difference between the VMD or the SMD. Distinctions that are significant in atomized sprays in combustion chambers, measured a few tens of millimetres apart, are of less significance in large rooms, measured metres apart. Further, the devices used to measure drop diameters themselves may introduce differences in the representative means. Optical technologies that are available for drop size measurement include (but are not limited to) the Bete shadowgraphic video system, the Malvern laser diffraction instrument, laser Doppler anemometers, and phase/Doppler particle analyzers. Researchers are aware of the need to do comparative studies of the results of measurements taken on different instruments. A potential difficulty with comparative studies, however, will be in ensuring that not only the particle size instruments are calibrated, but also the instruments to measure nozzle pressure and flow rate (Lefebvre 1989). Furthermore, it makes a tremendous difference where, in the spray, the drop size measurement is taken. The NFL research indicates that, in a downward-directed spray, drop size increases with distance from the nozzle as the differences between the velocities of individual drops reduces, and drops collide and agglomerate. In a horizontal spray, drop size increases with both vertical and horizontal distance, up to the point where larger drops have fallen out of the spray and only the finest fraction remains drifting in the air. Measurements taken 0.4 m from a nozzle will, for example, show a 100 micron $D_{V0.5}$, but at 1.6 m from the nozzle, a VMD of 200 microns. There is often a similarly wide variation in the VMD at different points radially within the spray. With all of the possible variations in measurement technique and macro-scale conditions, it appears unrealistic to be concerned about distinctions finer than 50 microns in comparing sprays. There is, nonetheless, great utility in using a single representative diameter to describe a spray; it is important to appreciate the limits of precision to the measurements, however.

It is in the well-mixed spray distributed throughout a large compartment that evaporation, heat transfer and radiation attenuation occur, which result in suppressing a fire. After the spray leaves the nozzle and interacts with other spray jets and obstructions in the space, the spray distribution will bear little resemblance to the spray distribution measured under laboratory conditions close to the nozzle. Figure 2 shows the difference between the spray distribution for a single nozzle measured close to the tip, and for several nozzles of the same type, measured at mid-height in the middle of the obstructed room. From a single nozzle operating at optimum pressure, the spray starts out with drop size parameters $D_{V0.1}$ and $D_{V0.9}$ between 50 and 142 microns, with a VMD ($D_{V0.5}$) of 92 microns. But at mid-height in the room, with many nozzles operating, the mixed spray has drop diameters ranging from 140 to 380 microns, with a $D_{V0.5}$ of 230. The difference is due mostly to the agglomeration of drops as they move turbulently in the compartment. It is the blended, agglomerated spray that is transported by convective currents around the room, cools the gases in the fire plume, penetrates into shielded areas, and interacts with the fire.

It is not an easy matter to predict, from the bench test distribution curves of individual nozzles, the drop size distribution of the combined spray inside a particular compartment. It could possibly be done using computational fluid dynamics models, validated with relatively easy-to-take drop size measurements. More work is required in this area.

Spray Flux Density

Flame suppression with fine sprays requires that a certain minimum mass of water droplets be suspended as spray. Therefore, a spray must have a density, or mass flow rate, that is appropriate for the fire scenario and compartment conditions. Whether the extinguishment mechanism is due to heat extraction as fine droplets evaporate, to displacement of oxygen by steam expansion, to radiant heat feedback attenuation, or a combination of all three effects, a certain minimum number of droplets per volume of space will be required to accomplish suppression. Determining what spray flux densities are required for particular fire scenarios will be the primary subject of research into water mist suppression systems for at least the next decade. For this discussion on the desirable characteristics of sprays for fire suppression, it is intended only to point out that the volumetric output from the nozzle and the uniformity with which that volume is distributed in space, are important factors.

Selecting full cone, rather than hollow cone, spray patterns allows us to assume that the spray will, at the outset, be relatively uniformly distributed. Next of concern is the actual mass flow rate of water through that spray volume. The initial spray density must be high enough to allow for losses of spray due to drops falling out or depositing on the surfaces of obstructions, and still have enough suspended water particles per unit volume of air to be able to extinguish a fire. For example, some nozzles produce a very fine spray (with drop sizes ranging from 50 to 100 microns), but the volumetric flow rate may be too low to introduce a sufficient mass of water into the space. For a flow rate of only 3 Lpm, for example, and depending on the size of the compartment, the distance the spray has to travel to reach the fire, and the total area of obstructing surfaces, it is likely that not enough droplets will survive the losses and be available to suppress the fire. The flow-through of 3 Lpm might be quite adequate for a small, unobstructed compartment, but inadequate for a larger, or heavily obstructed, compartment. Thus, a nozzle must have not only the desired drop size distribution, but a total mass discharge rate appropriate for the geometry of the compartment.

The matter of describing the density of water mist warrants discussion, and further research. Drop size distribution measurement systems, conforming to ASTM E-799, report drop concentration or flux density when possible, usually in units of cm^3 of water per cm^3 of sample volume ($\mathbf{F_d}$). The flux density is computed using the measured frequency counts, the computed volume per drop assuming a spherical shape, and the volume of the measurement field (which is instrument dependent). In the NFL experiments, measurements of droplet concentrations ($\mathbf{F_d}$) in sprays of comparable appearance varied widely, ranging from $5 \times (10^{-5})$ to $5 \times (10^{-7})$ cm^3 per cm^3. It was suspected that the wide variation in volume density measurement for otherwise comparable sprays was due to very localized differences in the spray. At this stage, then, the drop/volume concentration obtained as part of the drop size measurements was not considered to be a practical parameter for characterizing spray density.

Another way to visualize spray concentration is to compute a theoretical average density over the entire volume of the compartment, or $\mathbf{D_v}$. This is done by dividing the total volume flow rate (Q in Lpm) of the nozzles by the volume of the compartment, without regard for the volume occupied by internal objects:

$$\text{Avg. Density per unit volume } \mathbf{D_v} = Q_{total} / V_{total} \quad [\text{Lpm/m}^3] \tag{1}$$

Applied in the case of a total flooding system, this approach implies that the spray is uniformly distributed throughout the enclosure. In fact, there may be large differences, depending on the number and size of objects in the room, the location of the nozzles and the geometry of the room. The average density so calculated may be quite different from the local density that actually extinguishes flame. For example, density will be higher near the floor than near the ceiling. Expressing spray density as mass per unit volume is appealing, however, because it corresponds to our expectation that that is the most appropriate measure of ability to extinguish fire. It is also the form that is useful for computational fluid dynamics modeling, which considers the mass of water droplets per control volume. For practical reasons, however, it is difficult to actually measure localized spray density in volume/volume units. A full discussion of the difficulties associated with such a measurement is beyond the scope of this paper.

A simpler way to characterize spray density is to use the traditional means of characterizing sprinkler spray density, i.e., total flow rate per unit area:

$$\text{Avg. Area Density, } \mathbf{D_a} = Q_{total} / A_{total} \quad [\text{Lpm/m}^2] \tag{2}$$

Density expressed in this way can be measured by collecting spray on sample surface areas, over a known time interval. Because it can be relatively easily measured, it is, in our opinion, the most practical way to talk about the density characteristic of a spray. Although it is a feature that can be quantified, it is nevertheless one step removed from the real physical condition that is involved in the interaction of spray drops with hot gases or flame.

Notwithstanding the uncertainty mentioned earlier about the variability in the spray flux density readings obtained using the drop size analyzer ($\mathbf{F_d}$), it is of interest to convert $\mathbf{F_d}$, in units of cm^3 per cm^3, to Area Density, $\mathbf{D_a}$, in Lpm/m^2. To do this, the velocity of the spray must be known or estimated. Assuming that the spray is uniformly distributed throughout a volume with a cross-sectional area of 1 m^2, has a uniform velocity across the entire cross-section, and that 1 cm^3 of water weighs 1 gram:

$$\mathbf{D_a} = 60{,}000\ (\mathbf{F_d})\ (\mathbf{v}) \quad (3)$$

$\mathbf{D_a}$ = Area Density as would be measured on a collection surface, [Lpm/m^2]
$\mathbf{F_d}$ = Flux Density from drop size measurements, [$cm^3/cm^3 = g/cm^3$]
$\mathbf{v}$ = average spray velocity, assumed to be uniform, [m/s]

For example, for an $\mathbf{F_d}$ reading of 5.0 (10^{-5}) cm^3/cm^3, and a spray velocity of 5 m/s, the estimated equivalent average $\mathbf{D_a}$ would be 15 Lpm/m^2.

Using the terminology of standard sprinkler design, we would like to be able to relate the Actual Delivered Density (ADD) to the Required Delivered Density (RDD) for a particular fire scenario. The experimental basis for determining RDD's for fine sprays is just beginning. Some information has been acquired for unobstructed pool and liquid jet fires. For example, in the NFL's work involving pool fires in obstructed machinery spaces, average densities of 3.2 Lpm/m^2 from a network of 18 ceiling nozzles completely extinguished pool fires 3.4 m below, depending on the degree of obstruction. Even lower overall densities were successful if nozzles were located closer to the fire, under the bilge decks. If complete extinguishment is not the objective, it is believed that control over temperatures in the room could be achieved at lower densities. However, much more research is needed to build the data base for a wider range of compartment conditions. The effects of obstructions and convective air currents on determining the ADD have yet to be quantified, and again, much research is needed.

Neither the average flow rate per compartment volume, nor the average flow rate per total floor area, is a particularly good way to quantify the spray density needed to extinguish a fire. It is probably the localized density in relation to the fuel source that is most important. As an example, in an obstructed shipboard machinery compartment with a pool fire in a bilge area under deck plates, a few nozzles placed below the deck plates will bring about rapid extinction, because they direct a relatively high spray density directly into the flames, while a much lower spray density from ceiling nozzles is all that is required to cool the room.

Spray Angle

The spray angle is more a characteristic of the nozzle than the spray, but it is nonetheless important to understand its significance in defining appropriate sprays for fire suppression applications. Spray angle directly affects the velocity and direction of the droplets leaving the nozzle. Therefore, for modeling with computational fluid dynamics at least, the range of directions of initial droplet trajectories is of interest. Spray angle is a critical factor in determining nozzle spacing to ensure a relatively uniform distribution of spray, without large void areas between nozzles. Finally, spray angle is very significant in determining the initial velocity and momentum of the spray, which in turn determines its ability to penetrate obstructions in the compartment.

Spray Projection (Kinetic Energy)

The ability of the spray to get past obstructions in the compartment, and to interact with the flame of a fire, depends on the momentum, or kinetic energy, provided by the nozzle. Considering only the mass of the spray, kinetic energy is defined as:

$$\mathbf{KE} = \frac{1}{2} \mathrm{M} \bullet \mathbf{v}^2 \tag{4}$$

KE = kinetic energy of the spray
M = mass of unit volume of spray, g
v = mean velocity of a unit volume of spray, m/s

For comparable mass flow rates and drop size distribution, sprays with higher initial velocity in a particular direction will have higher kinetic energy than sprays with lower initial drop velocities. It is possible to derive an expression to calculate the average kinetic energy per cubic metre of spray (**KE/m³**), using the volume flux density obtained from the drop size analyzer ($\mathbf{F_d}$), and a measured velocity of the spray:

$$\mathbf{KE/m^3} = 10^6 \bullet \mathbf{F_d} \bullet \frac{\mathbf{v}^2}{2} \tag{5}$$

KE/m³ = kinetic energy of 1 m³ of the spray
$\mathbf{F_d}$ = Flux Density from drop size measurements, [cm³/cm³ = g/cm³]
v = average velocity of a unit volume of spray, uniform, [m/s]

Although equation (5) is theoretically appealing as a way to quantitatively compare the energy levels of spray, it requires special equipment to obtain both $\mathbf{F_d}$ and **v**, and is therefore of limited practicality. Without measuring either droplet size or net spray velocity, the kinetic energy of a particular spray can be at least qualitatively judged by comparing the horizontal projection of the sprays. The projection ability of the nozzle is partly determined by the spray angle, but also by the mechanism for producing the spray. Nozzles with a wide spray angle will have a lower projection than narrower spray angle nozzles. To maximize spray projection, higher nozzle pressures and reduced spray angles are needed. Higher pressures have an associated energy cost, and reduced spray angle will mean closer nozzle spacing; both factors, therefore, may involve a higher installation cost. One way to keep water pressure requirements low and still achieve good spray drop size and high kinetic energy, is to use air-atomizing nozzles. The energy added by compressed air produces a good drop size distribution and imparts a high initial velocity to the spray, at lower water pressure than a "pressure-only" nozzle. The requirement to provide compressed air to every nozzle trades one cost for another, however.

Based on experiments at the NFL with pool fires in an obstructed compartment, an energetic spray with reasonably high projection has two advantages. The first advantage is that the percentage of spray that gets past obstructions increases, so that fewer nozzles are needed to achieve a sufficiently dense distribution of spray in the room. As noted earlier for obstructed spaces, the representative drop size increases as spray moves away from the nozzles. A spray with higher initial velocity will still have a finer spray distribution than a spray of initially lower velocity, after it has been modified by the obstructions. A spray with high energy will reflect from surfaces and continue to move in a turbulent fashion through the space. Reflected spray can move behind obstructions and around corners, thus permitting filling of the recesses of the compartment volume with spray using a minimum number of nozzles.

The second advantage of high initial kinetic energy is that extinguishment is greatly improved (for pool fires, at least) if the spray droplets penetrate the actual flame in a turbulent fashion. Turbulent mixing of flame and droplets resulted in rapid extinction, whereas quiescent surrounding of flame with mist was unable to bring about extinguishment. In order to penetrate the flame zone, the direction of the spray movement had to be at an angle to the flame plume. In several of the NFL tests in which the spray had a high energy, but in which its direction of movement was parallel to, and in the same direction as, the flame plume (co-current), the turbulence and additional air provided by the air-atomizing nozzles actually increased flame intensity. More research is needed to determine the minimum required spray density that actually penetrates the flame to cause extinction.

Spray energy that is very high creates rapid pressure changes in the compartment, which may force smoke and fuel out of the compartment. In some cases, excessive turbulence around the flame in a small space may accelerate burning. This occurred in some of the NFL tests when the direction of the spray was co-current with the direction of the fire plume.

Summary of Characteristics of Sprays

To characterize a fine spray suitable for fire suppression, it is necessary to describe more than a single representative droplet diameter. At least two parameters are needed, one to describe a representative diameter, and another to describe the range. Preferably, a plot of cumulative percent volume versus diameter should be provided. Various empirical distribution functions (such as Rosin-Rammler) are used to input the drop size distribution into computational fluid dynamics model codes.

The drop size distribution measured very close to the nozzle will be much finer than when measured at a distance from the nozzle. Interaction of spray with adjacent spray cones and obstructions results in agglomeration of drops, so that the VMD of the spray in the midst of a space flooded by fine spray may be as much as 100% larger. The range of drop sizes will increase as well.

Spray density is very important for fire suppression although, as yet, it is difficult to relate actual delivered density to required delivered density for different fire scenarios. Expressing density as average density per unit volume in a total flooding system, using the total flow rate and the total compartment volume, is only useful for basic comparisons, because of large differences in localized densities. Traditional measurement techniques for fluxes, in volume flow per minute per unit of floor area, are easier to obtain but are not very useful for computational fluid dynamics modeling. Neither volume flow rate per volume nor volume flow rate per floor area are particularly relevant to either actual delivered or required delivered densities. It is probably much more important to understand and have control over the localized densities in relation to the fuel source than to quantify spray density in broadly average terms.

Spray angle and spray momentum are factors that influence nozzle spacing, and the ability of the spray to fill the compartment volume in spite of obstructions. Sprays with high momentum interact turbulently with the flame and appear to improve extinguishment.

Methods of Producing Sprays (and their Limitations)

For the NFL experiments, it was practically possible to achieve a spray with good appearance, projection and flow rate, with an initial drop size distribution from a single nozzle operating at optimum pressure with parameters $D_{V0.1}$ and $D_{V0.9}$ between 50 and 142 microns, with a VMD ($D_{V0.5}$) of 92 microns (see Figure 2). Spray drop size distributions in this range can be produced practically, for fire protection purposes, using impingement nozzles, moderate to high pressure nozzles, or air-atomizing nozzles. Impingement nozzles position a deflector, either a single probe, plate or a specially shaped spiral, in front of the orifice, so that the high velocity jet strikes the deflector and breaks up into a spray. Pressure nozzles rely on water pressure to force water through one or more small orifices at a high velocity, so that the jets breaks up into fine droplets. Air -atomizing nozzles inject compressed air into a high velocity water jet or sheet and cause it to break up into fine spray. Each type has advantages and disadvantages. Practical considerations relating to each type are presented below.

Impingement Type Nozzles

The impingement-type nozzles produced coarser sprays than the other types of nozzles examined in the NFL tests. For the smallest nozzle tested, the spray had a high pressure requirement, low volumetric flow rate, and poor projection, although the initial drop size distribution of $Dv_{0.1}$, $Dv_{0.5}$ and $Dv_{0.9}$ of 75, 125 and 200 μm, respectively, was reasonable. The orifice was prone to plugging, and the deflection pin was easily bent by water-borne debris. Once the deflection pin was bent, suitable spray-production was no longer possible.

More robust impingement nozzles with spiral-type deflectors produced more energetic sprays, with reasonable projection and substantial flow rates. The drop size distributions at moderate working pressures (550 kPa (80 psi)) tended to be too coarse, however, with at best $Dv_{0.1}$, $Dv_{0.5}$ and $Dv_{0.9}$ of 280, 350 and 410 μm, respectively. The higher number of larger drops would be a disadvantage for suppressing pool fires, as they could cause splashing. The impingement nozzles were rejected for further testing in the NFL tests in favour of nozzles with equivalent flow rates but finer spray distributions. Nevertheless, spiral type nozzles are robust and simple in design. If the spray distributions were improved, they could be suitable for some applications of water mist fire suppression systems.

Pressure-Type Nozzles

Generally, it is less costly to design, operate and maintain a pumping/piping system that operates at low pressures rather than at high pressures. Depending on design, commercially available moderate pressure-type nozzles may require pressures between 550 and 690 kPa (80 and 100 psi) to produce a reasonably fine spray with the appropriate flux density and kinetic energy. The SSC 3/4 7G-5 nozzle is an example (see Figure 1). Although this nozzle has a reasonably fine initial drop size distribution, wide spray angle and good projection, its volume flow rate at 550 kPa is nearly 30 Lpm (8 gpm). If used in a total flooding system, the cumulative flow and pressure requirements may be excessive. For example, for a compartment requiring 10 nozzles to provide the desired spray distribution, the combined flow for a total flooding system would be typically 330 Lpm

(87 gpm), allowing 10% for "overage." With a starting nozzle pressure of 552 kPa (80 psi), allowing 69 kPa (10 psi) for elevation head and 200 kPa (29 psi) for pipe friction losses, the final pressure requirement at the pumping source could be as high as 821 kPa (119 psi). This flow/pressure demand of 330 Lpm at 821 kPa (87 gpm at 119 psi) is just within "normal" fire suppression system pumping and piping practices.

To protect a larger compartment requiring more nozzles, the capacity of a "normal" fire suppression system would quickly be surpassed. Furthermore, because the flow rate is high, the total amount of water pumped into a closed compartment over the discharge time accumulates rapidly. At 330 Lpm (87 gpm) for 5 minutes, a total of 1650 litres (435 gal) would be pumped into the enclosure. For a shipboard application, such a high weight addition would be undesirable. It is suggested, therefore, that there is a practical upper limit to the size of compartment that can be protected using such nozzles in a total flooding configuration. It may instead be necessary to divide a large compartment into sub-zones, so that only the nozzles surrounding the fire operate. Such a design approach would require appropriate detection/activation technology, and the operation of enough nozzles to surround the fire with spray. Whether zoned operation of a water mist system is feasible will depend on the specifics of the fire scenario, detection system capabilities and the control objectives.

High pressure nozzle systems generally have an associated cost in equipment and maintenance that make them less cost-effective than low pressure systems. There is an economic incentive, then, to operate the water mist system in pressure ranges achievable using standard fire protection pumping equipment. High (ultra-high) pressure nozzles, such as the Marioff nozzle, require specialized pumping equipment and distribution piping. Nevertheless, good spray drop size distribution, high spray energy, low overall flow rates and the potential to electrically activate specific nozzles, may combine to still produce a cost-effective system. Again, the maximum size of a total flooding installation may be limited by the pumping capacity and the tolerance of the compartment for total water accumulation. For very large compartments, partial activation of zones within the space must be considered. Further research is needed to determine the design parameters of such zoned systems in large compartments.

Air-Atomizing Nozzles

Air-atomizing nozzles have the advantages of good drop size distribution ($Dv_{0.5} \sim$ 100 μm) and higher spray velocity at reasonable water and air pressures. Because the orifices are not as small as in pressure-type nozzles, there is less concern about plugging with foreign matter. The NFL tests demonstrated that air-atomized spray nozzles requiring 414 kPa (60 psi) water pressure, and 550 kPa (80 psi) air pressure were most effective at penetrating obstructions. It was therefore possible to install nozzles at ceiling level in an obstructed compartment, and extinguish pool fires in the bilge area, without having to install separate nozzles to protect shielded areas below the deck plates. For moderate-sized enclosures, where compressed air is available, air-atomizing nozzles can be cost-effective.

There are several disadvantages of air-atomizing nozzles. These include:

1. The total air flow demand of a system involving multiple nozzles can be very high. The compressed air may be supplied from plant compressor systems, or from dedicated cylinders of compressed air or nitrogen. As an example, the air-atomizing nozzle used in the NFL tests (Spraying Systems Company (SSC) 1/2J-SU89) required 53 Standard Cubic Feet per Minute (SCFM) of air when operating at 380 kPa (55 psi) water pressure and 503 kPa (73 psi) air pressure; the nozzle discharge rate was 6.3 Lpm (1.7 gpm). For a 6 m x 6 m x 3.6 m high room with 18 nozzles operating to provide an average density of 3.2 Lpm/m^2, the total air demand was 954 SCFM. Depending on the degree of obstruction covering the bilge space, it typically took 1.5 to 5.5 minutes to extinguish the test fires. Assuming minimum five minute operation of the system at an air demand rate of 954 SCFM, a substantial reservoir and compressor system is required. If high-pressure gas cylinders are used instead of a plant air system, a large number would be required for a single operation. The system would subsequently be out of commission until the cylinders were replaced. The cylinders would occupy wall space and would add considerably to the total weight of the suppression system. These factors indicate that there is a practical limit to the maximum size of a total flooding system using air-atomizing nozzles.

2. The installation of piping for air, in addition to the water piping, increases the system cost in labour and materials, as well as weight and maintenance. To reduce those costs, improvements in the design of air-atomizing nozzles are needed to facilitate the installation of multiple nozzles into a gridded piping system, with a minimum number of fittings.

3. Design of air and water distribution piping for the air-atomizing system requires that both hydraulic and pneumatic calculations be performed to determine the total air and water demands, and to optimize the pipe sizing. To do this, the air and water

discharge rates from a nozzle must be determined at different combinations of air and water pressure. The documentation provided by air-atomizing nozzle manufacturers seldom presents the pressure-discharge information in a manner suitable for performing the hydraulic/pneumatic calculations. Manufacturers should provide plots of liquid and air discharge rates versus air to liquid ratio (Qw and Qair versus ALR). Figure 3 shows the type of information needed to allow both the hydraulic and pneumatic calculations to proceed. Both curves can be characterized by a best fit equation, for use in standard calculation software.

Effects of Additives on Spray Characteristics

To this point, the nozzle has been viewed as the primary factor influencing the spray characteristics. The properties of the liquid also play a role, however. It is clear from theoretical considerations of spray development that the viscosity, surface tension and density of the liquid will effect the break-up of jets or sheets into drops. For fire suppression purposes, "pure" water is the usual liquid. There are instances, however, when it is desired to use additives in the water, such as surfactants, foaming agents, or anti-freeze, or to use other than "pure" water, such as salt water. To determine whether these additives had an adverse effect on the spray characteristics, several tests were conducted as part of the NFL experiments. Nozzle performance was measured and compared using fresh water, salt water (2.5% by weight, the salinity of sea water), and a low percentage (0.2%) of foaming agent (AFFF).

Figure 4 shows that neither additive had a significant effect on the nozzle discharge characteristics. For hydraulic calculations, then, the effect of the additives was considered to be negligible. Figure 5 shows the drop size distribution curves for the air-atomizing nozzle with and without the additives. The additives tended to increase the number of large droplets, as evidenced by the increase in the $D_{V0.9}$ from 140 μm to 170 μm for salt, and 200 μm for AFFF. The finer fraction of the sprays was not significantly changed. As was shown in Figures 1 and 2, however, the variations in drop size distribution due to variations in nozzle pressure and encounters with obstructions in the space are generally much larger than the increase in $D_{V0.9}$ caused by the additives. For practical purposes, the effect of the additives on drop size distribution was considered to be negligible in comparison to other factors affecting drop size distribution in large compartments.

Summary of Methods of Producing Sprays

For all three types of spray nozzles, there are practical limits to the size of compartment that can be protected by a total flooding type of system. Although the discharge from individual nozzles is less than a standard sprinkler, the cumulative discharge from a network of nozzles still represents a significant volume of water. Also, the pressure required for optimum operation of a single nozzle, whether of the pressure-only or the air-atomizing type, is significantly higher than for standard sprinklers. The total pressure demand for a water mist system may therefore surpass the capacity of regular fire protection water supplies, possibly requiring additional pumping capacity. A moderate pressure boost can usually be achieved without excessive cost, however, given that the water flow rate is low. On the other hand, the air-flow requirements for air-atomizing type nozzles are quite substantial, and will quickly limit the cost-effectiveness of large total flooding systems using such nozzles. The zoning of water spray systems within a large compartment, coupled with sophisticated detection/activation equipment, presents an alternative to a total flooding approach. More research is needed to determine the performance limits of such a system.

For small compartments and equipment enclosures in which only a few nozzles are required, any of the three types of mist-making nozzles could be applied. Both pressure-only and air-atomizing nozzles are capable of producing sprays with good drop-size distribution, volumetric flow rates, spray angle and spray projection.

Spray Flux Densities Required for Suppression

A great deal of work has been done over the last 40 years aimed at answering the question of what minimum application rate of spray is needed to extinguish a fire. One hypothesis relates the ratio of spray volume to flame volume, concluding, for example, that a flame will be extinguished if the water mist occupies 10 percent of the flame volume. Others have suggested that there is a relationship between the percent reduction in radiant heat energy and the probability of extinction for a fire engulfed by water mist (personal communication, Fire Research Station, UK, 1992). Other research has shown a relationship between the mass flow rate of a gaseous fuel and the mass flow rate of water droplets entrained in the fuel jet (Evans & Pfenning 1985). Wighus (1992) has shown a relationship between the total heat generated by the fire and the amount of heat absorbed by the spray, i.e., a Spray Heat Absorption Ratio, or SHAR. For example, when the SHAR approaches 0.6, pool fire flames will be extinguished. It is not the object of this paper to discuss the literature on this important subject. The NFL experiments have not yielded information to confirm or deny any of the suggested relationships. The experiments did, however, provide practical information about the effects of various compartment conditions on spray density, and the effects of the water spray on conditions created by the fire in the compartment. It is these observations, and their implications for the engineering design of spray systems in general, that will be discussed here.

The terms Required Delivered Density (RDD) and Actual Delivered Density (ADD) have already been introduced. The research, previously mentioned, to determine the minimum spray density required to accomplish extinguishment, was directed at determining the RDD. The RDD depends on the type of fuel and its arrangement; the type of fire – flaming or smouldering, small or large; the ventilation conditions in the compartment; and the fire safety objective. The ADD depends on the performance and location of spray nozzles; the degree of obstruction in the compartment; the ventilation conditions; the intensity of the fire; and the strength of fire-induced convective air-flows. Measurements of ADD of fine spray under fire conditions in compartments containing obstructions and shielded areas have not yet been made.

Full-scale fire testing using fine spray has demonstrated that it is easier to extinguish a large, flaming fire than a small flaming fire. In the NFL tests involving a 2 MW pool fire in a compartment with limited ventilation, the rapid flaming fire lowered the oxygen concentration in the room to below 15 percent at the time of activation of the spray. Extinction of the fire in the bilge area below deck plates was rapid, regardless of the degree of obstruction presented by the deck plates. It is surmised that the low oxygen levels, coupled with increased evaporation of spray and subsequent steam displacement, worked in concert to extinguish the fire. On the other hand, with a smaller fire of 600 kW and the same ventilation conditions, the fire took longer to extinguish, and the degree of deck plate obstruction mattered. Again, it is surmised that the relative importance of the different extinction mechanisms changed, according to the size of the fire. For the smaller fire, there was a greater need to have spray interact with the visible flame, where it could extract heat and act as a barrier to the thermal feedback to the fuel surface. For the larger fire, steam displacement of oxygen reduced the need for direct spray-flame interaction.

What are the general implications of the observed phenomena for design of water mist fire suppression systems? It is counter to traditional fire safety engineering practice to allow a fire to get big before attacking it; such an approach might be tolerable under some circumstances, but not usually for the type of facility presently protected with halon, for which water mist is considered to be a potential alternative. A more appropriate strategy for an automatic suppression system would be to design with the intention of extinguishing the fire while small. This means that nozzles should be located so as to maximize the probability that spray will interact with the flames. Applying this strategy in the case of the compartment studied in the NFL experiments, the recommended design would call for spray nozzles below the deck plates, in spite of the fact that under certain circumstances the fire can be extinguished using ceiling nozzles alone. In other words, high localized spray densities in the vicinity of the fire source are recommended. To achieve this, strategic location of nozzles based on the potential fire surfaces might be more effective than locating nozzles to provide uniform density throughout the compartment. Furthermore, strategic location of nozzles closer to the fire source means that the spray cloud will consist of finer drops than would be the case for water mist descending from ceiling nozzles. With this scenario, the spray density applied from ceiling nozzles can be kept quite low, and still be very effective at extracting heat from the fire gases, and preventing radiant heat damage to objects in the compartment.

This line of reasoning illustrates the advantages of general versus local spray application, but sheds little light on the magnitude of the spray flux needed to achieve extinction. In the NFL experiments, it was not possible to determine the minimum required density accurately, partly because of wide variation in the results of the full-scale tests. Also, it was not possible to measure spray flux density in any way that would determine the mass of water per unit volume actually arriving at the flame front. As illustrated, in principle, by Figures 1 and 2, the spray drop size distributions changed significantly as the spray moved through the compartment. Thus, any relationships between average flux densities expressed in terms of flow rate per compartment volume or floor area, and what was occurring at the flame front, were unreliable. More testing would be required, but under laboratory conditions that allow for more control over variables than is possible in full- or even intermediate-scale testing. In practical terms, however, fire suppression systems are never designed for minimum water application rates determined under ideal conditions. The initial spray density provided by the spray system must be high enough to overcome losses to interior surfaces, and to compensate for less-than-perfect correspondence between spray direction and the fire source. The movement of fine spray throughout the shielded portions of a compartment depends on highly variable forces such as the kinetic energy of reflected sprays, ventilation and fire effects.

Subject to the limitations on their significance just described, extinctions were achieved in the NFL tests with average spray densities as low as 3.2 Lpm/m^2, or 0.83 Lpm/m^3, calculated using the combined flow from ceiling nozzles averaged over the entire compartment floor area or volume. The time from spray-on to extinction of the last flames ranged from 1 minute to 3.5 minutes in tests that were considered to be successfully extinguished. Although the actual extinction of the last remaining small flames took several minutes, flames were reduced to small localized areas very quickly, and maximum ceiling temperatures were reduced to less than 65°C within 45 to 90 seconds in almost all cases. The fastest extinctions occurred where nozzles were placed below the bilge deck plates, in which case spray was able to impact directly on the flames, with no ceiling nozzles operating at all. The average localized density below the bilge decks, calculated based on the floor area "covered" by individual nozzles, was nearly 4.5 Lpm/m^2. Based on the volume "covered" by each nozzle in the 1 m high bilge area, the volumetric flux density was 4.5 Lpm/m^3.

The Effects of Obstructions on Spray Density

Every surface engulfed in a cloud of spray will become coated with water, and will extract water mass from the spray as it goes by. Obstructions "scrub" the spray from the air; this phenomenon is used to advantage in industrial scrubbers intended to remove aerosols and mist from emission stacks discharging from industrial processes. Obstructions reduce the velocity and momentum and cause changes in direction of the spray. As a result, in designing a water spray suppression system for a heavily obstructed compartment, it is extremely important to take the obstructions into account.

It has been imagined that fine water mists would act in the same way as gaseous suppression agents, and move freely into all recesses of a compartment to the seat of the fire, and extinguish it. To a certain extent, this is true; some mist transports itself into all parts of a compartment. Unlike gaseous agents, however, the mass of water per unit volume of air reduces as it passes every obstruction. As has been previously described, the success of a spray in extinguishing a flaming fire appears to require that the spray have some momentum, to be able to push droplets into the interior of the flame. In the NFL experiments, 0.5 m diameter pool fires surrounded by fine mist with a momentum co-current (parallel) with the fire plume, continued to burn, in spite of the presence of the water droplets. This is consistent with the observation that it is possible for a person to stand in the mist-filled compartment without drowning. The fire was able to draw the oxygen it needed to continue burning from the mist. Only when the mist was able to push itself into the core of the flame, was it able to extinguish it.

Figure 6 shows the results of tests conducted to measure the effect of increasing degree of obstruction on the density of a horizontal spray moving through a 1 m x 1 m plenum. Each obstruction grid consisted of 6 horizontal tubes spaced approximately 150 mm apart vertically, with a total surface area of 0.83 m^2. Spray density was measured with a special collecting cone that averaged the mass flow rate per square metre over the height of the plenum. Spray density was measured with 0, 1, 2 or 3 such grids in the path of the spray. The figure shows that operating the nozzle at a very high pressure to overcome the obstructions was counter-productive. The increased turbulence and violence of impacts on the obstructions accelerated the reduction in spray density, so that after passing through 3 grids, the remaining flux density was only marginally higher than for the nozzle operated at a lower pressure. For the nozzle operated at a lower pressure, the spray flux density decreased by 16, 35 and 57 percent with 1, 2 and 3 grids, respectively.

Obstructions in the compartment act to reduce both spray momentum and density. Under favourable circumstances, an obstruction might deflect the spray directly into a flame zone and improve extinguishment. Under less favourable circumstances, the loss in momentum will reduce the effectiveness of the spray. The conservative assumption must be that conditions will seldom be favourable. The way to compensate for obstructions, then, is to reduce nozzle spacing, increase initial spray energy, and look for strategically favourable nozzle locations. Although it would be convenient to be able to install ceiling mounted nozzles for all compartments, in the same way that standard sprinklers are installed, the design of a water mist system may require more detailed consideration of nozzle location.

Criteria for judging "strategic locations" include the projection capability of the nozzle, the spray angle and initial flux density, and the geometry of the obstructions. Nozzles may have to be positioned to project horizontally into some spaces in order to maximize the coverage volume, and to keep the spray direction parallel to, rather than orthogonal to, cable trays or ducts, for example. For large machinery compartments, it becomes impractical to use nozzles with horizontal projection distances less than 3 or 4 m, due to the economic disadvantage of having to install too many nozzles.

Ventilation Considerations

The NFL experiments demonstrated that extinction is easier when the oxygen concentration in the compartment is low. Where it is considered to use water mist as an alternative to halon, as for example, to replace an existing halon system, it can be assumed that the compartment is designed to have no leaks. In that case, the ventilation system is usually designed to be closed automatically upon receipt of a detector signal. This is a potential advantage from the point of view of suppression, because the same extinction capability may be achieved at a lower spray density than would be required in an open, fully-ventilated compartment. Consideration must be given, however, to the feasibility of using air-atomizing nozzles for total flooding of closed compartments. It has already been described that air atomizing nozzles require substantial air flows – for example 50 SCFM per nozzle at 550 kPa (80 psi). Discharging air at that rate from several nozzles into a closed compartment will quickly pressurize the compartment. This has implications for potential smoke spread from the fire compartment into adjacent zones, either through dampers into the ventilation system, or through door or hatch openings made to allow entry into the space. A similar effect on room pressure may occur with high energy pressure-only type sprays, as a result of the spray momentum.

In facilities where smoke damage is of concern, a smoke extraction system may be provided for the compartment being protected. Upon receipt of a smoke detection signal, both the suppression system and the smoke extraction system may be activated simultaneously. As room air moves toward the exhaust inlets, increased air velocities could alter the distribution of water mist in the compartment. Such a possibility must be taken into account during the design stage, not only for the effect on the spray distribution, but also for the effect of the additional water in the extraction system duct work.

It is worth remarking that water mist systems have been demonstrated to operate very well on pool and jet fires in open compartments, and even fully in the open, i.e., outdoors. The success of the system depends more on the way in which the spray interacts with the flames, whether it enters the flame volume and extracts heat from the combustion process or blocks thermal feedback to the fuel surfaces, than on steam displacement of oxygen. There is probably no need to require that the fire compartment be cut off from combustion air, any more than such control over ventilation is required for standard sprinkler systems. The particular benefit of water mist systems may be that they effectively block radiant heat and cool the fire plume, so that fire, even if it is not fully extinguished, does not spread or cause excessive collateral damage.

Where fire is contained in an enclosure, activation of a water mist system causes some rapid pressure fluctuations. This phenomenon is well recognized by the fire service, as cases of windows imploding into a compartment upon application of a water spray are well documented. It is observed in the literature that when a spray is injected directly into the flame or hot gas layer, the rapid cooling causes a strong contraction and reduction in gas volume. The gas contraction is much greater than the expansion of steam as the droplets evaporate (Rosander & Gisellson 1984). This phenomenon was recorded in the NFL fire tests. A plot of room pressure versus time for a typical test is shown in Figure 7. Upon activation of the water spray from ceiling nozzles after a 90 second pre-burn time, the room pressure became strongly negative, -10 Pa or greater. A sudden negative ΔP of that magnitude could cause large windows to implode, depending on their size and strength. In tests conducted in the same room involving standard sprinklers, which have much coarser sprays than the fine sprays under consideration here, it was noted that the pressure reduction upon activation of the sprinklers was not so dramatic, and never went entirely into the negative pressure region. The exceptional cooling effectiveness of the very fine sprays is evident.

In the NFL tests, the spray was activated after 90 seconds of free-burning. The fast-flaming pool fires had generally reached their peak burning rate in that time. Because of thermal inertia, however, objects in the compartment were just beginning to respond to the fire, and temperatures were not very high when the spray was activated. If the fire had burned for a longer time before activating the spray, the steel structures and all of the objects in the room would have been much hotter. For late activation of spray into a hot compartment, the rate of evaporation would be much greater than in the early-activation case, with the likely result that a steam explosion would occur. The need to deal with a fully-developed or post-flashover fire in a compartment is more likely to be a matter for manual fire fighting. It should be assumed that water mist systems are intended to activate automatically early in the growth of a fire, so that very high compartment temperatures at time of activation are not an issue.

Concluding Remarks

The purpose of this paper has been to discuss a number of practical issues relating to the design of water mist fire suppression systems. There is presently a lot of interest among fire safety engineers in using water mist systems as an alternative to halon, on the basis that the mist will act like a gaseous suppression agent to fill all recesses of a compartment. Although there is a growing confidence that water mist systems can successfully extinguish or control flammable liquid pool fires and high pressure jet fires with very small amounts of water, there is a need to develop engineering criteria that will allow designers to match a water mist system to a range of fire scenarios and compartment types. This paper draws a parallel between the long-established practices for design of standard sprinkler systems, which allow any experienced designer to custom-fit a sprinkler system to a wide variety of fuels and buildings, and the need for similar principles for the design of water mist systems. Research being carried out by various research agencies has just begun to collect the information required to establish general design criteria for mist systems. The work has concentrated on just a few of the possible fuel types, fuel configurations, and compartment conditions.

Starting with the need to define both the fire hazard and the fire safety objective, the paper presents information on characterizing sprays suitable for water mist systems. The often-asked question "what is the optimum drop size for fire suppression?" is not answered directly, however. Instead, it is pointed out that macro-scale effects in large volume compartments cause agglomeration of droplets, so that what starts out as a very fine spray ends up as a much coarser spray. It is also pointed out that the types of nozzles available for producing suitably fine sprays have fairly high pressure demands and, in the case of air-atomizing nozzles, very high compressed-air demands. These factors set a practical limit on the size of compartment that can be protected in a cost-effective way by total flooding systems. An alternative to total-flooding systems for larger compartments would be zoned piping linked with a sophisticated detection system. Much experimental work will be needed to validate such systems.

The matter of determining the spray flux density required for suppression is discussed in depth. It is suggested that methods that average the spray flux density over the entire compartment area or volume, although easy to compute, are quite imprecise when it comes to determining what flux density is required to actually cause extinction. Spray density is likely to vary enormously throughout a compartment as a result of removal of spray on the surfaces of obstructions. It is more efficient to achieve high localized densities in the vicinity of the known fire source by strategic location of nozzles, than to attempt to create a single uniform density in the compartment. More than spray density is required to extinguish flames, however. There must be enough spray energy to interact turbulently with the flame. In this respect, water mist does not act in the same way as gaseous suppressants. A method of measuring actual delivered density in terms of mass of suspended water per volume of air is needed.

Finally, the paper discusses some of the factors relating to ventilation of the compartment, and the effects of spray systems on the pressure conditions in the fire room. The feasibility of discharging a number of air-atomizing nozzles into a closed compartment is questioned. The effects of sudden contraction or expansion of hot gases upon application of the water spray are also discussed.

This paper does not state conclusive design criteria for particular hazards. Instead, it concentrates on the general principles of defining the hazard, deciding on the objective or desired performance of the system, understanding the practical limitations of the equipment, and preparing for the actual interaction of the system with the fire. It is from this basis that the development of design criteria and procedures for a wide variety of hazards must start. Design criteria for particular hazards will have to be built, case by case, application by application, as they were for standard sprinkler systems. With the strong demand to build a data base for efficient design quickly, however, there is a need to combine the efforts of all agencies working on the problem.

APPENDIX A

List of Figures

3/4 7G-5 at 552 and 896 kPa, 0.47 and 1.6 m from nozzle.

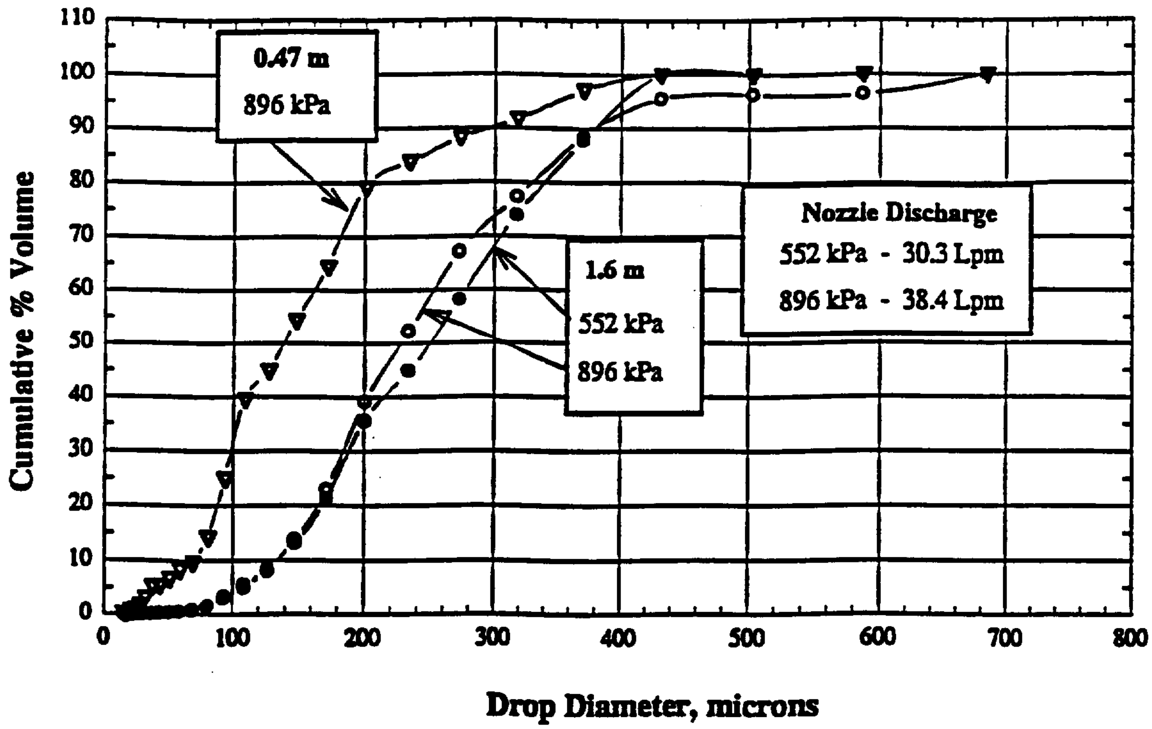

Figure 1. Drop size percent cumulative volume distribution curves for a pressure-type nozzle, at different distances from the nozzle and different operating pressures.

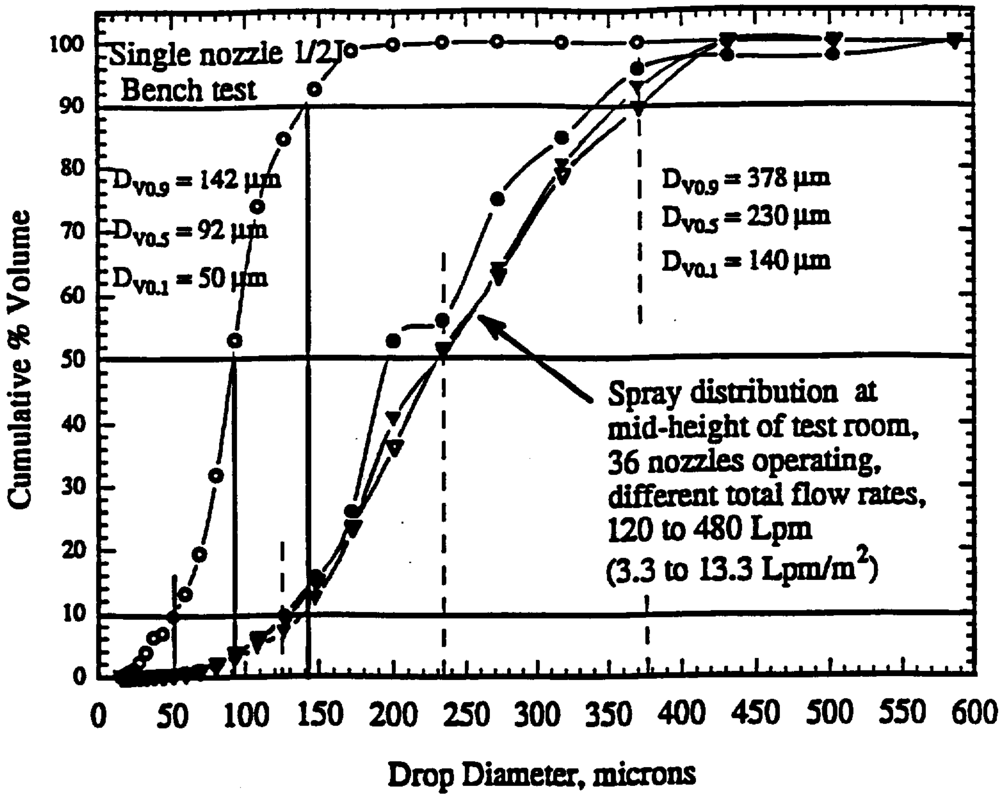

Figure 2. Spray distribution curves for a single air-atomizing nozzle measured 0.47 m from the tip (bench test), and for multiple ceiling-mounted nozzles measured at mid-height in 6 m x 6 m x 3.6 m high test room.

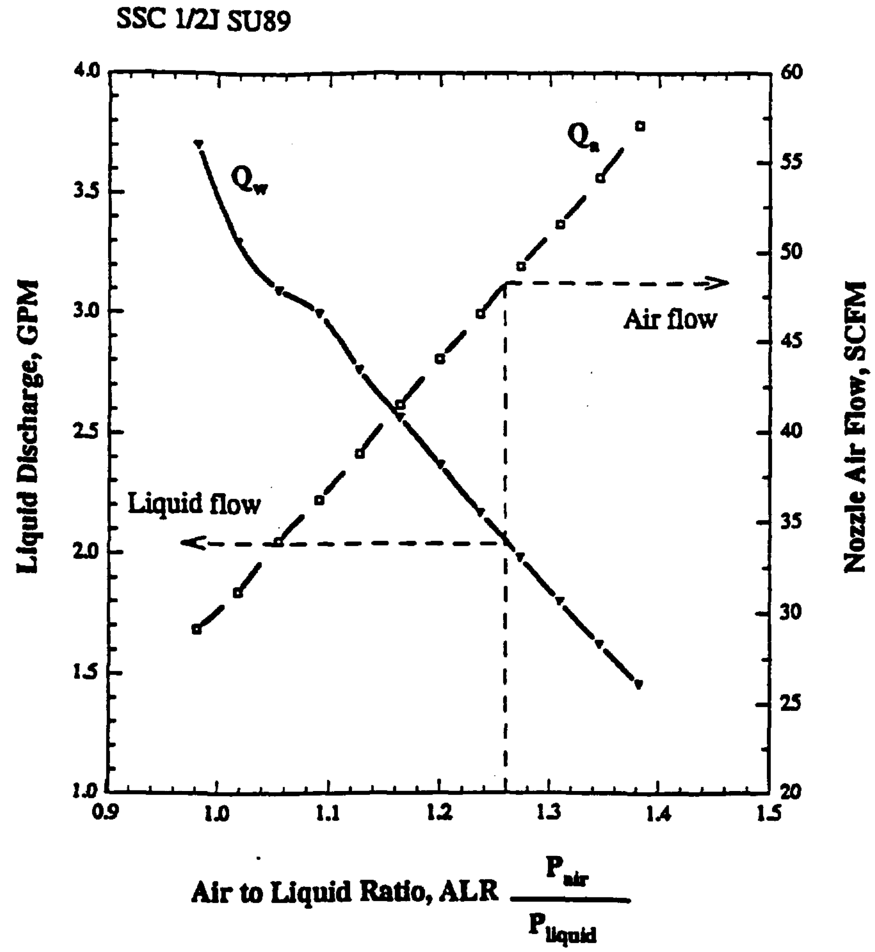

Figure 3. Example of nozzle air and liquid discharge versus air-to liquid pressure ratios (ALR) for air atomizing nozzles.

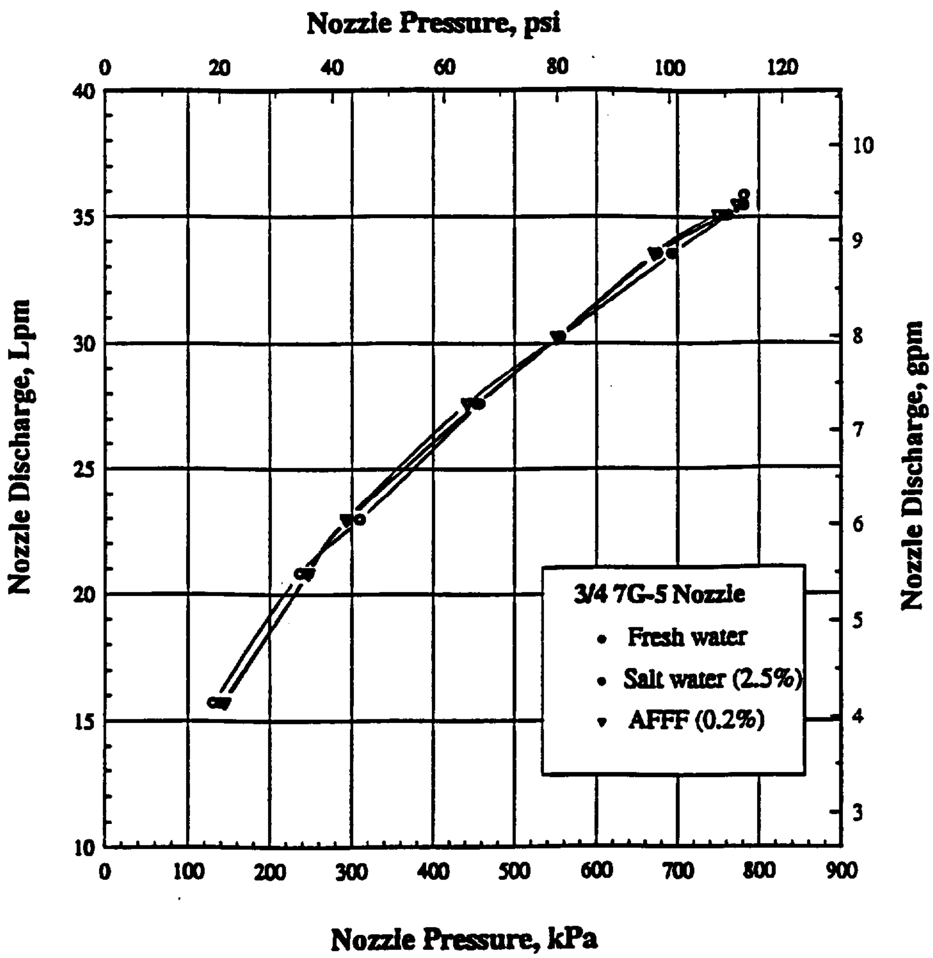

Figure 4. The effect of additives on nozzle discharge characteristics.

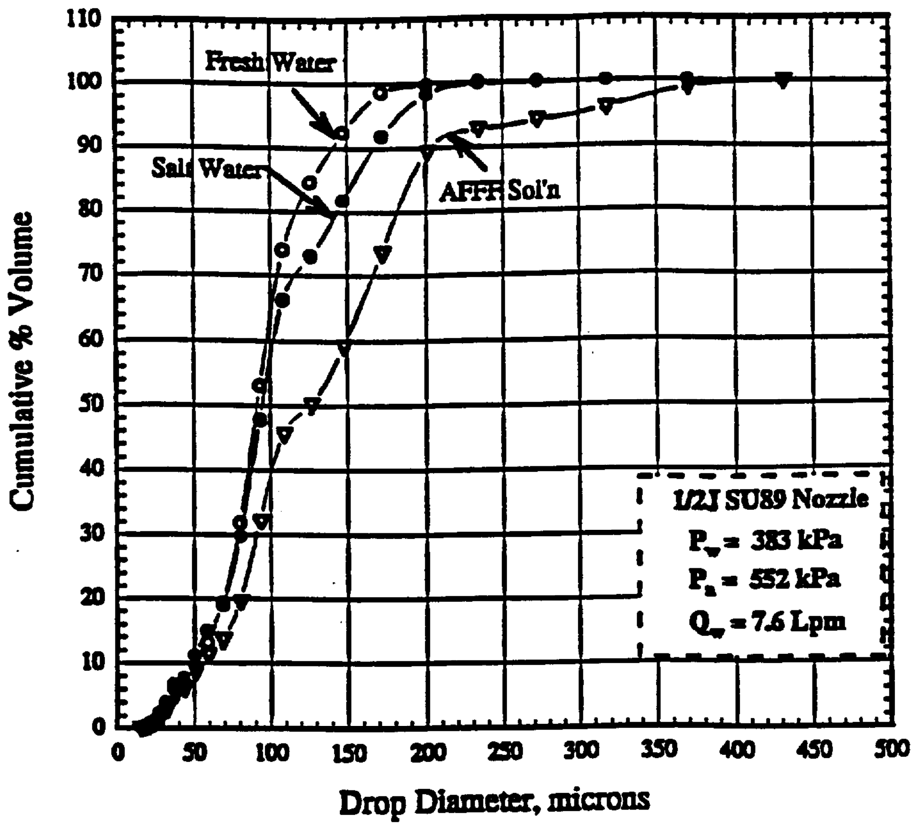

Figure 5. The effect of additives on the drop size distribution of an air atomizing nozzle.

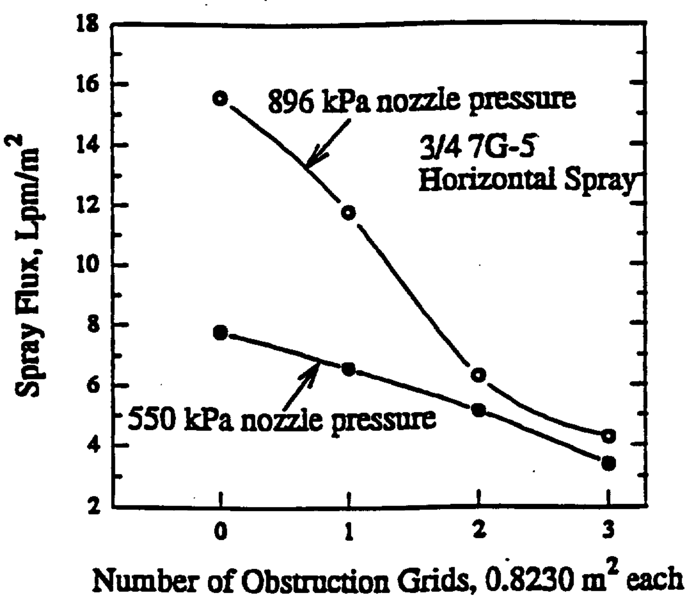

Figure 6. The effect of obstructions on spray flux density.

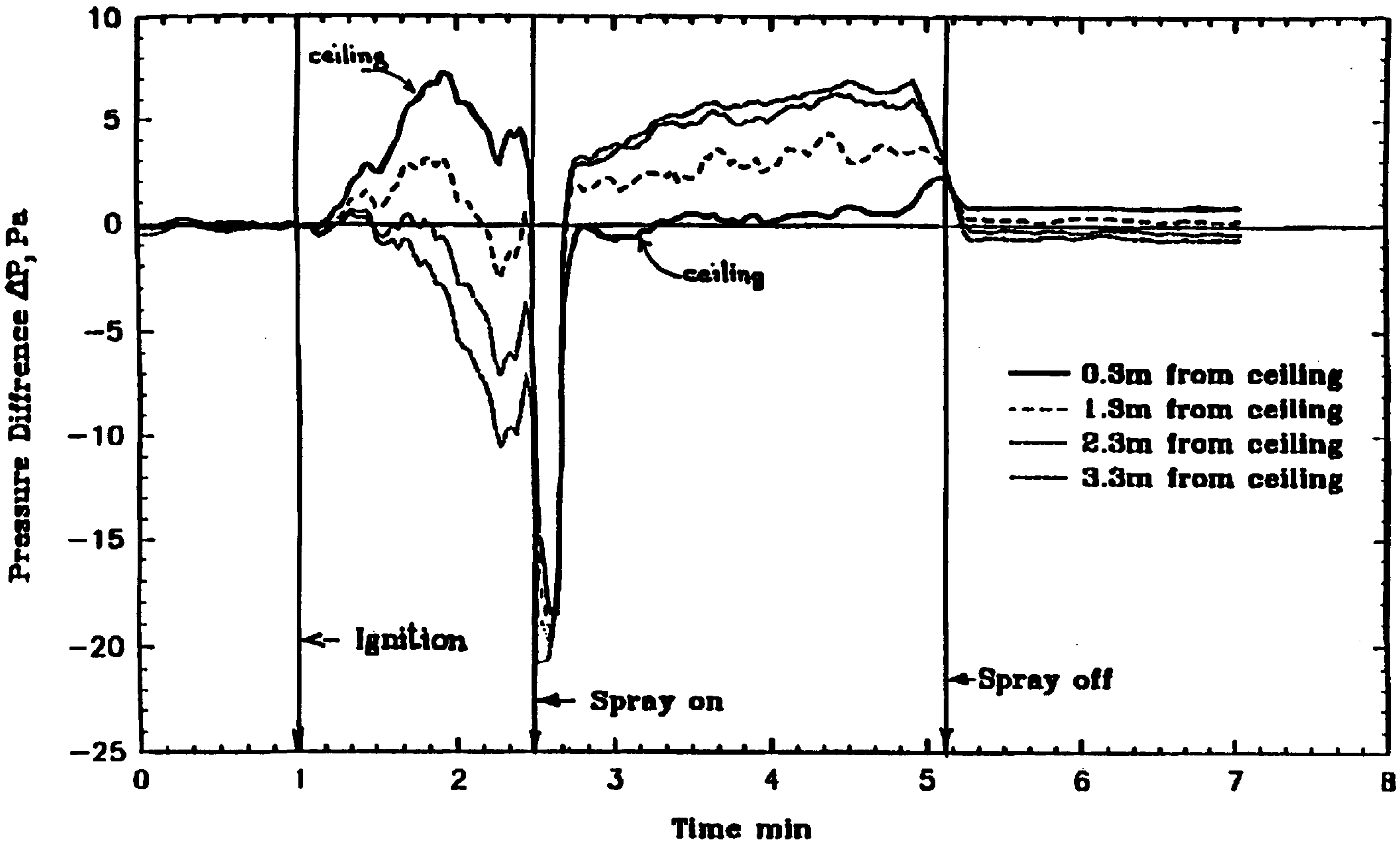

Figure 7. Pressure differences between the fire compartment and adjacent spaces, at four elevations in the room.

Advances in Spray Drop Size and Velocity Measurement Capabilities for the Characterization of Fire Protection Systems

William D. Bachalo
Aerometrics, Inc.
550 Del Rey Av.
Sunnyvale, CA 94086

Summary

The applications of sprays and mists for extinguishing fires requires further research to establish the most effective application parameters. Some of these conditions are the water flow rate directed onto the fuel, drop size and drop size distribution, velocity of the entrained air, and the drop velocity. The phase Doppler instrument is capable of providing these data in realistic environments, including measurements within the fire. Details of the local drop size, size distribution, drop size-velocity correlations, gas phase velocity, number density and volume flux can be measured. A brief description of the phase Doppler method is given along with the validations of the measurement capabilities.

1. Introduction

Fire prevention and extinguishing of fires in solid and liquid fuels remains as a very important area of research and development. One need only recall the images of the incredible disaster that occurred recently in the Berkeley hills to appreciate the destructive results of a fire out of control. The properties of water sprays as extinguishing agents have been studied for decades, if not, centuries [1,2,3,4]. The water acts as an extinguishing agent through its capacity as a cooling agent of the burning fuels. The water is normally applied in the form of a jet or a spray. The spray has the advantage of exposing a greater surface area of cooling water to the flame. In the case of the jet, the jet can penetrate into the flame even under strong convection driven air currents. Upon reaching a solid surface, the jet breaks up into a spray or film of water over the surface which enables the water to remove the heat.

Properties of the water sprays that have been found relevant to the extinction of fires include [4] mean flow rate per unit area in the region of the fire, direction of application, mean drop size and drop size distribution, velocity of the air flow due too the entrainment by the spray, and the velocity of the drops. Clearly, to be effective in cooling the fuel to its ignition point, the spray must be able to penetrate the flames to the source and be capable of removing heat effectively.

More recently water mists have been proposed as a means to extinguish fires. Although this author is not familiar with the technology, one might surmise that the use of mists would minimize the damage normally produced by the use of sprinklers and water jets. One problem with mist application may be that of delivery of the mist to the point of the flame source.

In this review paper, methods for the characterization of spray and mist drop size distributions will be described. The phase Doppler method developed by Bachalo and Houser [5] has undergone extensive development over the past 12 years [6,7,8,9] and has been thoroughly evaluated over a wide range of difficult applications. The instrument has the additional valuable capability of being able to measure the drop velocity simultaneously. This allows the determination of the drop dynamics in even the most complex flow field [10,11]. As with most turbulent two-phase flows that we have studied, it may be assumed that the interaction of the spray or mist with the turbulent air flow will serve to redistribute the spray. This information will be valuable in the analysis of the efficiencies of these methods in extinguishing fires. Other important capabilities of the method is the measurement of the local drop number density and volume flux. This information will be useful in estimating the delivery of the water to the burning surfaces.

The following sections will provide a description of the method in sufficient detail to allow the reader to appreciate its capabilities and limitations. Typical configurations of the instrument will be given to demonstrate the nonintrusive measurements can be made even in large scale facilities. An overview of the recent developments in the technology are presented to show how improvements in the instrument performance and accuracy have been made as well as simplifications to its operation. Representative test results will be provided in an effort to demonstrate the measurement accuracies of drop size and velocities, number density, and mass flux.

2.0 The Phase Doppler Particle Analyzer (PDPA)

Theoretical Description

The phase Doppler method is an extension of the well-known LDV method used for measuring the flow velocity. In addition to measuring the frequency of the scattered light, it was demonstrated by Bachalo and Houser [5] that the phase shift in the signals obtained from two or more adjacent detectors could be used to determine the size of spherical particles. A significant advantage of this approach is that the measurements depend upon the laser wavelength which is not altered by the intervening spray field as is the laser light intensity.

A helium neon or argon ion laser can be used as the light source for the instrument. The beam is split into two equal intensity beams and focused to an intersection with the transmitting lens, figure 1. In a simplified description of the method, it may be assumed that an interference fringe pattern is formed at the beam intersection as shown in figure 1. Light scattered by spherical particles passing through the beam intersection is collected by the receiver optics located at a suitable off-axis angle. A small aperture is used to limit the detection of light from only the beam intersection region. Unlike with the LDV, three detectors are used in the phase Doppler approach. Each detector receives light that passes through a segment of the receiver. The scattered light forms an interference fringe pattern at the plane of the detector that has a spacing that is inversely proportional to the particle diameter. By placing pairs of detectors or a segmented lens in the fringe pattern, two signals that have the same frequency but are shifted in phase will be measured, figure 2. Once again, in this figure, a simplified description of the approach is represented wherein a fringe pattern is assumed to be formed at the intersection of the two laser beams. The drop then acts as a magnifying element that projects the fringe pattern to the detectors. The magnification of the pattern is inversely proportional to the size of the drop. The phase shift in the time domain can be related to the spacing of the interference fringe pattern produced by the scattered light using the following simple relationship:

$$\frac{\Lambda}{s} = \frac{\phi}{360}$$

where Λ is the fringe spacing, s is the fringe spacing, and ϕ is the phase shift between the signals. It remains to accurately describe the functional relationship between the spacing of the scattered fringe pattern and the drop diameter. This has been carried out using the geometrical optics approach and the Lorenz-Mie theory. The response, as shown in figure 3, is linear which is the most desirable response for particle sizing.

Three detectors are used to extend the measurement size range while maintaining good size sensitivity. The two phase angles also serve as a redundant measurement for additional validation of the signals and allows the measurements to be carried out over phase angles greatly exceeding 360 degrees (typically, to as large as 1000 degrees). The large range in the phase measurements would allow the measurements of particles over a factor of 200 or more. However, the particles scatter light approximately as their diameter squared so the required detector amplitude response would be 10^4 for a size range of 50 to 1 if the effect of the nonuniform laser beam intensity is also taken into account. The recent development of the Fourier transform based signal processor has helped to extend this size range to a factor to 50 to 1 since the signals from small particles with a much lower SNR can be detected and processed reliably.

Theoretical Predictions of the Instrument Response

The detailed response of the phase Doppler method to the measurement of spherical particles has been described by Bachalo and Houser [5], Bachalo and Sankar [12], by Sankar et al. [13]. The original analysis, albeit correct, did not delineate all the details of the light scattering phenomena that could affect the performance of the instrument. Thus, a more detailed theoretical model of the light scattering phenomena was derived using the geometrical optics but accounting for the light scattering components. The physics of the light scattering can be better-examined and understood using the geometrical optics approach.

The details of the analyses are given in Sankar and Bachalo and only the pertinent results will be discussed here. As anticipated by Bachalo, the optimum light detection angle for most applications and especially when measuring water drops was determined to be 30 degrees from the forward direction. It is also possible to make reliable measurements at an angle of 150 degrees from the forward scatter direction. Oscillations were found to occur when measuring particles smaller than 3 μm if the light collection f# was not small enough. These oscillations were shown to be a result of the collection of light scattered by reflection, as well as the light scattered by refraction. The interference between these two light scattering components produced a secondary interference fringe pattern. The consequence of this is that the resolution for the small particles is limited to approximately 0.5 micrometer. This is not a limitation for the present application in which the measurement accuracy of particles smaller than 3 μm is not so critical. Similar resolution may be obtained in the 150 degree backscatter direction, provided that a sufficiently large aperture is used for the light collection.

In our more recent paper (Sankar et al.,[13]) we examined the effects of the random particle trajectories through the Gaussian beams. The particle trajectory through the Gaussian beam will affect the relative magnitudes of the light scattered by refraction versus that scattered by reflection. This could cause a measurement error as the phase shift attributable to reflection is different from that owed to refraction. The problem occurs for large particles that approach the diameter of the focused beam. When the drop passes on a trajectory that is to the side opposite the collection aperture, the peak intensity of the beam will strike the drop at a point that is reflected to the receiver. The incident intensity for the light scattered by refraction is low. Although the light scattered by refraction is approximately two orders of magnitude greater than that scattered by reflection, on these few trajectories, the scattered intensity by reflection can be significant and lead to a measurement error.

Both the theory and experiments were used to study this potential source of measurement error. We found that the error could be reduced significantly with the proper design of the optics. One approach that could be used was to increase the size of the focused beam diameter at the sample volume. However, this will create problems when attempting to size particles in relatively dense sprays. In such cases, the sample volume must be made as small as possible to insure a high probability of only a single particle existing in the sample volume at one time. Using our detailed analytical approach, it was discovered that the mutual interference between the reflection and refraction which have the same frequency not only depended upon the relative amplitude of these two scattering components but also upon the phase shift between them. In other words, the magnitude of the trajectory dependent sizing error depends upon the relative magnitudes of the reflected and refracted components and their individual phase shifts. By changing the laser beam intersection angle, it is possible to change the phase of the reflecting and refracting components, and; hence, the spatial frequency of the scattered interference fringe pattern.

The effect of changing the beam intersection angle was further investigated analytically and experimentally. A stream of monodispersed drops was directed on precise trajectories through the sample volume in these experiments. The trajectory of the drops relative to the beam radius was monitored using a video camera. These studies showed that with the proper selection of the optical parameters, the error resulting from the trajectory effect could be eliminated. Figure 4. shows the analytical and experimental results. Note that in this example, the drops used were 0.7 of the beam diameter which is a severe case. Most drops are much smaller than the focused beam diameter. However, it must be emphasized that in the accurate measurements of D30 and the volume flux, the few large drops contribute by far the largest amount to these parameters so these drops must be measured accurately. Generally, the phase Doppler method has been thoroughly researched and the recent studies have served to improve the performance of the system.

Implementation of the Method

The Aerometrics phase Doppler instrument has undergone a great deal of development and is being used effectively in numerous laboratory environments and industrial process control situations. For special applications such as monitoring drop size and number density distributions in test facilities, research and development has been conducted to produce the optimum systems for reliable and efficient data acquisition.

As stated in the previous section, the performance of the method depends heavily upon the attentive design of the optics. For example, the largest possible beam intersection angle is desirable for good resolution and accuracy when measuring small drops. Furthermore, the largest possible receiver aperture or, more accurately, the smallest f# (focal length / lens diameter) should be used. Generally, 30 degree light scatter detection will provide the best performance for the measurement of particles in the size range of 3 to 10,000 µm.

Aerometrics has built instruments both very large optical systems for measurements in large scale facilities such as used for icing studies at Boeing and for the U.S. Army helicopter rotor studies. These large Cassegrain mirror-based optical systems provide good performance while making nonintrusive measurements of particles in the size range of 1 to 500 µm. Compact systems with multiple sensor heads have also been developed for on-line quality control testing and monitoring. Systems have also been built for applications in hostile and corrosive environments.

Most appropriate for the present applications is the fiber optics based systems, figure 5. The use of single mode polarization preserving fibers allows the transmission of the laser beams to a compact probe while keeping the laser in a secure environment. In these systems, the laser beam is directed into the beam preparation module or Fiber Drive. Here, the beam is split into two and one is shifted in frequency. The laser beam wavelengths are then separated to form a four beam matrix. The four beams are steered into the fiber optics couplers. The couplers are used to precisely align the beams to the fibers which have core diameters of approximately 5 µm. At the transmitter end of the fibers, they are arranged in a four beam matrix at the design spacing and secured. A transmitter lens is used to focus the beams to an intersection to form the sample volume.

A large aperture receiver optics are used to collect the scattered light and and focus it through a small aperture. The light is then transmitted to the photodetectors using multimode fibers. This arrangement ensures good immunity from noise and allows ease of protection from moisture damage.

Signal Processing

One of the critical components of the phase Doppler method is the signal processing. The phase Doppler method has the disadvantage of requiring complex signal processing. However, this is outweighed by the advantage that the signal must be a sinusoidal wave which allows exceptional possibilities in discriminating signal from noise. Methods based on the measurement of signal amplitude, for example, do not have this possibility. Over the past decade, the signal processing technology for both LDV and PDPA applications has improved significantly. It is known that, of the methods available, the Fourier transform provides the optimum means for frequency and phase measurements. The Aerometrics Doppler Signal Analyzer (DSA) was designed to incorporate the Fourier analysis for both the frequency and phase measurements. This has significantly improved the performance of the phase Doppler method under conditions of low signal to noise ratio and high flow speed.

The DSA was developed to cover both LDV and PDPA processing tasks over a very wide range of frequencies. With the 160 MHz quadrature sampling (equivalent to 320 MHz sampling frequency), the DSA can process signals with frequencies to 150 MHz which corresponds to maximum flow speeds in the hypersonic range and a turbulence bandwidth to over 100 MHz. The system design incorporates several features that enhance the performance. The system, figure 6, consists of a master oscillator that drives the Bragg cell, the calibration laser diode, the mixers, and the analog to digital converters. Using a single frequency sources ensures that even extremely small errors are subtracted out of the system. In the electronics, the Doppler burst signal shown in the inset on the figure is high pass filtered to remove the Gaussian pedestal from the signal to leave a symmetric burst signal also shown in the inset. The signal is then mixed in quadrature with a sine wave to reduce the frequency. The high "sum" frequency is then removed by filteringwith a low pass filter and the signal is sampled with a high speed ADC. These sampled signals are then sent to the computer to be processed with the discrete Fourier transform in array processors.

Burst detection and centering is the first function of the system. This is one of the essential functions since with particle sizing, there is a very large dynamic range in signal amplitude and consequently, in the SNR between the largest and smallest particles. Failure to detect and measure the signals from the small particles reliably can seriously bias the measurements. The DSA uses both the signal power in the time domain and the SNR in the frequency domain for burst detection. Time domain burst detection is the conventional approach wherein the signal is rectified and essentially squared and then a threshold is used to detect the burst when the voltage rises above the threshold level. This approach works well when the SNR is greater than about 5 dB. The method will fail to efficiently detect the burst signals at lower SNR.

Recently, we have developed an innovative approach to burst detection using the Fourier transform (patent pending). The incoming signal is continuously sampled with this method irrespective of whether a Doppler burst signal is present or not. A 16 point discrete Fourier transform (DFT) is performed on the record at a maximum rate of 20 million DFT's per second. Thus, no part of the incoming record is missed. The SNR values of these DFT's are compared to a preset level in real time to determine if a coherent signal was present. Burst detection occurs based on the SNR exceeding this level. The method has the significant advantage of being independent of the background noise amplitude that may result from flare light and it is also independent of the signal amplitude. This is important in particle sizing where the signal amplitude varies with the particle size. The method can reliably detect Doppler burst signals even when the SNR is below 0 dB. Furthermore, the signal frequency is determined to sufficient resolution with the burst detector, so that signal frequencies corresponding to velocities outside the selected range can be ignored. Hence the burst detector can perform a filtering function. The burst detector does not require adjustment as the measurement conditions change as in the case of the time domain burst detector which helps to simplify the operation of the instrument.

Evaluations were made using simulated and real Doppler burst signals. In these studies, the SNR (recorded after filtering the signal) was decreased in steps and the data rate measured. The frequency measurements remained accurate to within 0.2 % throughout the range of SNR. Note that in figure 7, the time domain burst detector validation rate drops rapidly for SNR below 5 dB. On the other hand, the FTBD validation does not begin to fall until the SNR drops below -5 dB. This shows the remarkable improvement in detecting the Doppler burst signals with the FTBD.

Volume Flux and Number Density Measurements

Perhaps the most difficult task has been to achieve acceptable accuracy in the measurement of the volume flux and the drop number density. Both quantities depend upon the accurate definition of the sample volume. For example, the volume flux is given by

$$F = \frac{\pi}{6} D_{30}^{3} \frac{N}{At}$$

where N is the number of drops measured and A is the probe area. Previously, the sample volume was determined using the measured diameter of the beam waist and the length along the beam delineated by the receiver aperture. Because of the Gaussian beam profile, the effective diameter of the sample volume will change with the particle size. That is, small particles must pass closer to the high intensity center of the beam than larger particles to produce a detectable signal. This behavior can also be predicted using the fact that the beam intensity profile is Gaussian. Because of this behavior, the measured variation in the sample volume size must be used to correct the size distribution. The problem of determining the sample volume size accurately is further exacerbated by attenuations of the beam and scattered light resulting from the intervening drop field and windows, if any. For this reason, Aerometrics has developed an in situ means for measuring the probe volume size.

The diameter of the sample volume can be measured by measuring the transit times for particles in each size class. Reliable measurement of the transit time requires reliable burst and burst length detection which has been achieved with the FTBD. A statistical distribution of particle trajectory lengths through the probe volume are computed by taking the particle velocity times its transit time and these results are accumulated for each drop size class. The maximum measured lengths in each distribution indicates particles that passed through the diameter of the probe volume and; hence, can be used as a measure of the diameter. These results are then fit with the theoretical curve and used to estimate the probe volume size and the correction needed to make the sampling probability the same for all size classes.

The probe length is also a significant parameter in defining the sample volume size. This length is delineated by the aperture in the receiver, the magnification of the receiver and the off-axis light detection angle. Although high quality air-spaced triplet lenses are used in the receiver, there is a degree of blur in the image of the drops formed on the aperture. Clearly, the cutoff of the particles by the aperture will also depend on the size of the drop. A larger drop passing just outside the slit image across the beam may still produce a detectable signal. Smaller particles passing on the same trajectory will not be detected. This bias has not been addressed previously and may be the cause of the variance observed in the number density and flux data. Analysis of this effect is currently being carried out.

3.0 Validation of the Results

Evaluations of the Particle and Velocity Measurements

Over the past decade, the Aerometrics Phase Doppler Particle Analyzer has undergone very extensive tests to prove its reliability and accuracy while performing measurements under a wide range of conditions. The most basic approach used in the calibration and testing of the instrument is the monodispersed drop generator. This device produces a laminar jet of water at a precisely set flow rate. A sinusoidal disturbance at the Rayleigh frequency is imparted to the jet to cause the jet to break up at the excitation frequency to form drops of uniform size. These drops are formed to monodispersed sizes that can be determined to within a fraction of a percent error. Measurements of these drops represents an ideal situation for the instrument and calibration and repeatability of the measurements are most often to within a 1% error bound.

Other means have also been devised for evaluating the measurement accuracy under more realistic conditions. A mixture of classified polystyrene particles (PSL) was used to simulate a particle size distribution that would be representative of a mist has been used. In this case, 4 different sizes were mixed together in proportions by counts that would simulate a particle size distribution. The measurements were made with a standard phase Doppler instrument configured to have a minimum size resolution of +/-0.5 μm. As can be seen from the results, figure 8, the data agree with the expected sizes. The spread in the measurements for each size class is due, in part, to the spread in the PSL samples.

Comparative measurements have also been made to other established techniques. Figure 9 shows a comparison of data obtained in the NASA Lewis Icing Research (IRT) wind tunnel [14]. In this facility, aircraft icing clouds are simulated. A great deal of care has been devoted to the cloud drop simulations and measurements since this facility is a national resource used in the FAA certification process for aircraft. The "calibration" data shown on the plot were obtained with the PMS probes (Particle Measuring Systems). This was the preferred approach until the development of the Aerometrics PDPA instrument. Note that the agreement in the measurements is good except that the PDPA data show smaller median volume diameters at the highest operating pressure. This may be due to the fact that the PDPA is more sensitive to the smaller drops.

In figure 10, comparisons were made to the Malvern instrument that use Fraunhofer diffraction as a means for sizing the drops. This instrument performs a line-of-sight measurement. In order to make comparisons to the point measurements across the spray made with the PDPA, Dodge [15] performed a deconvolution on the measurements using the Abel inversion scheme. As can be seen in the figure, the agreement is excellent providing confidence in the measurement capabilities of both methods.

Evaluations of the measurements in realistic spray environments were conducted using a less direct approach. There is a very high level of confidence in the measurements of the drop velocities. In this capacity, the instrument is simply a laser Doppler velocimeter and as such, is a highly developed technology. The approach used to evaluate the sizing capability was to generate a spray in our two-phase flow wind tunnel and allow it to impinge on a cylinder [16]. The flow along the stagnation streamline can be easily calculated or measured based on particles of less than 5 μm in diameter. Measurements of the drop size and velocity were obtained at stations well upstream of the cylinder and at stations up to the cylinder surface. The drop lag (difference between the local drop velocity and the air flow) will be proportional to the drop mass, figure 11. With the assumption of a suitable drag law, the particle size can be calculated from the velocity lag. These results were compared to the measured drop sizes and found to be in excellent agreement.

This approach is useful in evaluating the instrument under a range of conditions including different drop size distribution, flow turbulence levels, and drop number densities.

Evaluations of the Particle Number Density and Volume Flux Measurements

Significant effort has been devoted to the verification of the number density and volume flux measurements. Experiments that involved measuring the radial distributions of sprays and comparing the integrated volume flux to the flow rate into the nozzle have been used. When these tests were conducted carefully and the atomizer produced a uniform axisymmetric spray, good agreement was achieved. We have also used sampling probes positioned under the measurement point of the PDPA to collect a sample for determining the actual volume flow rate. These results were compared to the PDPA data and sample results are shown in figure 12. In this case, where the direction of the drops was known to be nearly unidirectional, the agreement was excellent. If the drops are in a highly turbulent swirling environment, the results are not always as reliable.

More recent work has been devoted to the further development of the methodologies required for measuring the number density and volume flux in highly turbulent flows [17]. Number density measurements were obtained in various swirling and non-swirling sprays. Comparative measurements of the number density were made using beam extinction and the Beer-Lambert Law along with the size distribution measurement. An example of these results are shown in figure 13.

Liquid water content (LWC) data were obtained at NASA Lewis and compared to their data obtained with other methods. These data are shown in figure 14. Although there is some scatter in the results, the greatest portion of the results falls within a +/-10% error band. It should be acknowledged that the methods used for comparison will also have some variance in their results. Thus, we have further confidence in the potential measurement accuracy for the mass flux.

Summary

The phase Doppler method has evolved as a very useful research tool for spray characterizations. The drop size distributions are measured directly with this instrument without a need for distribution functions or elaborate and unreliable inversion schemes. Since the measurements are based on the wavelength of the light, the results are not affected by the intervening spray environment. Another significant advantage of the system is that it does not need calibration after leaving the factory. The optical systems have been designed to cover a wide range of applications from small compact probes to large systems for long range measurements. Signal processing based on the Fourier transform has led to a significant improvement in the instrument performance especially when conducting measurements in difficult environments.

The theoretical analysis of the technique has been thoroughly researched over the past ten years and the parameters affecting the measurements are well understood. There remain some special cases such as the measurement of slurries and other multi-phase drops that require additional study.

The measurement accuracy of the method has been evaluated by a number of researchers and found to be better than required for most research applications and for other quality control tasks. The size and velocity measurements have been shown to be exceptionally reliable. Measurements of the number density and volume flux have not always been as satisfactory. However, a combination of developments in both the signal processing electronics and the software algorithms have led to some significant improvements in this area.

Acknowledgements

The phase Doppler method was developed and evaluated under an original contract from NASA Lewis Research Center, Mr. Jack Oldenburg, Contract Monitor and later, with additional support from the Air Force Office of Scientific Research, Dr. Julian Tishkoff, Contract monitor. We will always be grateful for this support that resulted in a very successful instrument for spray research. The National Science Foundation has also supported advances in the method that have expanded the range of applications to spray combustion.

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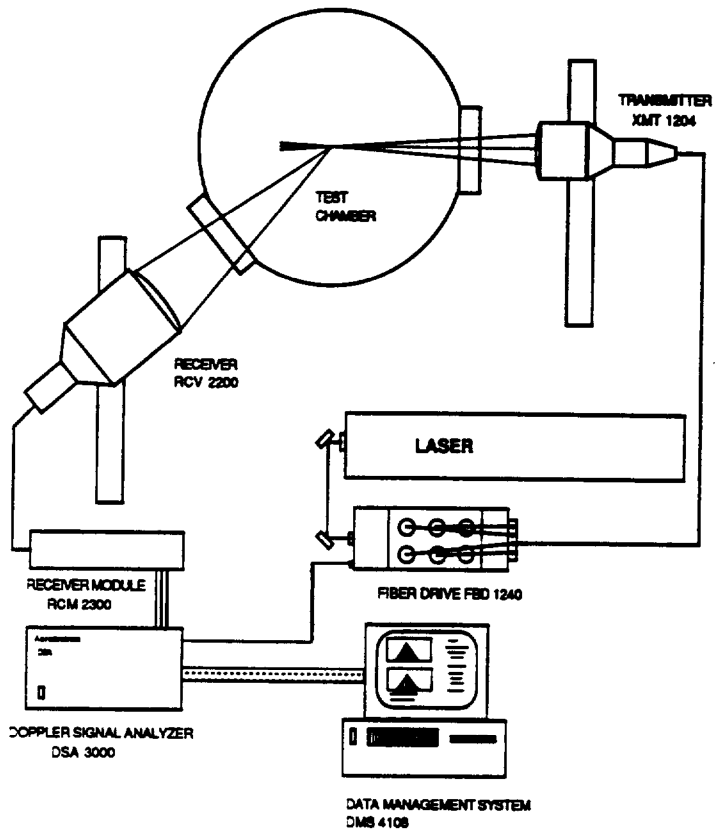


Figure 5. Schematic of the Two-Component Phase Doppler Particle Analyzer Using Single Mode Polarization Preserving Fibers on the Transmitter, Multimode Fibers For the Receiver, and the Advanced Fourier Transform Signal Processor, DSA.

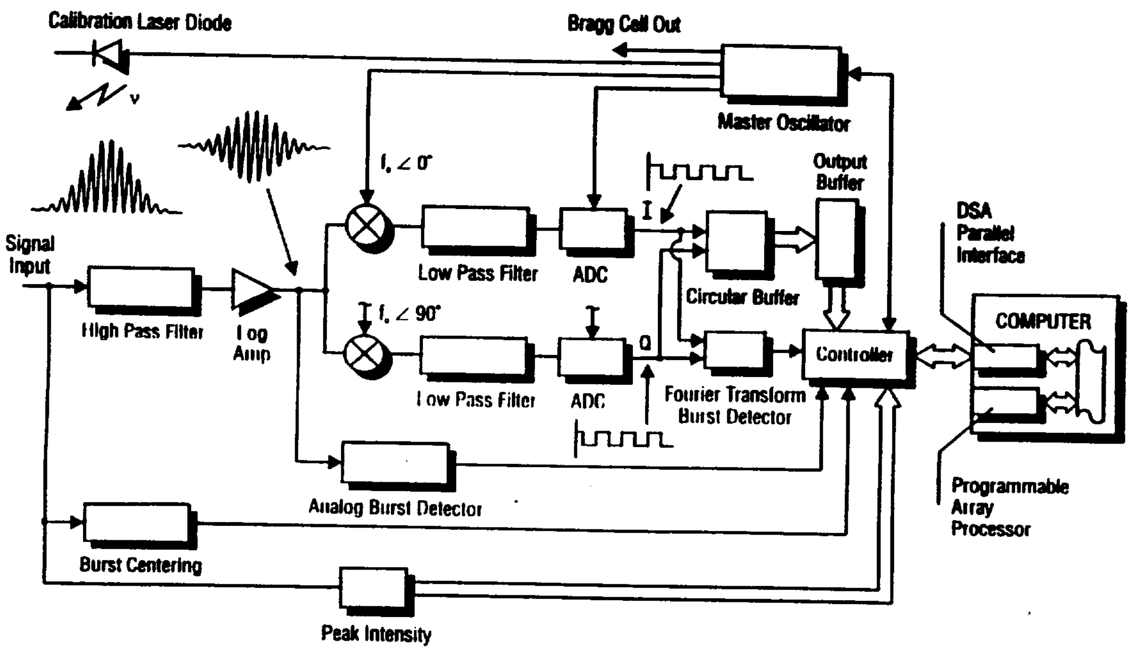
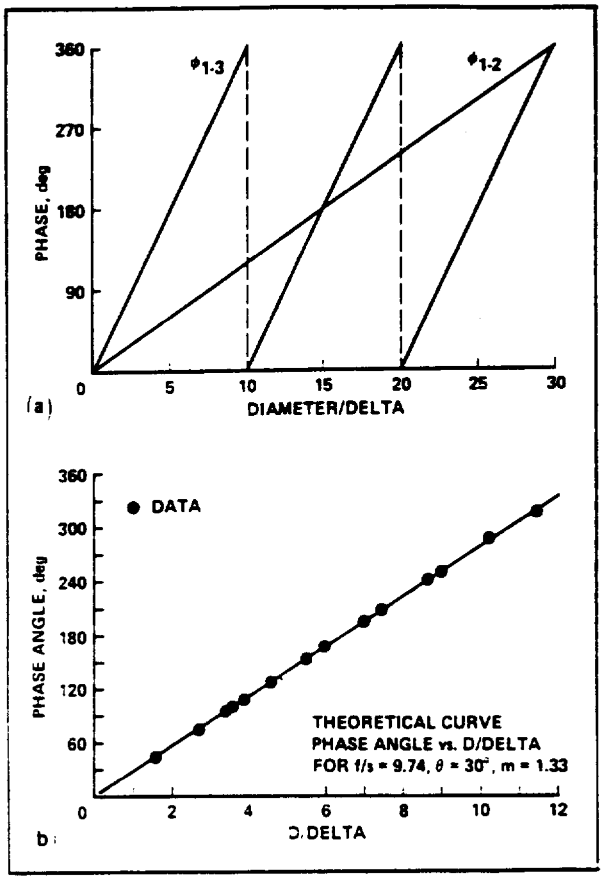


Figure 6. Block Diagram of the DSA Fourier Transform Signal Analyzer (DSA) Showing the Signal Filtering, Down Mixers, Analog-to-Digital Converters, and the Burst Detection System.



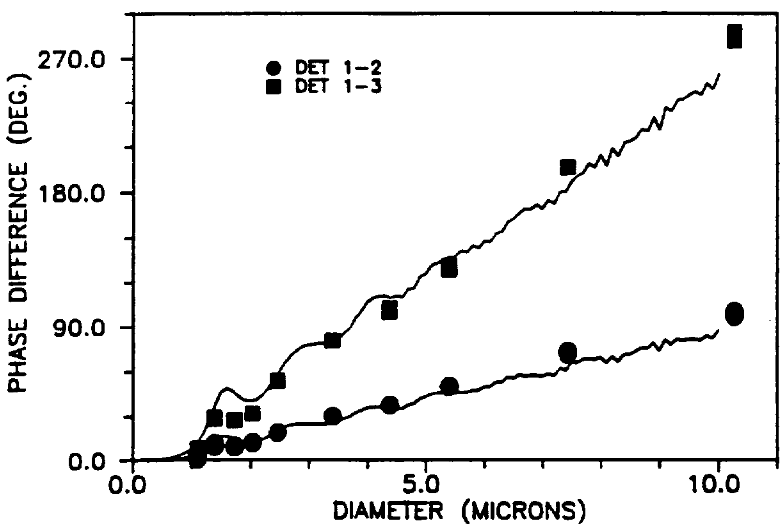
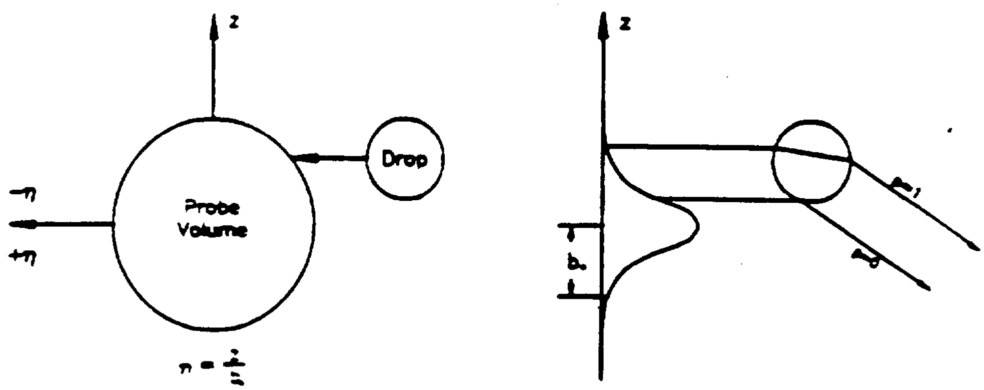


Figure 3. Theoretical Prediction Showing the Phase Variation With the Dimensionless Drop Size: (a) Relationship for Three Detectors and (b) Comparisons With Experiment for Very Small Particles, (c) Comparisons Using a Dimensionless Size Format.



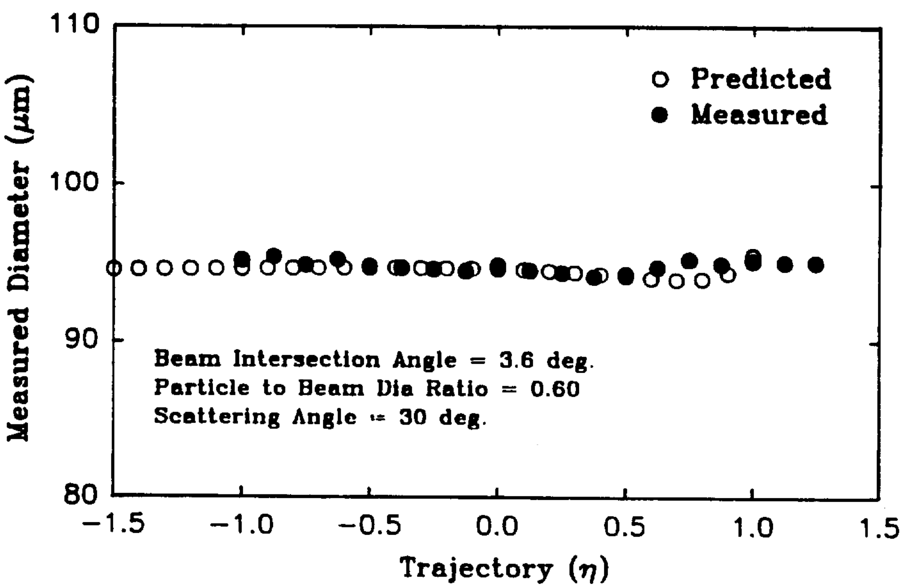


Figure 4. Analysis of the Trajectory Dependent Light Scattering Showing a Schematic of the Particle Trajectory Through a Gaussian Beam, the Light Scattering Mechanisms of Reflection and Refraction Involved, and the Improvement Using a Larger Beam Intersection Angle.

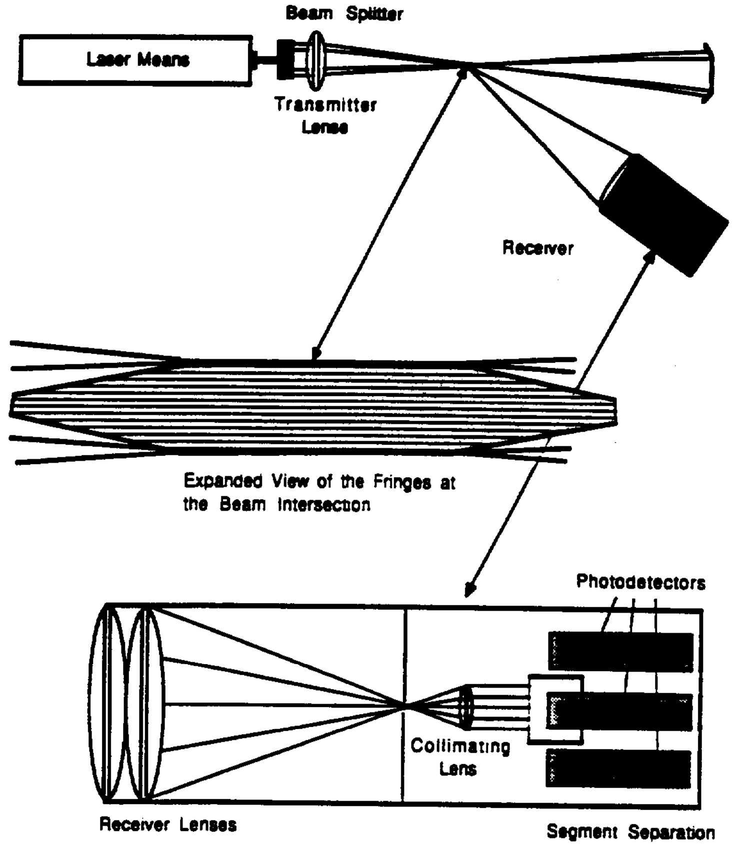


Figure 1. Schematic of a Basic Phase Doppler Optical System showing the Transmitting and Receiving Optics, the Fringe Pattern Formed at the Beam Intersection, and the Construction of the Receiver with the Segmented Lens and the Three Detectors.

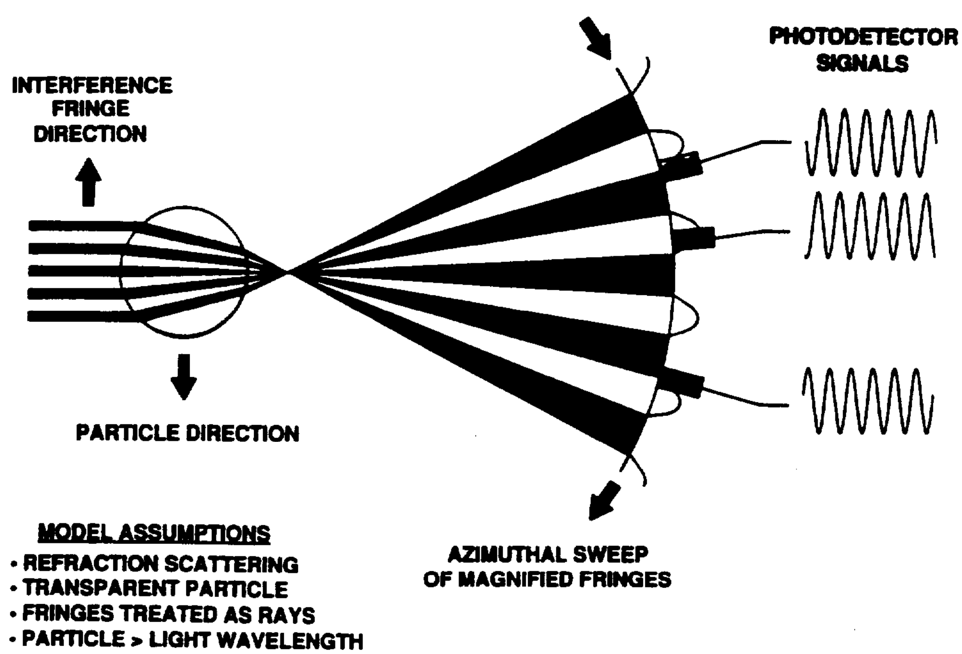


Figure 2. Diagram Illustrating the Method With the Fringe Model Where a Fringe Pattern is Formed at the Sample Volume and the Drop Projects the Pattern to the Receiver.

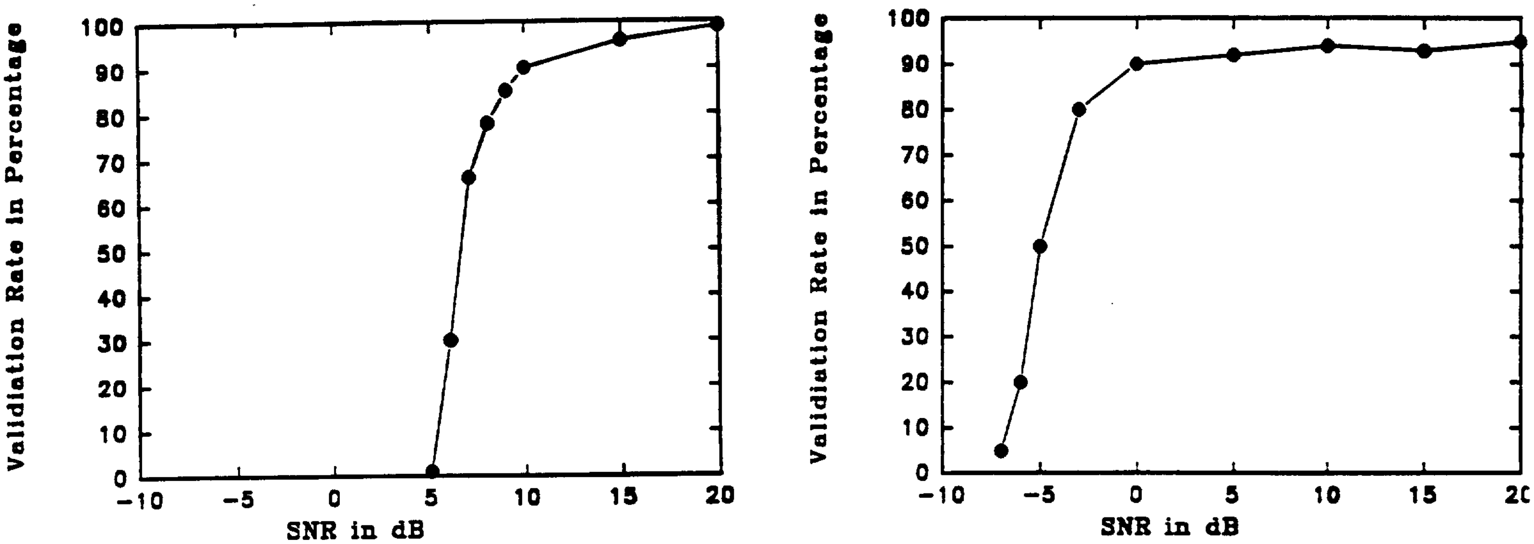


Figure 7. Plots Showing the Performance Comparison Between the Conventional Analog Burst Detector and the New Fourier Transform Burst Detector Indicating How Reliable the Method Is Even at Low Signal To Noise Ratios.

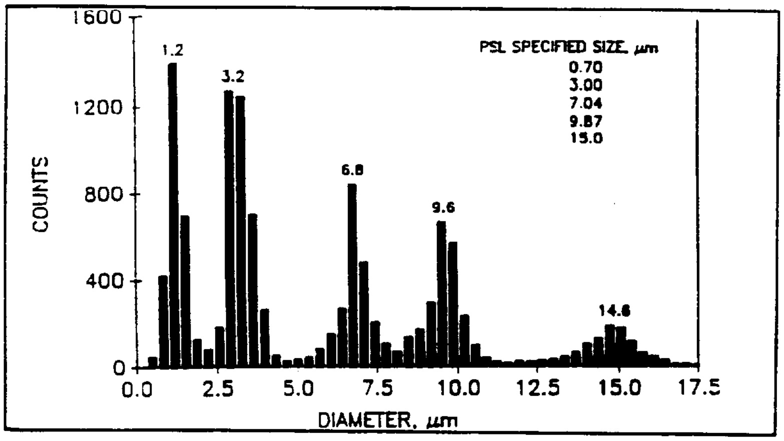


Figure 8. Validation of the PDPA Particle Size Measurements Using a Mixture of Polystyrene Particles of Five Known Sizes and In a Proportion to Simulate a Size Distribution.

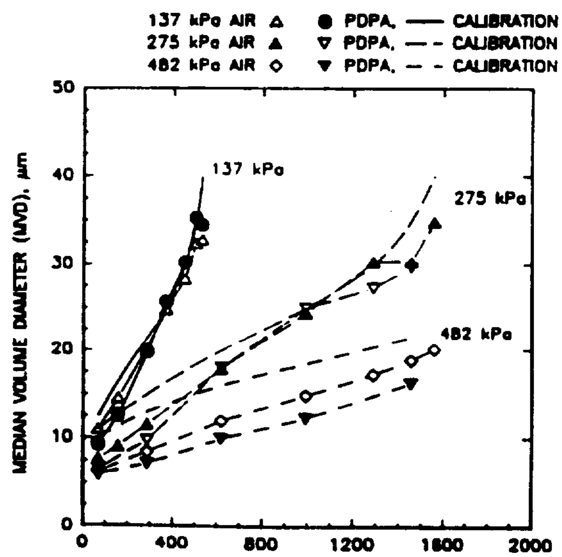


Figure 9. Validation of the PDPA By Way of Comparison to Measurements Obtained With a PMS Instrument For Data Obtained in the NASA Lewis Icing Research Wind Tunnel.

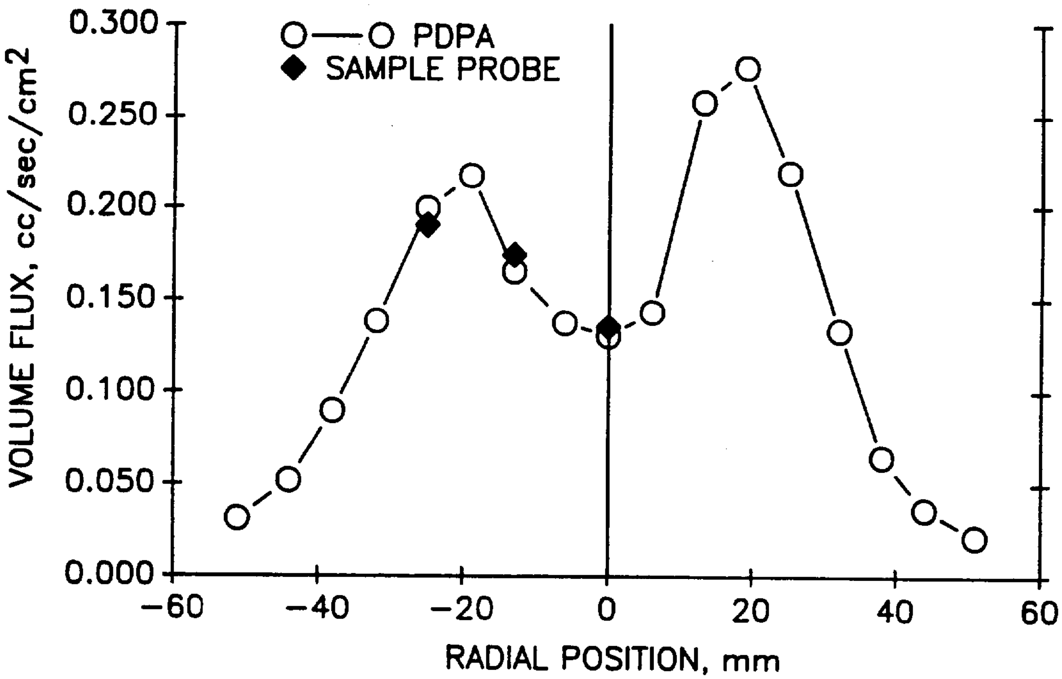


Figure 12. Volume Flux Measurements of a Spray With Measurements Compared to Sampling Probe Data.

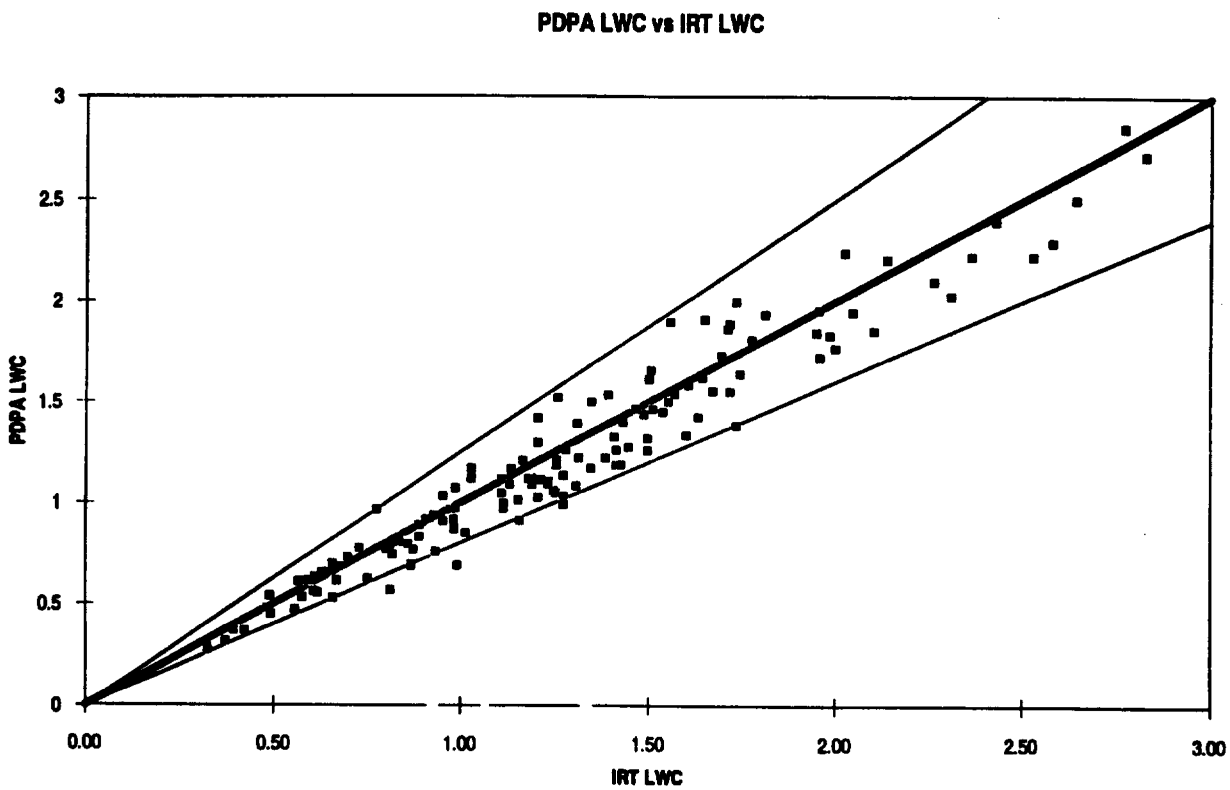


Figure 13. Liquid Water Content (LWC) Data Obtained in the NASA Lewis Icing Research Tunnel With the PDPA and Compared With Other Methods For Obtaining These Data.

Evaluation and Optimization of an On-Board Water Spray Fire Suppression System in Aircraft

RICHARD G. HILL
TIMOTHY R. MARKER
CONSTANTINE P. SARKOS
Federal Aviation Administration Technical Center
Atlantic City International Airport, New Jersey 08405

ABSTRACT

This paper describes a series of full-scale fire tests to evaluate and develop an on-board aircraft cabin water spray system against postcrash fires. The initial system consisted of an array of nozzles, at the ceiling, which continuously discharged water throughout the cabin for 3 minutes. Several fire scenarios were examined, including a wind-driven external fuel fire adjacent to a fuselage opening and a quiescent fuel fire impinging upon an intact fuselage. Also, both narrow-body and wide-body test articles were utilized. An analysis of the hazard measurements using a fractional effective dose model indicated the water spray provided approximately 2-3 minutes of additional survival time for all but the most severe scenario tested. Additionally, a zoned water spray system was conceptualized, designed and tested under full-scale conditions in an attempt to reduce the weight penalty of water. Test results indicated that a zoned system may be designed to give more protection and improved visibility than a continuous spray system with approximately 10 percent of the water.

1. INTRODUCTION

Aircraft crash fires are almost always initiated by the ignition of spilled jet fuel. The intensity and size of a postcrash fuel fire presents a complex and severe design threat for the aircraft manufacturers and regulatory agencies responsible for fire safety in transport aircraft. Since the mid-1980's, the Federal Aviation Administration (FAA) has adopted a series of new fire safety standards to enhance postcrash fire survivability (ref. 1). The main focus has been on the improved fire performance of cabin materials. FAA full-scale fire tests have demonstrated that seat cushion fire blocking layers and low heat release panels delay the onset of flashover, providing more time for escape. In addition, it has been shown that heat resistant evacuation slides and floor proximity lighting increase the evacuation rate of passengers.

The FAA has now embarked on a program to develop and evaluate an on-board cabin water spray fire suppression system. The baseline water spray system was designed in the United Kingdom (U.K.) by Safety Aircraft and Vehicles Equipment, Ltd. (SAVE). It basically consists of a large number of small nozzles, mounted throughout the ceiling, which discharge a fine water spray with a mean droplet diameter of about 100 microns for a period of 3 minutes (ref. 2).

The FAA program is comprised of two phases (ref. 3). Phase 1 is essentially completed and was a feasibility study of the baseline SAVE system in terms of the following factors: (1) effectiveness against postcrash fires, (2) potential benefit in past accidents, and (3) adverse impact of an accidental discharge on safety of flight, passengers, and restoration to service. The Phase 1 study indicated that a water spray system is feasible. Phase 2 is underway and includes such tasks as optimization of the system to reduce weight penalty and development of requirements and specifications.

The purpose of this paper is to summarize the results of full-scale fire tests to determine the effectiveness of a continuous discharge cabin water spray system under postcrash fire conditions. In addition, test results on a zoned water spray system to minimize weight penalty are presented.

2. TEST SETUP

The test arrangement simulated a survivable aircraft crash involving fuselage exposure to an external fuel fire. The fire source was an 8- by 10-foot pan of burning jet fuel which had been shown previously to be representative of the severe thermal threat created by a large fuel spill fire. Two types of postcrash fire scenarios were evaluated. The most commonly used scenario located the fuel fire adjacent to a hole (simulated rupture) in the test fuselage the size of a Type A door opening (76 by 42 inches). A variable speed exhaust fan in the front of the fuselage created a draft inside the cabin, allowing the degree of flame penetration through the hole and the resultant severity of the fire inside the cabin to be varied. In the second type of scenario the fuel fire was adjacent to an intact fuselage, and fire penetration into the cabin occurred after penetration or burnthrough of the fuselage shell. Fairly strict control over the fuel fire conditions was maintained because the tests were conducted inside a building, assuring test repeatability.

The tests were conducted in both a narrow-body fuselage and a wide-body fuselage. The former is a surplus B-707 airplane while the latter is a 130-foot-long hybrid consisting of a 40-foot DC-10 section married to a 90-foot cylinder.

3. EFFECTIVENESS TESTS

Narrow-Body Test Article. A plan view of the narrow-body test article is shown in figure 1, indicating the SAVE water spray system nozzle arrangement and location of instrumentation and cabin materials. The water spray system consisted of 120 nozzles which discharged 72 gallons of water over a period of 3 minutes. Instrumentation consisted of thermocouples, smoke meters, gas analyzers, gas sampling equipment, calorimeters, and photo and video cameras. A 24-foot-long section of the test article, centered at the external fire pan, was outfitted with 5 rows of passenger seats, ceiling panels, stowage bins, sidewalls, and carpet. All materials were compliant with the current FAA fire test standards (ref. 1).

A zero ambient wind condition was simulated by not operating the exhaust fan. With the absence (initially) of flame penetration through the fuselage opening, the fire threat was dominated by intense thermal radiation. The results of the zero wind tests, with and without water spray, are shown in figure 2. The shaded curves in this and subsequent figures show the range in measurements at a particular fuselage station. In all cases, the highest readings were at the highest locations, and the readings decreased the closer the measurement location was to the floor. Temperature was measured at 1-foot increments from a location 7 feet high (slightly below the ceiling) to a location 1 foot above the floor. Smoke was measured at three heights: 5 feet, 6 inches; 3 feet, 6 inches; and 1 foot, 6 inches. All gas measurements were at 5 feet, 6 inches and 3 feet, 6 inches.

Figure 2 exhibits a rapid rise in temperature and toxic gas production and a decrease in oxygen concentration at approximately 5 minutes in the test without the water spray. This behavior indicates the development of a flashover condition at 5 minutes. However, when water spray was used, survivable conditions prevailed for the entire 7-minute test duration. The time interval of actual water spray discharge was from 15 seconds until approximately 195-200 seconds into the test. Therefore, in addition to the reduction in cabin fire hazards during the water spray discharge, there were notable improvements in the cabin environment after the discharge was completed.

Survival time was calculated from the measured hazards by employing a fractional effective dose (FED) model developed recently (ref. 4). The model is believed to reflect the current state-of-the-art data in terms of incapacitation of humans subjected to a single toxic combustion gas. It assumes that the effect of heat and each toxic gas on incapacitation is additive. It also assumes that the increased respiratory rate due to elevated carbon dioxide levels is manifested by the enhanced uptake of other gases. The FED plot in figure 2 shows incapacitation at 5 minutes without water spray discharge, corresponding to the time of flashover. Discharge of water spray prevented flashover within the 7-minute test duration and maintained a survivable environment within that increment (FED<0.1 at 7 minutes). Therefore, the increase in survivability provided by water spray discharge was much greater than 2 minutes.

A "moderate" wind scenario was devised, by operating the exhaust fan to induce fuel fire flame penetration through the fuselage opening, in order to create a more severe fire threat than imposed by the zero wind condition. Figure 3 shows the results of those tests. The profiles are quite similar to the zero wind test (figure 2) but are transposed earlier in time by about 2 minutes. Flashover occurred between 150 and 180 seconds without water spray. With water spray, flashover occurred much later (close to 300 seconds) and with a much lower intensity (less temperature rise and gas production). The FED plot shows that the increase in survival time was 215 seconds. Figure 3 also shows the effectiveness of water spray in removing water soluable acid gases such as hydrogen fluoride.

The water spray system was also evaluated against a "high" wind scenario. In this case, the fuel fire flames penetrated across the ceiling practically to the opposite side of the cabin. The fire was so severe that it overwhelmed the water spray, and it became necessary to terminate the test after only 60 seconds. The test illustrated that the benefits of fire safety design improvements are highly dependent upon the fire scenario, and for some scenarios, it is virtually impossible to improve survivability by design changes.

Conversely, the water spray system proved effective against the burnthough scenario. In this case, the fire entered the cabin, at approximately 1 minute into the test, by burning through the floor and sidewall area. FED analysis indicated that 132 seconds of additional survival time was provided by the water spray system.

Wide-Body Test Article. Installed inside the wide-body test article, the SAVE system consisted of 324 nozzles arranged in 5 rows along the length of the fuselage, discharging 195 gallons of water over a period of 3 minutes. The fuel fire conditions, instrumentation, and arrangement of interior materials were similar to the narrow-body test article setup. Again, there were 5 rows of interior materials centered about the fire door, which was located at fuselage station 940 (78 feet from the front of the fuselage). Of course, the quantity of interior materials was far greater; e.g., 9 seats across/double aisle in the wide-body versus 5 seats across/single aisle in the narrow-body.

A "moderate" wind condition, causing fuel fire flame penetration through the fuselage opening, was utilized to evaluate the effectiveness of water spray in the wide-body test article. Figure 4 shows the results of those tests. As in the narrow-body tests, significant reduction in cabin temperatures and toxic gas levels were evidenced during the water spray test. Of some concern is the light transmission profiles reflecting the loss in visibility due to smoke. For more than half the test duration, because the water spray tends to lower and distribute the ceiling smoke layer, there is a greater reduction in light transmission while the water is being discharged. Apparently, the amount of smoke particulate removal or "washing out" by the water spray is more than offset by the lowering of the smoke layer. Later, however, the reduction in light transmission with an unabated fire becomes more significant.

The FED curve indicates a loss of survivability at 215 seconds without the water spray system. Examination of the temperature and gas levels, particularly oxygen concentrations (not shown), indicates the onset of flashover at about 210 seconds. With water spray, flashover was prevented over the 5-minute test duration and the cabin environment (away from the fire source) remained survivable. On the basis of the FED calculation, the improvement in survival time was 85 seconds at the end of the test (5 minutes) but would likely have been considerably longer, perhaps 2-3 minutes, had the test not been terminated.

4. SYSTEM OPTIMIZATION

Because of payload, weight penalty is an overriding consideration in aircraft design. The weight penalty associated with the SAVE system is somewhat excessive, if not prohibitive. Therefore, a zoned water spray system for the expressed purpose of weight reduction was conceptualized, designed, and tested.

The zoned concept divides an airplane into a series of water spray zones. Discharge of water within each zone is independent of the other zones and triggered by a sensor within the zone. In this manner the quantity of water discharged is dictated by the presence and spread of fire, eliminating the ineffectual and wasteful discharge of water away from the fire as in the SAVE system (ref. 5).

A zoned water spray system design has been tested in the narrow-body test article. Each zone is 8 feet in cabin length. Four spray nozzles are mounted at the cabin periphery in each of the two boundary planes, with the spray discharge directed toward the center of the zone. Specifically, each nozzle is mounted perpendicular to the supply line and at a 45° angle with the vertical traverse plane (figure 5). Testing to date has been limited to 5 zones, centered about the fire door, comprising approximately 1/3 of the cabin length. Based on preliminary tests, a temperature of 300 °F was selected to activate water discharge (manually). The temperature is measured at the centerline of the zone, about 6 inches below the ceiling. The water supply line from the storage tank is charged with water up to a separate solenoid valve connected to each zone, mounted as close as possible to the zone, in order to minimize lag times and line losses. The plumbing inside the test article is initially dry.

Since the zoned system comprised approximately 1/3 of the test article, the initial series of tests utilized 24 gallons of water (versus 72 gallons for the SAVE system). In effect, the tests were simulating a system failure causing 2/3 of the water supply to be unavailable. Three types of nozzles were evaluated: low, 0.23 gallons per minute (gpm) (SAVE nozzle); medium, 0.35 gpm; and high, 0.50 gpm. A more severe simulated wind condition than employed previously was used as a test condition (external fuel fire/fuselage opening scenario).

The calculated FED profiles from the initial series of optimization tests are shown in figure 6. The SAVE water spray system increased the survival time by 110 seconds. More importantly, the medium and high flow rate nozzles, discharging a total of only 24 gallons of water, increased the survival time beyond the SAVE system by about 55 seconds and 35 seconds, respectively. The improvement provided by the higher flow rate nozzles is apparently due to the application of larger quantities of water where it is needed most--in the immediate fire area. An interesting result is that the medium flow rate nozzles provided more protection than the high flow rate nozzles. A possible explanation is that the discharge time was longer with the medium flow rate nozzles; i.e., 180 seconds versus 140 seconds.

A second series of tests was undertaken to evaluate the impact of an even smaller supply of water. Eight gallons, or 1/9 the SAVE system total, was selected for examination. Figure 7 compares the FED profiles for the low and medium flow rate nozzles at 24 and 8 gallons of water. Figure 8 presents the temperature and carbon monoxide histories for these four tests. In figure 7 it is noteworthy that the survival time is 50 seconds <u>greater</u> at 8 gallons than at 24 gallons for the low flow rate nozzles. Also, the survival times are about equal for the medium flow rate nozzles for both water quantities and are greater than the low flow rate nozzles.

It is difficult to explain the longer survival time at 8 gallons, as compared to 24 gallons, for the low flow rate nozzles. Analysis of the data and the FED calculations indicate the higher levels of CO in the 24 gallon test (figure 8) and the dominant effect of CO in the FED model caused the smaller survival time. What caused the CO levels to be higher in this test is not completely clear. It may be that the longer discharge time at 24 gallons cooled and lowered the smoke layer enough to raise the CO levels at 5 feet, 6 inches. Additional tests are required to analyze these effects. What is clear and most important, however, is that relatively small quantities of water in a zoned system provide a significant improvement in survival time compared to a system that discharges water simultaneously throughout the cabin. For example, 8 gallons of water with a zoned system and medium flow rate nozzles provided a 55-second longer survival time than the SAVE system, which requires 72 gallons of water.

A zoned system test with 4 gallons of water was conducted to determine whether this relatively small quantity of water could be effective against a postcrash fire. Figure 9 compares the FED calculations for zoned system tests at 4, 8, and 24 gallons, using medium flow rate nozzles, with the baseline test without water and with the SAVE system test. Even with only 4 gallons of the water, the zoned system was effective; however, the additional escape time was less than with the zoned systems employing larger quantities of water or with the SAVE system. Nevertheless, it is impressive that such a small quantity of water can provide a finite improvement in survival time at all.

Improved visibility is another advantage of a zoned water spray system. As discussed earlier, continuously discharging water throughout the airplane tends to disrupt the concentrated smoke layer located at the ceiling and redistribute the smoke throughout the distance from the ceiling to the floor. With a zoned system the disruption of the smoke layer is primarily confined to the spray zones. Outside of the spray zones it appears that the smoke restratisfies, forming a distinct smoke layer, with improved visibility below the smoke layer. Figures 10, 11, and 12 show the light transmission measurements for selected zoned system tests compared with the baseline test without water and with the SAVE system test, at a height of 5 feet 6 inches, 3 feet 6 inches, and 1 foot 6 inches, respectively. The improvement in visibility (greater light transmission) provided by the zoned system is evident in these figures. Also, it is interesting that the amount of improvement becomes greatest at the lowest cabin heights.

A total of 9 water spray zoned tests were conducted, employing 4 water quantities and 3 nozzle flow rates. The results are summarized in figure 13 in terms of the additional available escape time beyond the baseline test without water discharge. The results of the SAVE test are also shown (108 seconds additional escape time). Each of the zoned tests indicated a significant improvement in the additional escape time, which was greater than the improvement with the SAVE system in 5 of the 9 cases.

The effectiveness of a water spray system per unit gallon of water discharged, or its efficiency, may be defined as the ratio of the additional available escape time to the quantity of water discharged. This efficiency is designated SPG, an abbreviation for its units, seconds per gallon. Figure 14 compares SPG for the various water spray configurations on the basis of nozzle flow rate. From figure 14 it is evident that the optimum nozzle type is the medium flow rate nozzle (0.35 gpm) and that the optimum zoned water spray configuration is a water quantity of 8 gallons. The optimum zoned water spray system (SPG = 20.4) is a factor of 13.6 more efficient than the SAVE water spray system (SPG = 1.5). It is significant that as much as 20 seconds of additional available escape time may be achieved by a water spray system, operating effectively in a postcrash fire environment, where each second of available escape time is critical.

5. SUMMARY

Full-scale fire tests demonstrated the effectiveness of an on-board water spray system, comprised of an array of ceiling nozzles, discharging water throughout an airplane cabin for 3 minutes. Approximately 2-3 minutes of additional survival time were provided for several postcrash fire scenarios in both narrow-body and wide-body test articles. Additional full-scale tests demonstrated that a zoned system, designed to discharge water at 300 ^{o}F in each zone, may provide even more protection with only about 10 percent of the weight of water.

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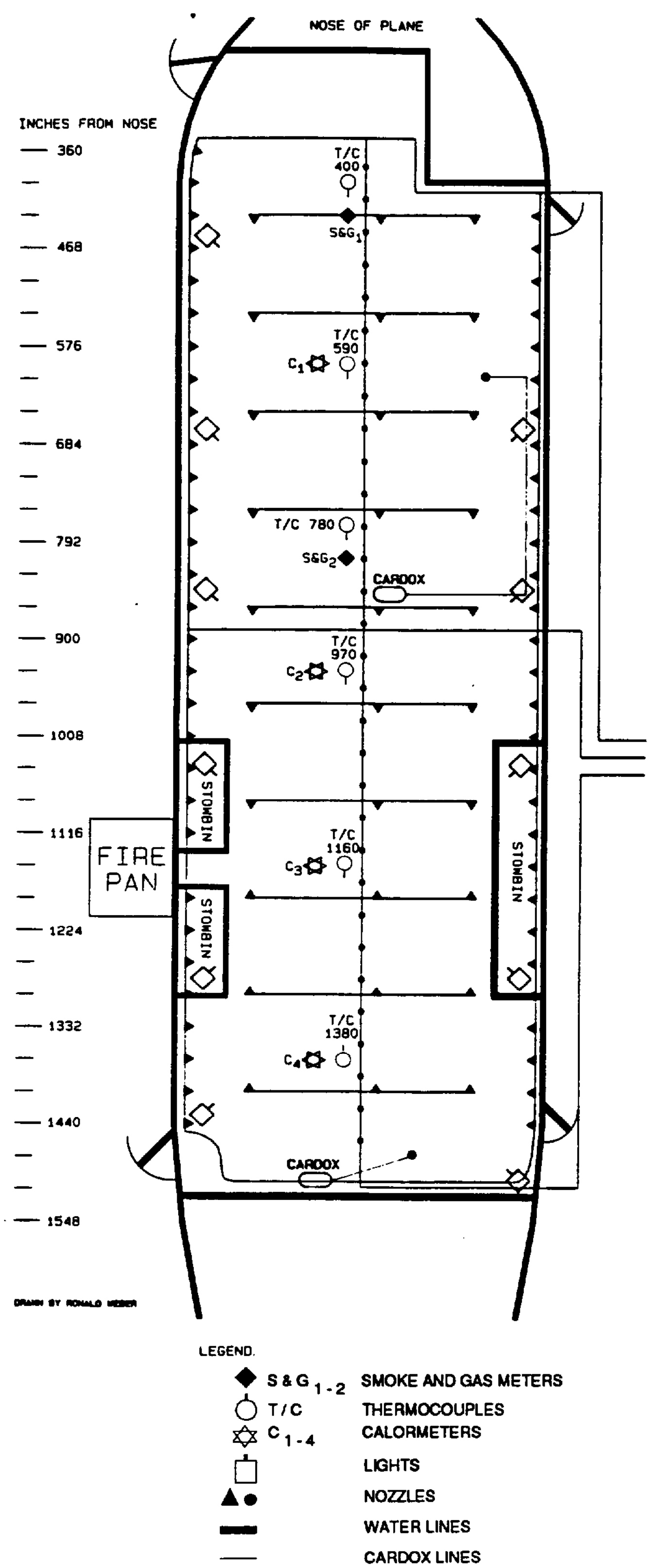

FIGURE 1.
NARROW BODY TESTCONFIGURATION

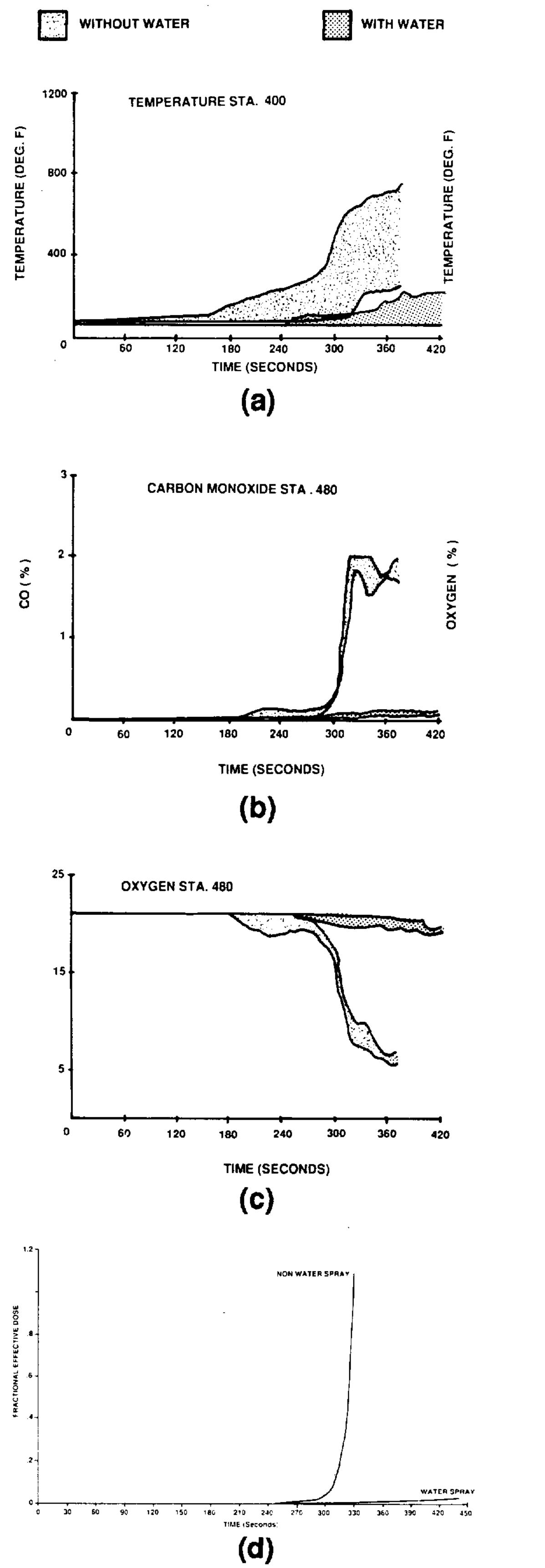

FIGURE 2.
NARROW BODY RESULTS/ SAVE SYSTEM/ ZERO WIND/ FUSELAGE OPENING

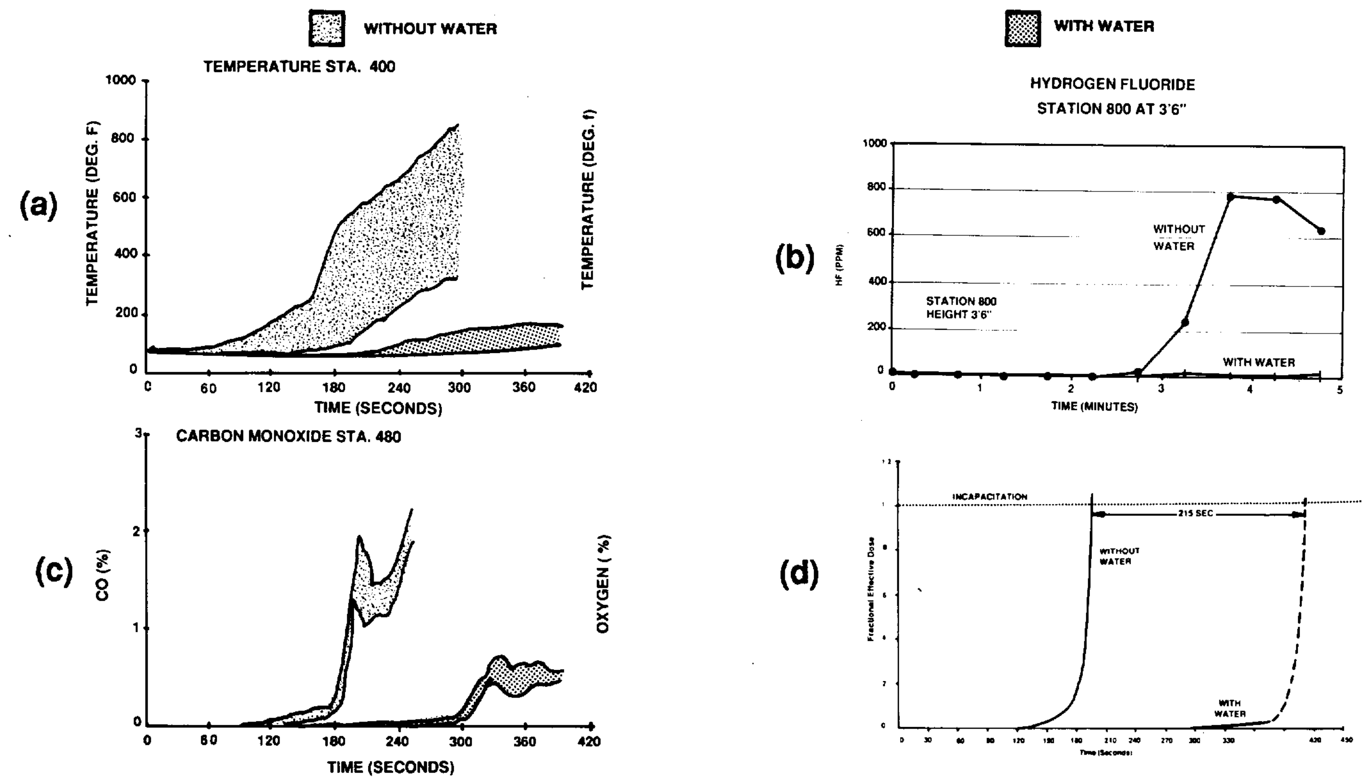

FIGURE 3.
NARROW BODY RESULTS/ SAVE SYSTEM/MODERATE WIND/FUSELAGE OPENING

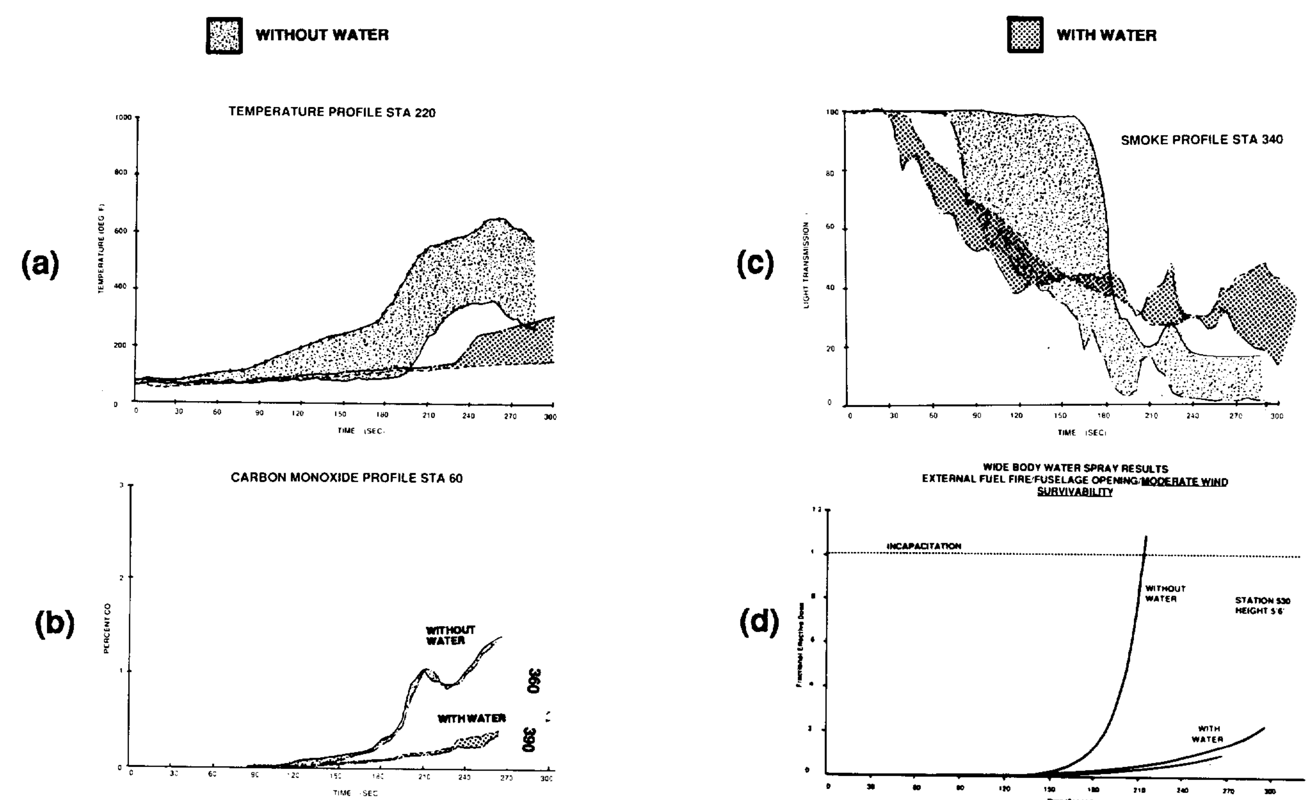

FIGURE 4.
WIDE BODY RESULTS/ SAVE SYSTEM/MODERATE WIND/FUSELAGE OPENING

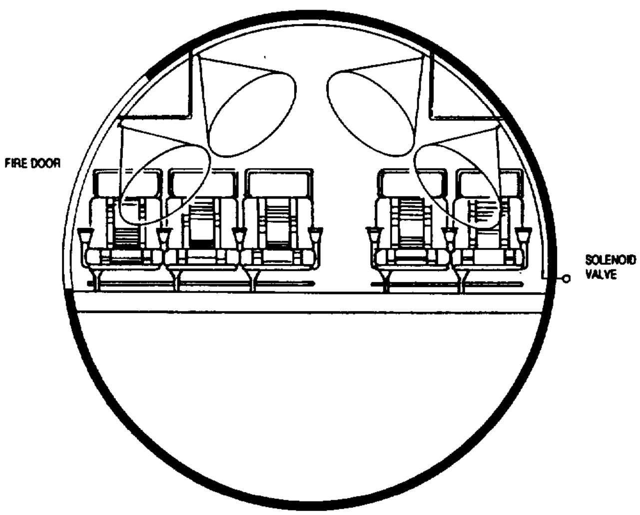

FIGURE 5.
ZONED SYSTEM DISCHARGE PATTERN

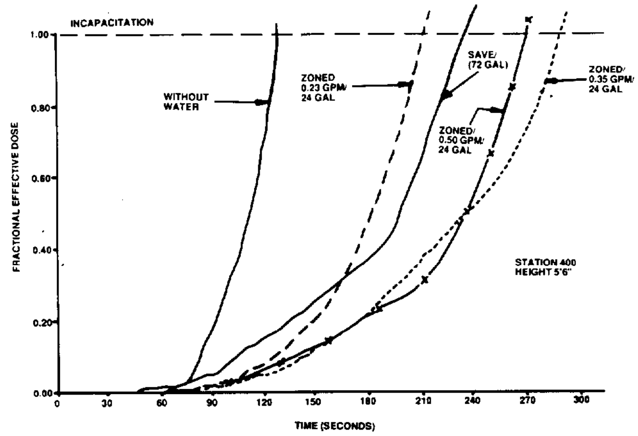

FIGURE 6.
ZONED SYSTEM SURVIVAL TIME IMPROVEMENT 24 GALLONS

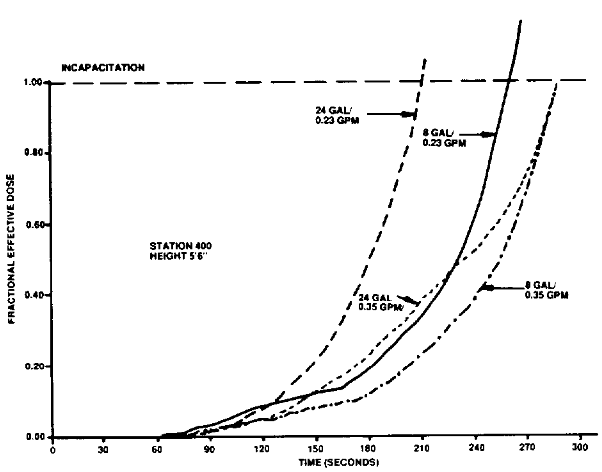

FIGURE 7.
ZONED SYSTEM SURVIVAL TIMES/24 AND 8 GALLONS

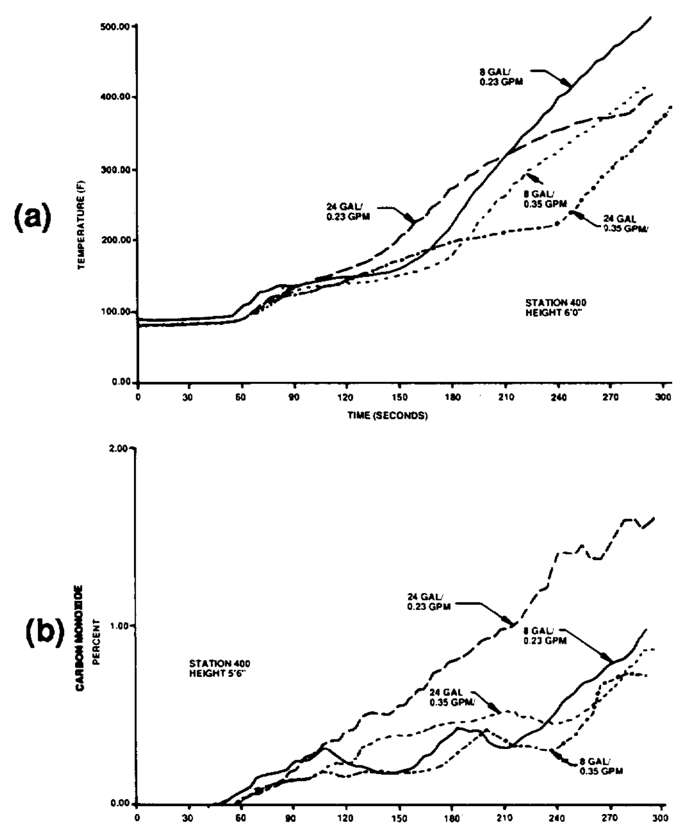

FIGURE 8.
ZONED SYSTEM/TEMPERATURE AND CARBON MONOXIDE RESULTS/24 AND 8 GALLONS

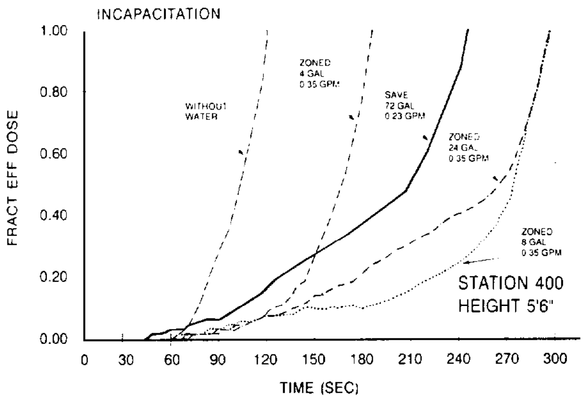

FIGURE 9
ZONED SYSTEM SURVIVAL TIME IMPROVEMENT / 4, 8 AND 24 GALLONS

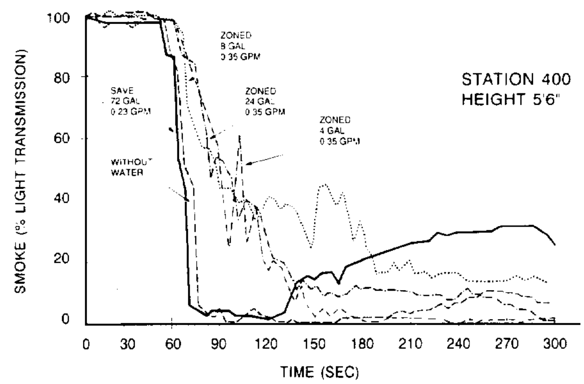

FIGURE 10
ZONED SYSTEM SMOKE OBSCURATION IMPROVEMENT / HEIGHT = 5' 6"

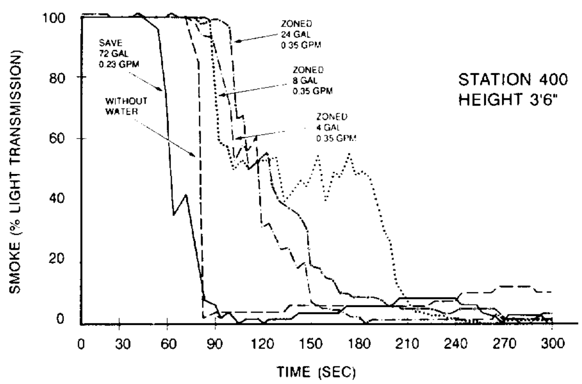

FIGURE 11
ZONED SYSTEM SMOKE OBSCURATION IMPROVEMENT / HEIGHT = 3' 6"

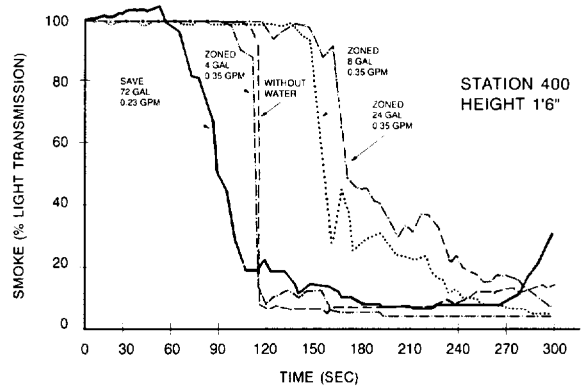

FIGURE 12
ZONED SYSTEM SMOKE OBSCURATION IMPROVEMENT / HEIGHT = 1' 6"

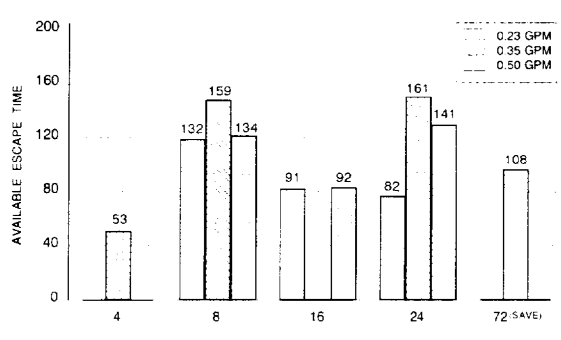

FIGURE 13
ZONED SYSTEM AVAILABLE ESCAPE TIME

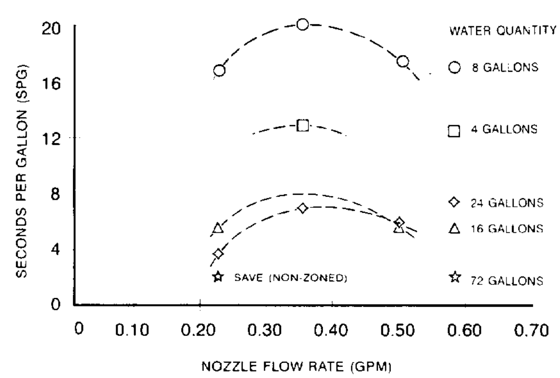

FIGURE 14
ZONED SYSTEM OPTIMIZATION

WATER MIST IN MARINE APPLICATIONS

Antony R.F.Turner
Marioff Hi-fog Oy,
P.O. Box 25, SF-01511 Vantaa, Finland.

SUMMARY

This paper is designed to present an up-to-date picture of practical applications for water mist / fog fire fighting technology in marine markets. The paper will introduce the reasons for the development of the technology, discuss the test program undertaken by Marioff and highlight the insights this has provided concerning the firefighting capability of water fog systems. Practical applications in the marine markets for accommodation areas, engine rooms and other spaces will be given with reference to the actual ships on which Hi-fog systems have been fitted. Land based uses will also be discussed, with references to systems installed or on order.

1. INTRODUCTION

Marioff have for eight years specialised in the development and supply of innovative high pressure hydraulic products to the offshore and marine markets. Service companies within the group have been responsible for testing, flushing and commissioning high integrity systems such as subsea control packages and complete offshore platform oil piping systems.

The high incidence of arsonist fires on passenger ships culminating in the "Scandinavian Star" disaster off Denmark, when over 150 people lost their lives, recently prompted the International Maritime Organisation (IMO) to require all passenger ships to have sprinkler systems fitted in the accommodation areas by 2005 or earlier. The need to quickly develop a lightweight sprinkler system that could be practically retrofitted to a passenger ship was apparent, and in 1991 Marioff became involved in the development of a high pressure water fog sprinkler system specifically designed for this application. Due to the small pipe sizes of a high pressure system, installations including the water filled pipework have typically been 10% of the weight of a conventional sprinkler system according to current SOLAS rules, and installation is much quicker and less expensive.

The rapid phasing out of Halon use for environmental reasons prompted IMO to prohibit the installation of Halon on new vessels since July last year. The need to develop alternative safe and environmentally friendly fire extinguishing methods for ships' engine rooms led Marioff to develop a suitable water fog extinguishing system for machinery spaces.

Two years of intensive development work, including over 400 fire tests at internationally recognized testing laboratories, has resulted in approval of Hi-fog systems by European Authorities including the UK Department of Transport and major Classification Societies including Lloyds Register and American Bureau of Shipping. Systems have been, and continue to be, installed in Europe and Scandinavia. (See Table 1.)

The development of this technology for marine applications has also recently led to many practical uses on land based special hazard situations. (See Table 2.)

2. BACKGROUND

The efficient fire suppressing effect of fine water fog or mist has been recognized for many years. This suppression is due to the large total surface area of the droplets and the high rate of speed at which they turn to steam, thus absorbing the energy of the fire. The average droplets contained in a water fog yield a total surface area at least 100 times greater than conventional sprinkler drops for the same water volume. Therefore much smaller amounts of water are required by fog to absorb energy from the fire. See Table 3.

Practical use of water fog / mist in fire protection has been restricted to very few applications such as extinguishing fires in chimneys. One of the reasons for not bringing water fog systems to the market has been the difficulty in combining the small water droplet size with efficient penetration of flue gases. Although water fog or mist is extremely efficient at air cooling (and therefore absorbing energy in the combustion area) compared to conventional sprinklers or water spray systems, the light weight of the droplets has made it impossible to penetrate the flue gases produced by even a moderate combustion source.

Marioff has overcome this problem by using experience gained with high pressure hydraulic technology. By forcing water at high pressure through specially developed nozzles arranged on spray or sprinkler heads, a water fog is propelled at a speed high enough to penetrate the flue gases of even a flashover fire.

As well as fire tests, droplet size measurements have been made, which suggest that droplet size distribution is an important factor.

The combination of correct water droplet size, distribution and high speed of penetration are the factors which we believe, through the testing undertaken, to be the key to fast suppressing and extinguishing capability even in adverse ventilation conditions. In the engine room hydrocarbon fire tests carried out in Sweden and Finland, extinguishing times were so fast that an additional effect was suspected. It was realized that in addition to the cooling effect, in a high temperature fire the water fog turning to steam causes an inerting effect and drives out the oxygen from the combustion area.

As a manufacturing and systems supply company, Marioff has concentrated on carrying out practical fire tests to prove fire suppression and extinguishing capability, test components and establish design and installation criteria in order to satisfy the regulatory authorities in Europe.

3. WATER FOG SPRINKLER SYSTEM FIRE TESTS

A series of tests was undertaken at SP, the Swedish National Testing & Research Institute from November 27th to December 12th 1991 and also on February 18th 1992. The purpose of the test program was twofold. Firstly, Marioff needed to evaluate alternative head designs, locations and spacing in the different fire scenarios. Secondly, it was necessary to ensure that the Hi-fog system installed on board a passenger ship would provide at least an equivalent level of fire protection for life and property as a traditional sprinkler system designed according to Chapter II-2 Regulation 12 of the SOLAS convention.

More than 60 different tests were performed in order to study the effects of the system against fires in cabins, large rooms, and in public open spaces on board a passenger ship.

3.1. Cabin / Corridor Tests

Location: SP. Swedish National Testing & Research Institute

Date: November - December 1991

Report: 91 R30141

Figure 1. shows the layout of the test cabin / corridor mock up. The cabin was equipped with standard polyether mattresses in a pullman type bunk bed. In most of the tests the lower beds were made with a backrest of the same material as the bed itself. The amount of burning material was enough to create a flashover in the cabin. The tests were performed in the SP fire hall which is equipped with large-scale measuring equipment making it possible to simultaneously measure the rate of heat release from the fire.

The temperatures in the cabin and in the corridor as well as smoke production and rate of heat release were measured during the tests. The air supply to the cabin was arranged by a ventilation unit placed in the ceiling of the cabin. The air supply was 40 L/sec (1.41 ft^3/sec). Tests were carried out with the cabin door open and closed, and included simulated arsonist fires and flashover fires of over 1 MW.

Figure 2. shows the temperature in the cabin during Test 1.9 with automatic activation and the door closed. Figures 3 & 4 show the temperatures and rate of heat release in Tests 1.34, simulating a flashover fire with manual activation.

SP Observations:

"The tests showed that the Hi-fog extinguishing system gives equivalent or better reduction in fire hazard for the cabin fire compared with conventional sprinklers."

3.3. Open Space Fire Tests

Location: SP, Swedish National Testing & Research Institute

Date: December 1991

Report: 91 R30141

In this test series the intention was to verify the results from previous tests which were made under a fire calorimeter hood. A number of tests were carried out against a simulated restaurant or other public space fire. Tests were performed with Hi-fog sprinkler and spray heads fitted to a suspended ceiling with a size of 10 x 10 m (1076 ft^2). The configuration was open and thus there were no restrictions in air supply to the fire. As it was important to study the influence of the ceiling height on the sprinkler performance, tests were performed with one and two deck ceiling height 2.5 m (8'2") and 5 m (16'4") ceiling height.

SP Observations:

"For the open areas the result from the tests showed that it is possible to control a fire in a group of furniture if a deluge system with a minimum area of operation of 100m^2 (1076 ft^2) floor area is used."

3.2 Closed Room Fire Test

Location: SP. Swedish National Testing & Research Institute

Date: February 18, 1992

Report: 91 R30141 (Tests 2.21 & 2.22)

In addition to the main test series, two additional tests were performed in a room 9.6 x 6.0 m (623 ft^2), with ceiling height 3,10 m (10'2"). The ceiling was fitted with five 5 Hi-fog sprinklers. Two sofas made of cold foam were placed in the room, and a fire was started on one. The sprinklers activated automatically.

SP Observations:

"The result showed that the Hi-fog system is able to control a furniture fire in a relatively large confined room with only two heads operating."

3.5 ISO 6182-1.2 Wood Crib Fire Test

Location: SP, Swedish National Testing & Research Institute

Date: 10-11th April 1992

Report: 91 R30189A

After the SP test report was issued it was decided to carry out four wood crib fire tests generally to ISO 6182-1.2 based on UL 199 standard. A group of Hi-fog heads was positioned in the ceiling according to Marioff's installation guidelines based on room size of 100m^2 (1076 ft^2). The test should run for 30 minutes after which the wood crib is dried and weighed. Weight loss should be maximum 20%.

SP Observations:

"The main impression from the tests with the Hi-fog system was the rapid extinction of the wood crib and the heptane spray including the ignition torch (38 seconds). It was not possible to run the test for the 30 minutes test period because of the extinction of the heptane spray and the ignition torch."

4. MACHINERY SPACE SYSTEM FIRE TESTS

In order to provide alternative protection to Halon in ships' engine rooms, a water fog system for machinery spaces should successfully complete a fire test program which simulates the worst case fire conditions that can occur. The Marioff Hi-fog machinery space system uses low pressure water fog as a cooling and controlling medium, and high pressure fog for extinguishing. In order to extinguish a hydrocarbon fire, it is necessary to propel the water droplets into the space at very high speed so that they will penetrate the flue gases and reach the combustion area. With the Hi-fog machinery space system, this is done by using a stored energy system consisting of accumulators loaded with high pressure water. The activation of the Hi-fog nozzles at high pressure ensures that the fog is blasted into the combustion area and the continuation of the low pressure gives continuous cooling so reignition cannot occur.

4.1 Prototype Machinery Space Fire Tests

Location: Upinniemi, Palokoulutuskeskus, Finland

Date: 15-16 July 1991

A series of tests was carried out in Finland for the Marine Directorate of The Department of Transport, United Kingdom. The tests were carried out to demonstrate the capability of the Marioff Hi-fog sprinkler system in extinguishing high temperature hydrocarbon fires in a simulated ship's engine room. The tests were carried out in a purpose built fire test engine room of 261 m^3 (9,217 ft^3) at Upinniemi, Palokoulutuskeskus, a Naval Base 40 km (25 miles) from Helsinki, Finland over two days. The temperatures were measured by VTT Fire Technology Laboratory.

Nine gas burners (400 KW) were ignited to heat a steel plate simulating a split oil pipe or filter housing. When the temperature reached aprox. 600 deg C. (1,112^o F.), oil flow of 10 L/min (2.56 gal/min) at 130 Bar (1,185 psi) was sprayed over the hot steel plate to ignite and flow into the bilges. After several minutes the system was manually activated.

In the five official tests, extinguishing time was between 6 and 35 seconds, and between 6 - 34 litres of water was used for the extinguishing.

4.2 Machinery space development fire tests

Location: SP, Swedish National Testing & Research Institute
Upinniemi, Palokoulutuskeskus, Finland

Date: April - June 1992

Report: 91 R30189

A series of full scale tests were carried out to evaluate the performance of the Hi-fog fire protection system against pool and spray fires in a simulated ship's engine room. The tests were carried out by SP, the first and second series in SP's fire hall in a 8 x 10m (861 ft^2) room with 4.8 m (15'8") ceiling height (13,561 ft^3). The third and fourth test series were carried out in the simulated engine room at Upinniemi under SP's control. In all tests the same engine mock-up was used with Hi-fog heads positioned above and over the bilge area. (See Figure 5).

Fuel Oil, diesel oil and lubrication oil pool fires varying from 2 to 11 m^2 (21.5 to 118 ft^2) were used in the tests. Spray fires of the same liquids and combination spray and pool fires with different preburn times were used.

Approximately 150 different tests were performed with the Hi-fog high pressure fire protection system to study the effect of the system against fires in a ship's engine room. A large number of the tests incorporated modifications and improvements as the system evolved. Extinguishing time for tests in Series 3 and 4 was between three and seven seconds.

SP observations:

"The tests show that the Hi-fog Fire Protection System is able to extinguish large engine room fires with pool and spray fires combined with natural ventilation from open doors and hatch.
Previous tests at SP have shown that a water spray system with 5 $l/m^2/min$ (0.12 gal/ft^2) according to to regulation SOLAS chapter II-2 Regulation 10 has a very limited extinguishing capacity against pool and spray fires compared with the Hi-fog system."

4.3 Large engine room fire tests

Location: VTT Fire Technology Laboratory, Helsinki, Finland

Date: November 5 and 6, 1992

Report: PAL 2210/92

Eight full-scale suppression experiments were carried out in the big test hall of the Fire Technology Laboratory at VTT.

The same engine mock-up as used in previous tests was constructed in the test hall to simulate a large ship's engine room with diesel oil as the fuel. The most intense fire in the tests consisted of four pool fires under the mock-up, one pool fire on top of it, total 11 m^2 (118 ft^2) and a spray fire beside it. The order of magnitude of the maximum heat release rate was estimated to be 20 MW.

The preburn time in each test was about two minutes from time of lighting the spray, after which the Hi-fog system was manually activated. Different water pressures were used in different tests.

The tests demonstrated the ability of the Hi-fog system to extinguish a 20 MW oil fire even in an unenclosed large space.

5. OTHER TESTS

5.1 Electric switchgear Tests

Location: ABB Strömberg Research Centre, Vaasa, Finland

Date: August 3 1992

Report: 9 AFX92-98

The objective of the tests was to find out if the operation of a Hi-fog fire protection system causes disruptive discharges in the main circuits of some typical electrical switching apparatus.

Main circuits of following apparatus were tested:

- low-voltage (690v) switchgear MDF including a frequency converter SAMI R3
- medium-voltage (24 Kv) switchgear MH
- medium-voltage (24 Kv) disconnector OJON 3-20
- busbar of low-voltage (690v) switchgear MDF supplied with DC current

Even with the Hi-fog heads spraying normal tap water directly into the open cabinets there were no disruptive discharges in eight of nine tests. The test which resulted in discharges was successfully repeated with deionised water, and later with tap water when heads were moved 30 cm (12") to the side of the cabinet.

5.2 Computer room smoke activated fire tests

Location: VTT Fire Technology Laboratory, Espoo, Finland

Date: July 2-3, 1992

Report: PAL 2196/92

A set of 11 experiments was performed in the smoke sensitivity room of the Fire Technology Laboratory at VTT. The experimental arrangement, i.e. the fire itself, the computer in the room and the Hi-fog sprinkler arrangement, was varied between the experiments. The two main objectives were:

1) to observe the performance of a Hi-fog system in extinguishing a computer room fire, and
2) to find out whether the combination of smoke from a polyvinylchloride (PVC) fire and fog from Hi-fog sprinklers cause any damage to computers that are not participating in the fire.

In all function tests the Hi-fog system was successful in extinguishing the test fires.

An independent smoke contaminations expert present at these tests commented: "It appears that the Hi-fog has the ability to "wash out" contaminates from the smoke thus greatly reducing the overall smoke damage effect."

5.3 Enclosed space fire suppression tests

Location: VTT Fire Technology Laboratory

Date: October 9 and 12, 1992

Report: PAL 2206/92

A series of sixteen tests were carried out to simulate fires in a typical small room as follows:

1) ticket stand (wood crib/heptane)
2) paint storage (paint/heptane)
3) transformer room (hydraulic oil)

All the experiments were performed in the fire test room 2.4 x 3.6 x 2.4m high (630 ft^3) of the Fire Technology Laboratory at VTT. The door of the room was kept closed during the experiments with a gap of variable size under the door. One Hi-fog sprinkler head was fitted in the ceiling and connected to a self-contained pressure bottle. Activation was either automatic or manual. Maximum amount of water used for each test was 6 litres (1.6 gal).

In all cases the fires were extinguished and reignition did not occur.

5.4 Postflashover fire suppression tests

Location: VTT Fire Technology Laboratory

Date: September 4, 1992

Report: PAL 2204/92

A series of 4 experiments were performed in a fire test room inside the big test hall of the Fire Technology Laboratory at VTT. Chipboard plates and wooden sticks were used. After ignition the fire was allowed to develop past flashover. Manual extinguishing with a Hi-fog head on the end of a lance was started at different times after the flashover.

VTT observations:

"All the postflashover fires were completely suppressed during the experiments. Fire control of a postflashover fire can be achieved with only a few litres of water and - strongly dependent on the amount of fuel - fire suppression requires more water, from 0 to the order of 100 litres in the present experiments."

6. WATER FOG SYSTEMS

6.1 General

In order to provide a working system which could be used in the marine market, system design and installation criteria had to be developed, based on the reports provided by the testing organisations, which were acceptable to the regulatory authorities. However as the use of high pressure piping and associated equipment is quite normal in ships, existing rules and standard components could be used which often were already approved. In some cases additional components had to be developed or modified for the power and control functions, and these have had to be tested and approved before being included in the systems.

6.2 Filtration

The question of cleanliness is vital for a high pressure water fog sprinkler or spray system which uses smaller orifices than conventional low pressure technology. The filtration philosophy which Marioff has adopted has been determined by Marioff's experience in cleaning and certifying high pressure hydraulic systems (such as subsea control systems) which require extremely high levels of cleanliness. Only stainless steel piping and compatible corrosion resistant materials are used and the system is primed and run with fresh water (although it can run on seawater in an emergency). The water is filtered through strainers before entering the system and as a final safeguard all Hi-fog sprinkler and spray heads have filters behind each nozzle.

6.3 Hi-fog sprinkler system

The Hi-fog sprinkler system consists of sprinklers, spray heads, section valves and a pump unit, together with alarm panel, piping and electric wiring. The piping is normally at a pressure of 10 - 20 bar (145 - 290 psi). Only when a sprinkler is activated is the high pressure 100 bar (1,450 psi) system started.

The lightweight pump unit now consists of several electrically driven pumps and a water tank, and is designed to provide minimal loading on the vessel electrical supply. The Hi-fog section valve incorporates a test and stop valve according to SOLAS requirements and is integrated into the automation system, which incorporates a control panel and alarm unit showing the position of all sections.

6.4 Hi-fog machinery space system

The Hi-fog machinery space system is simple and failsafe being based on standard hydraulic principles. It consists of a number of Hi-fog spray heads connected by stainless steel piping to a stored energy power unit, which places a minimal loading on the vessel's electrical supply. Activation can be manual or remote. On activation the stored energy is released to give a rapid high pressure blast of fog for fire extinguishing. This gradually reduces to a continuous low pressure fog for cooling to prevent reignition on hot metal surfaces.

The Hi-fog spray heads are positioned according to installation criteria determined by the testing results: above bilges, tank tops and other areas over which oil fuel is likely to spread and also above other specific fire hazards in the machinery space.

The Hi-fog power unit is lightweight and modular. It consists of one or more banks of gas/water pre-charged accumulators combined with an electrically driven low pressure water pump. The power supply automatically switches from main to emergency supply.

All main branch pipes are fitted with 'pipe break valves', which close automatically in the event of damage to the pipe by a fire or explosion, ensuring that pressure will not be lost for the rest of the system. As well as the fire alarm function, the system is provided with automatic alarms to signal if the pressure is lost in the power unit or the air supply.

6.5 Hi-fog self-contained system

The Hi-fog self-contained water fog system is designed for use where manual and/or automatic fire suppression is required in closed rooms or for local special risk protection.

The system consists of sprinklers, spray heads, accumulators,activating valves connected by stainless steel piping. Systems can consist of one accumulator assembly and one sprinkler or multiples of accumulator assemblies and combinations of spray heads and sprinklers.

Activation of system can be electrical, heat or manual or a combination of all three.

An addition to the self-contained system can be a low pressure water pump and break tank to supply cooling fog to an area after high pressure fog has been exhausted and additional cooling is required.

The accumulator is manufactured and tested to pressure vessel regulations and body material is steel internally coated with an epoxy paint to prevent corrosion. The accumulator valve incorporates a pressure gauge, burst disc to prevent over pressurisation, and nitrogen charge/vent connection, and water fill port.

6.6 Hi-fog lance extinguishing systems

Hi-fog heads and lances suitable for portable manual extinguishing with pumps or pressure accumulators are also currently being developed.

7. REFERENCES

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3. Swedish National Testing & Research Institute, Borås, Sweden, 91 R30189, Tests in simulates ship's engine rooms with Hi-fog Fire Protection System. July 28, 1992.

4. VTT Fire Technology Laboratory, Helsinki, Finland, PAL 2210/92, Fire suppression tests in simulated ship's engine room with a Hi-fog fire protection system. November 16, 1992.

5. ABB Strömberg Research Centre, Vaasa, Finland, 9 AFX92-98, Withstand voltage of switchgears in the presence of operating Hi-fog fire extinguishing system. August 3, 1992.

6. VTT Fire Technology Laboratory, Espoo, Finland, PAL 2196/92, Extinguishing tests of simulated computer room fires by a Hi-fog sprinkler system. August 11, 1992.

7. VTT Fire Technology Laboratory, Espoo, Finland, PAL 2206/92, Enclosed space fire suppression tests. October 23, 1992.

8. VTT Fire Technology Laboratory, Espoo, Finland, PAL 2204/92, Manual suppression of a postflashover fire with Hi-fog nozzles. September 11, 1992.

TABLE 1. MARIOFF MARINE REFERENCE LIST

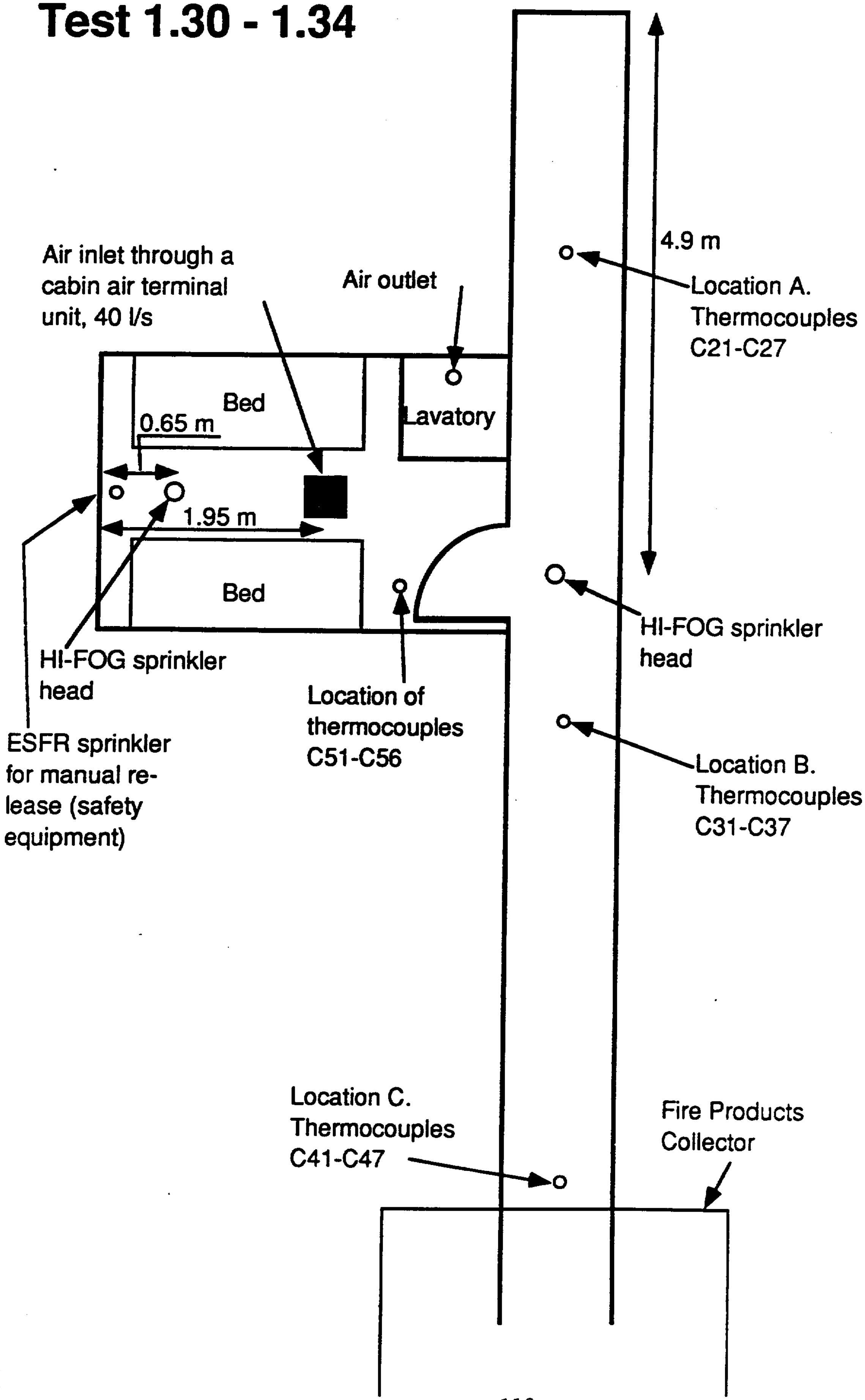
Vessel	*Type*	*Operator / Yard*	*System*	*Progress*
'Olympia'	Cruise ferry	Viking	Galley system	Installed
'Mariella'	Cruise ferry	Viking	Duty free store	Installed
'Franz Suell'	Cruise ferry	Euroway	1200 sprinklers	Installed
'Festival'	Cruise ferry	Silja	2200 sprinklers	Installed
'Karneval'	Cruise ferry	Silja	2200 sprinklers	Installed
'Kalypso'	Cruise ferry	Slite	Galley system	Installed
'Europa'	Cruise ferry	Slite	2340 sprinklers	Installed
'Topaz'	Seismic vessel	GECO	160 sprinklers + engine room	Installed
'Diamond'	Seismic vessel	GECO	160 sprinklers + engine room	Installed
'Linden'	Sailing ship	Linden	30 sprinklers	Pending
NB 373	Cruise ferry	Euroway	1200 sprinklers	Pending
'Robin Hood'	Cruise ferry	TT-Line	1200 sprinklers	Installing
'Athena'	Cruise ferry	Slite	Galley system	Installing
'Bergen'	Ferry	Askøy	750 sprinklers + engine room	Installing
8821	Surface effect ship	Polyship Belgium	24 sprinklers + engine room	Start March 93
Nils Dacke	Cruise ferry	TT-Line	1200 Sprinklers	Start April 93

TABLE 2. MARIOFF LAND BASED REFERENCE LIST

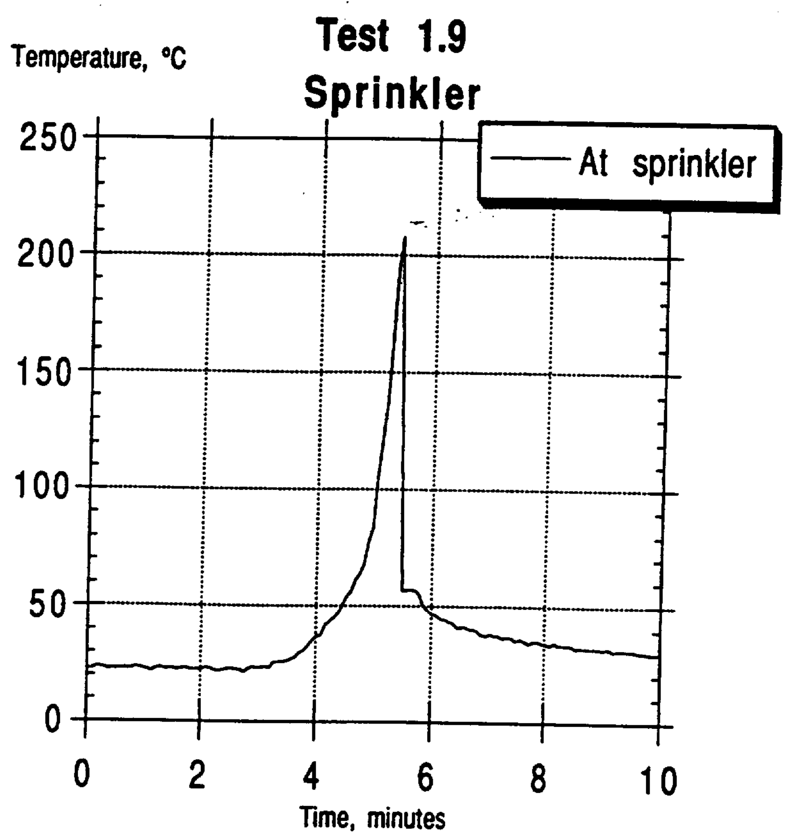
Customer / Project	*Protection*	*System*	*Progress*
London Underground	Store rooms Kiosks	Self-contained	Installed /Installing
London Transport	Paper archives	Self-contained/pump	March install
Agrekko/Shell	Generator room	Self-contained	Commissioning
Polarcup, Finland	Printing machinery	Sprinkler/pump	Commissioning
BMW, Germany	Test room	Self-contained	Ordered

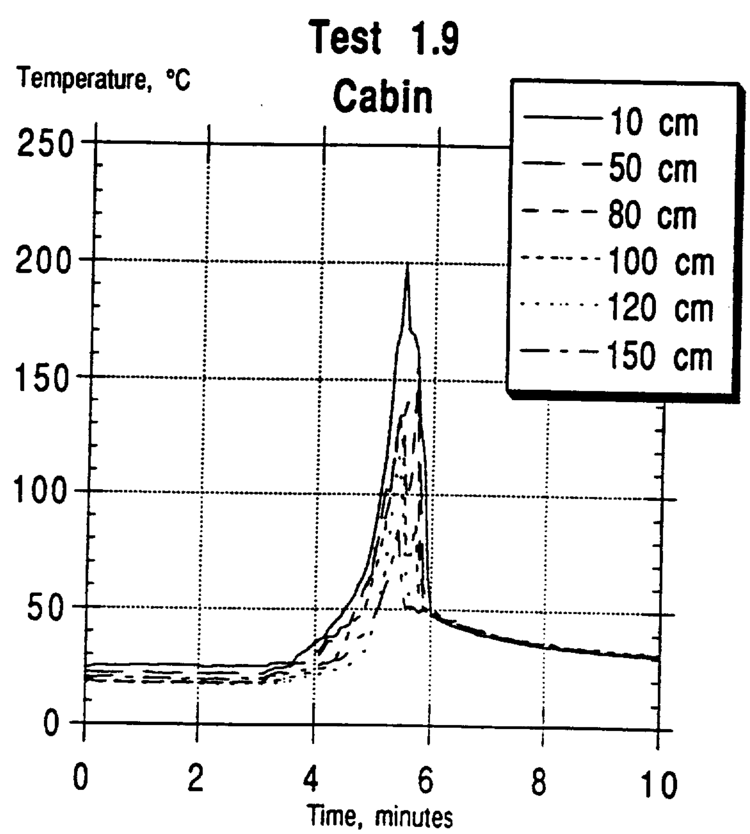
FIGURES

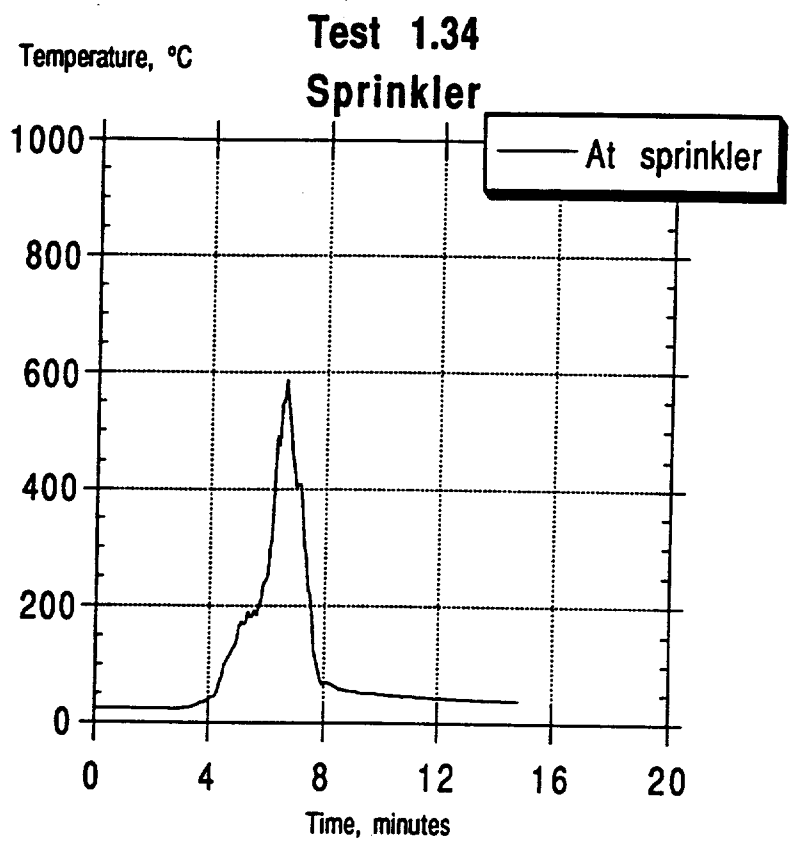
Test 1.30 - 1.34

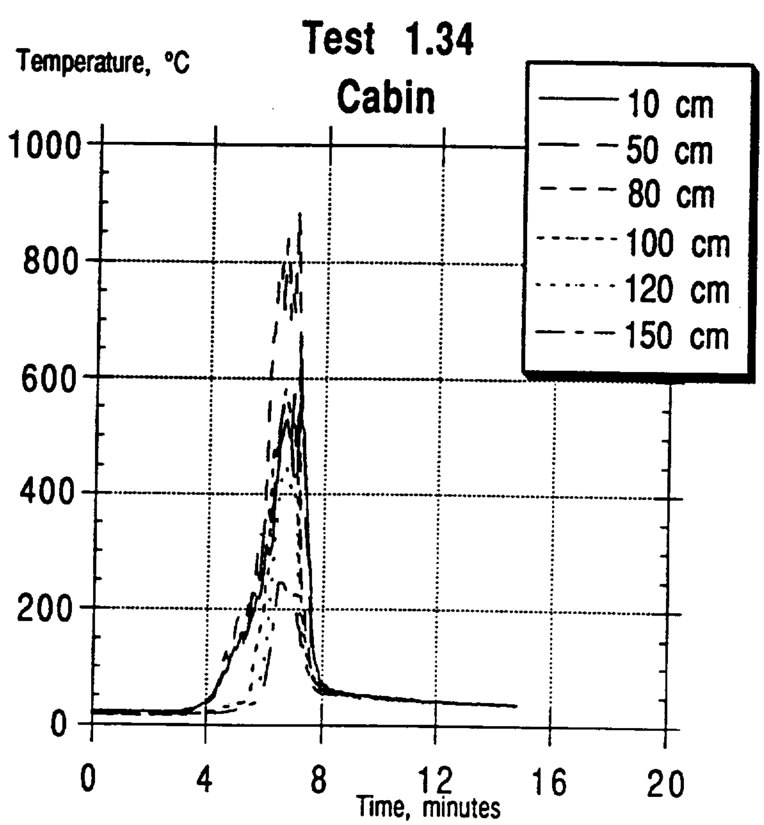


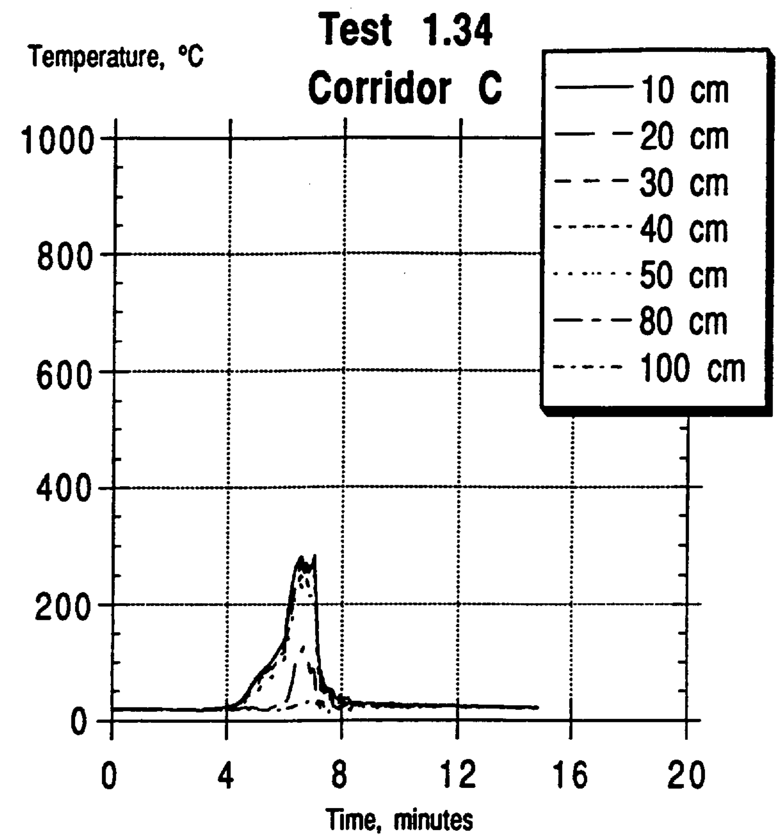
4.9 m
Air inlet through a cabin air terminal unit, 40 l/s
Air outlet
Location A. Thermocouples C21-C27
Bed
0.65 m
Lavatory
1.95 m
Bed
HI-FOG sprinkler head
HI-FOG sprinkler head
Location of thermocouples C51-C56
ESFR sprinkler for manual re-lease (safety equipment)
Location B. Thermocouples C31-C37
Location C. Thermocouples C41-C47
Fire Products Collector

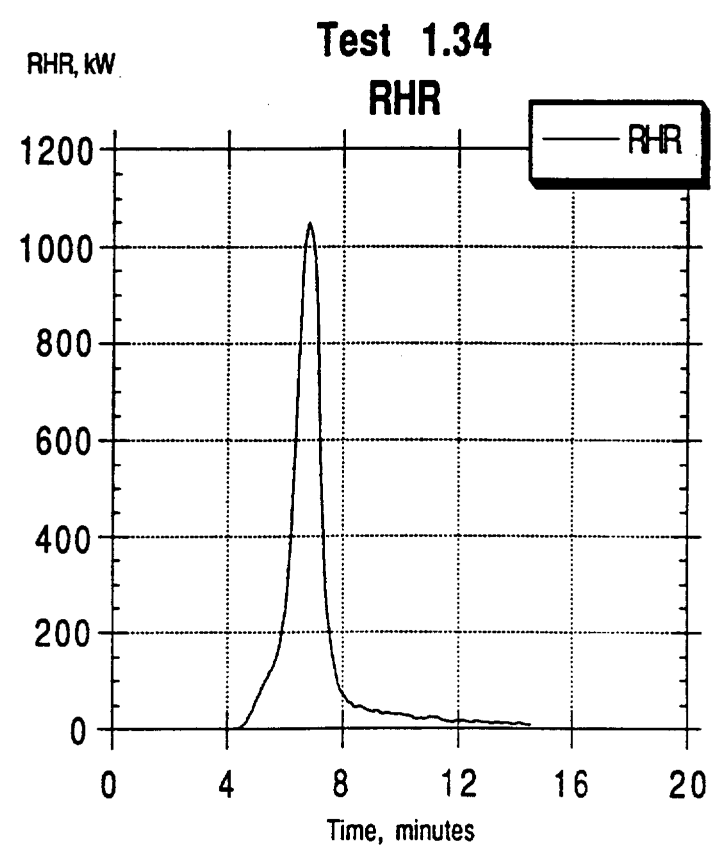

Test 1.9
Sprinkler
Temperature, °C
At sprinkler
250
200
150
100
50
0
0
2
4
6
8
10
Time, minutes

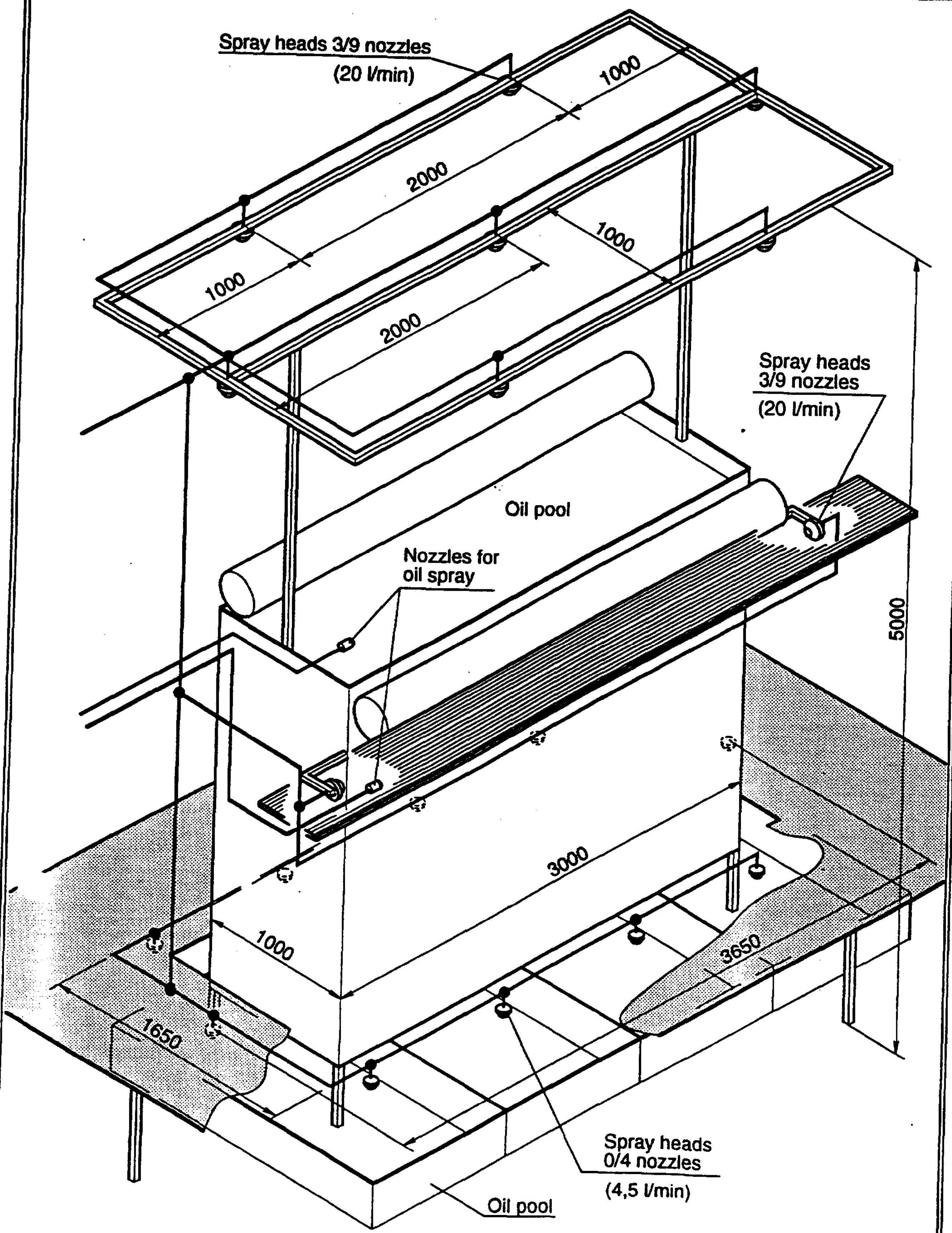

Test 1.9
Cabin
Temperature, °C
10 cm
50 cm
80 cm
100 cm
120 cm
150 cm
250
200
150
100
50
0
0
2
4
6
8
10
Time, minutes


Test 1.34
Sprinkler
Temperature, °C
At sprinkler
1000
800
600
400
200
0
0
4
8
12
16
20
Time, minutes


Test 1.34
Cabin
Temperature, °C
10 cm
50 cm
80 cm
100 cm
120 cm
150 cm
1000
800
600
400
200
0
0
4
8
12
16
20
Time, minutes


Test 1.34
Corridor C
Temperature, °C
10 cm
20 cm
30 cm
40 cm
50 cm
80 cm
100 cm
1000
800
600
400
200
0
0
4
8
12
16
20
Time, minutes


Test 1.34
RHR
RHR, kW
RHR
1200
1000
800
600
400
200
0
0
4
8
12
16
20
Time, minutes



Drawing no. 4-101-07

Hi-fog

Head layout - engine room tests
SP report R30189 - test series 3 and 4

MARIOFF

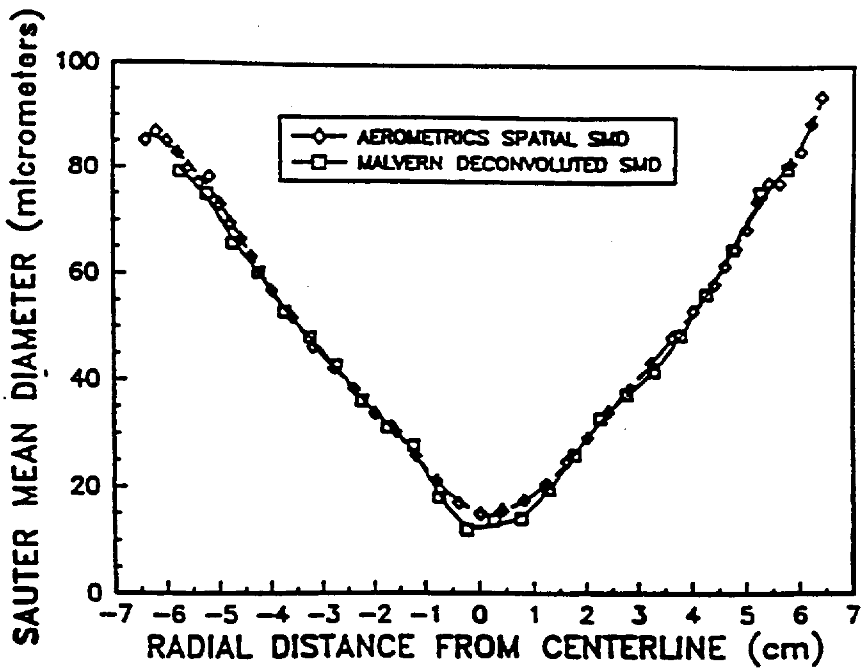


Figure 10. Comparisons of a the Radial Spray Distribution of the Spray Sauter Mean Diameter With the Malvern Fraunhofer Diffraction Method and Using an Abel Deconvolution on the Malvern Data.

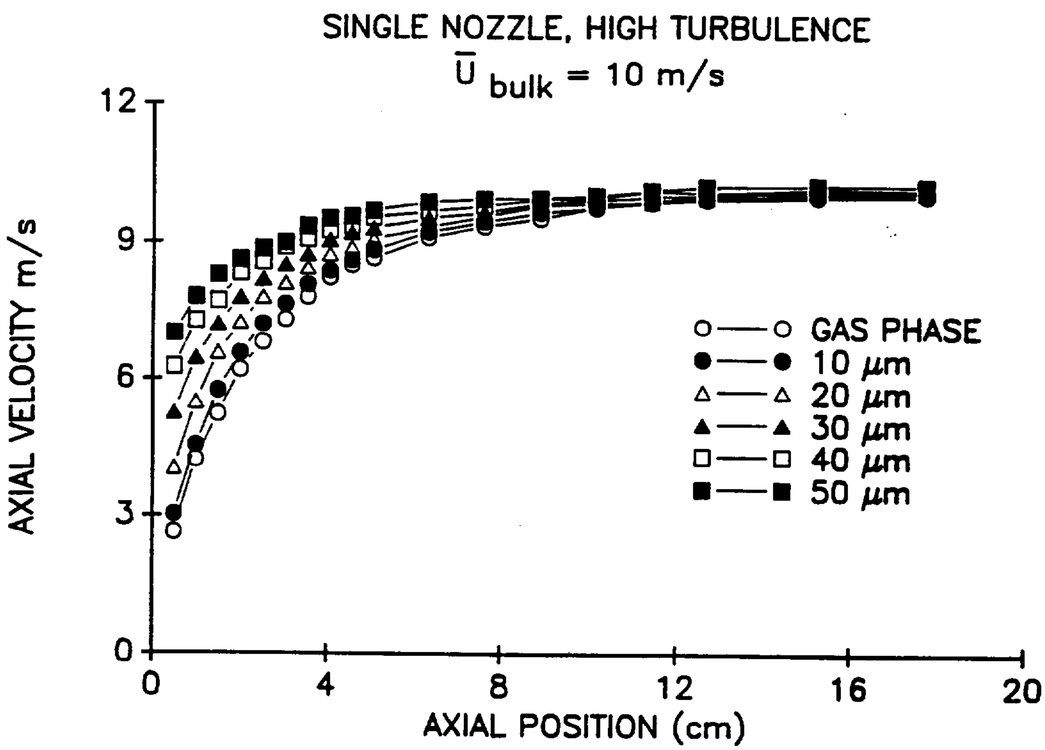


Figure 11. Drop Velocity Lag Data For a Spray Incident Upon a Cylinder At an Initial Flow Velocity of 10 m/s For a Discrete Set of Drop Size Classes. The Drop Lag Can be used to Infer the Drop Size and These Results Can be Compared to the Measured Size With the PDPA.

WATER MIST FIRE PROTECTION SYSTEMS FOR TELECOMMUNICATION SWITCH GEAR AND OTHER ELECTRONIC FACILITIES

Andrew T Hills, Terence Simpson* and David P Smith
Fire and Safety International - Research
Mill House, Poyle Road, Colnbrook
Slough, SL3 0HB, Great Britain

SUMMARY

Although water is known to be an effective Class A and B fire suppressant, scepticism remains over its use in Class C applications due to its conductivity. Therefore, a joint Kidde-Fenwal/GTE/FSI Research feasibility study into water mist fire protection in live telecommunication switch gear was carried out.

The switch gear bays, which were composed of vertically mounted, parallel printed circuit boards (PCBs), were found to be a considerable fire threat. A localised 'in cabinet' fire suppression system comprising single fluid spray nozzles operating at high pressure was used. Test fires were extinguished in 1-2 seconds using less than 1 L (0.26 US gal) of water. In addition, the current trips contained in the switch were activated when water was incident and this result, coupled with the low volume of water used, reduces the electric shock hazard considerably.

Therefore, water was found to be an efficient and safe fire suppressant in switch gear. Since these initial experiments, further tests have been carried out on alternative equipment supplied by Mercury Communications, for which findings are briefly presented.

1. INTRODUCTION

The FSI Research Department is a group of about 20 scientists and engineers which undertakes projects on behalf of the companies within the FSI Group (Kidde-Graviner and Kidde-Hartnell in Great Britain, Kidde-Fenwal, Walter Kidde Portables, Walter Kidde Aerospace, Fenwal Safety Systems and Detector Electronics in the USA, Deugra in Germany, Kidde-Dexaero in France and Pyron in Australia). FSI Research's extensive experience in water mist technology, including its computer cabinet fire protection studies, prompted Kidde-Fenwal, in conjunction with GTE, to initiate a feasibility study into water mist fire protection in telecommunication facilities.

Gas-flooding systems are commonly employed in computer installations whereby a gaseous fire extinguishing agent is introduced into an enclosed space via either a fixed pipe system from a large storage vessel or by a number of in situ pressurised bottles. The conventional agents used in these applications are the Halons 1211 and 1301 and CO_2. The advantages of these extinguishants when used as a means of protecting sensitive electronic equipment are that they are non-conductive and able to permeate to obscured fires.

* Author to whom all correspondence should be addressed

Problems arise when using CO_2 because the concentration required to suppress fires (around 30%) will be lethal to humans. Measures must be taken, therefore, to ensure that all staff are evacuated from the room prior to discharge, and that re-entry is delayed until the area is fully ventilated. Other problems encountered include damage to equipment caused when objects are dislodged by the fast discharge of a large volume of gas, and thermal shock resulting from the rapid cooling of the air during this process.

Halon 1211 has a suppression design concentration of 5 to 8%. This gas is toxic at these concentrations, however, resulting in dizziness and impaired co-ordination as well as some risk of cardiac arrhythmias. In common with CO_2, therefore, persons should not be present in the protected space during or directly following discharge. Halon 1301 is less toxic than 1211; a concentration of up to 7% does not cause undue effects in humans. Since it is inherently safer than 1211 or CO_2 at effective fire fighting concentrations, Halon 1301 used to be the preferred option for gas flooding.

Halons, however, have been shown to be responsible for a considerable part of the damage to the ozone layer observed since 1978. As a result, they were included in the list of compounds whose production is to be controlled and ultimately phased out under the Montreal Protocol [1]. This legislation sought to control the production of Halons at 1986 levels and subsequently reduce them. These control measures were further tightened in 1990 at the London Review Meeting of the Montreal Protocol [2]. A further review took place in Copenhagen in November 1992 and as a result, a total ban on Halon production is now being implemented as early as January 1994.

Clearly there is an urgent need to find a suitable replacement fire suppression system, with water mist being one possible candidate as it has been found to be an efficient Class A and B fire suppressant and is also non-toxic, cheap and environmentally friendly.

1.1 Water as a Fire Suppressant

Water's favourable physical properties are utilised when it is employed as a fire suppressant. Its high heat capacity (4.2 $J\ g^{-1}\ K^{-1}$) and latent heat of vaporisation (2442 $J\ g^{-1}$) result in the abstraction of heat from flames and fuel, leading to extinguishment. In addition, the steam produced upon evaporation aids extinguishment by diluting the vapour phase concentration of fuel and oxygen (water expands 1700 times upon evaporation to steam) [3].

To achieve its full thermodynamic potential, water is produced in the form of a spray thus maximising the surface area for heat absorption and evaporation. It follows that finer sprays are more efficient at heat absorption relative to more coarse sprays.

To extinguish Class A and B fires rapidly, direct impingement is essential. Also, for Class B fires, complete surface coverage of the fuel is important. For direct impingement to be efficient, the downward momentum of the spray must overcome the upward thrust of the flames and fire gases in order to penetrate to the combustion zone. Furthermore, droplet size must have a lower limiting value because droplets must be large enough to penetrate to the core of the fire [4].

In some environments, direct impingement of spray onto a fire is not possible. However, water fog can be used as a 'total flood' agent in these cases. Again small droplets facilitate extinguishment, the droplets being entrained into the flames. Extinguishment is brought about by the gradual cooling of the flames and the inerting effect of localised steam production.

Scepticism remains over the use of water in Class C environments as it conducts electricity which could lead to equipment damage and shock hazard to personnel. Recent research suggests it is possible to use water spray in Class C facilities safely and without causing damage [5]. The aim of this project, therefore, was to establish the feasibility of using water spray/mist in telecommunication installations. To this end, GTE donated 34 2EAS telecommunication switch gear bays plus power supplies to Kidde-Fenwal for trials work, the testing taking place at Fenwal Safety Systems Inc., Combustion Research Centre in Holliston, Massachusetts.

Fire suppression studies in telecommunication facilities have so far been limited to cable fires, where it is agreed the main fire threat lies, and it has been shown that water spray is effective against such fire challenges [5], [6]. We believe that this is the first study into fire suppression in telecommunication switch gear and intend to prove that there was indeed a fire threat associated with this equipment and that water fog can be an efficient, safe and non-destructive extinguishant.

It was made clear at the outset of this project that GTE did not want a total room flooding water mist system because of the potential disruption this may cause to non-affected switch gear bays contained in the suite; GTE stipulated that all switch gear bays not affected by fire must remain live. Tests were largely confined, therefore, to systems deploying water spray within the switch gear bays themselves.

2. EXPERIMENTAL CONSIDERATIONS

2.1 GTE 2EAS Switch Gear

The switch gear bays contained several types of PCBs separated at different intervals depending on the function of the bay. The PCBs contained in the switch were either relay boards, Complementary Metal Oxide Semiconductor (CMOS) control boards or power supply units. The dimensions of a typical switch are shown in Figure 1.

The switch gear bays chosen for all the fire tests had the densest array of printed circuit boards possible, with the boards being positioned such that void channels ran vertically through the bay, allowing direct impingement of top-mounted sprays onto the test fire. These bays had PCBs with separations of 0.01 m.

The switch gear bays were powered-up using a 50 V/10 A DC battery charger.

2.2 Ignition Method

Nichrome ribbon (0.5 m x 0.005 m) was weaved into four slits (0.10 m) cut into a reed relay board stripped of all its components (Figure 2). The wire was connected via spring loaded clamps to a 20 A variable transformer. The Nichrome ribbon glowed red and caused ignition within 30 seconds when approximately 30 V AC was supplied.

2.3 Instrumentation and Measurements

2.3.1 Temperature Measurement

A total of 12 mineral insulated bare tip type K (nickel chromium alloy/nickel aluminium alloy) thermocouples were deployed in most experiments. The positions of the thermocouples used during the test programme are given in Figure 3.

2.3.2 Smoke Measurement

The obscuration equipment was a two part system comprising a remote optical head unit linked to an amplifier/driver unit, the former being mounted above the switch (Figure 4). A 4 Hz light signal generated from a 2 V, 340 mA filament lamp was passed through a collimating lens and directed across a 30 cm path length to a collecting lens. The light was focused onto a BPW 21 photodiode and the resulting signal amplified and passed to the amplifier driver unit via a 20 m cable. Signals to the 4 Hz lamp and from the amplifier photodiode were fed into an AD630 phase detector integrated circuit in order to enhance the smoke obscuration signal, thereby enabling the unit to operate in high and variable ambient light conditions. The analogue voltage produced was then passed to an Orion data acquisition system (see section 2.3.7).

2.3.3 Radiation Measurement

An infrared (IR) flame detector was positioned at a height and distance of 0.5 m and 1.2 m respectively. The detector comprised a thermopile fitted with a 4.4 μm filter, with the signal produced being amplified and recorded by the data acquisition system. A flame flicker signal was also recorded by AC coupling the amplified signal.

2.3.4 Hydrogen Chloride Concentration Measurement

A Servomex 1490 IR analyser was used to monitor constantly the concentration of hydrogen chloride (HCl). The inlet tube for the analyser was positioned above the switch (Figure 4), the gas reaching the analyser by means of a small air pump.

2.3.5 High Sensitivity Smoke Detection

A Kidde-Fenwal high sensitivity smoke detector (Analaser) was used in some experiments. The inlet tube for the Analaser was placed above the switch gear bay (Figure 4).

2.3.6 Pressure Measurement

The pressure within the spray manifold was monitored using a Kistler piezoresistive transducer type 4045 A100 (Figure 5). The 0-100 bar output was amplified by a Kistler type 4601 unit and recorded by the data acquisition system.

2.3.7 Data Capture

All data were recorded on a Schlumberger Technologies Orion 3531 D data acquisition system (Figure 6). The Orion is a stand alone software-controlled unit which was programmed to scan the 17 sensor outputs at 0.5 second intervals, storing these data values to a 720 kbyte, 3.5 inch diskette. A 2 line alpha-numeric display was used to monitor continuously any 4 of the 17 data inputs.

At the end of each test, information on the diskette was converted into a Lotus 123 V2.2 worksheet for subsequent data analysis.

2.3.8 Current Leakage Measurements

Board current leakage evaluation was made by measuring the current flow between two parallel printed circuit tracks 10 cm in length and 1 cm apart. The tracks were supplied with 50 V DC (from a GTE battery charger) via a 1 MOhm, 0.25 W carbon resistor. By measuring the voltage across the resistor (using a Fluke 77 Digital Multimeter), the leakage current between the two circuit tracks was calculated using Ohm's law.

2.4 Spray Manifold

Water contained in a 10 L pressure vessel was pressurised in the 2-100 bar range using a regulated nitrogen cylinder (Figure 5). Spray manifolds were positioned at the top, bottom or front of the switch and comprised stainless steel tubing containing a number of ports for the insertion of various types of single fluid nozzles.

A variety of single fluid nozzles were used in the fire tests including full, hollow and elliptical cone types. In addition, some dual fluid (air atomising) nozzles were tested and some general room fogging experiments carried out.

2.5 Test Procedures

2.5.1 Unsuppressed Test

A fully instrumented unsuppressed test was performed to identify a suitable pre-burn time and to assess the fire threat associated with a single, isolated switch gear bay. The test was performed in a 15 m x 15 m x 7.5 m building fitted with an air handling system built to UL specifications.

2.5.2 Suppression Tests

For each nozzle manifold position, the fire challenge was the same in terms of relative position and intensity. The distance between the nozzles and fires was as large as possible and the densest array of PCBs was chosen to maximise the degree of obstruction to the spray.

Pre-burn was measured from the commencement of flaming combustion and was judged visually. The water fog was activated after flaming combustion was sustained on the level above the ignition source; the time for this to be achieved was usually between 90-180 seconds.

3. RESULTS

3.1 Unsuppressed Fire Test

Ignition was by the Nichrome ribbon method (see section 2.2) and the ignition board was placed in a central position at the base of the bay. Dense red smoke was produced upon ignition, the smoke obscuration above the bay reaching 100% in seconds. Upon the commencement of flaming combustion, the smoke lost its red coloration.

After ignition the fire was found to propagate vertically up the switch, with temperatures reaching 600-800 °C. As the intensity of the fire increased, more lateral spread was apparent and at its peak, temperatures were in excess of 1000 °C with flames rising 2-4 m above the bay.

Smoke obscuration inside the building reached 100% within 20 minutes. IR flame flicker measurements revealed combustion ceased after 30 minutes. No hydrogen chloride was detected in the course of this experiment.

3.2 Fire Suppression Tests

3.2.1 General Comments on Instrumentation Results

In general, maximum temperatures at the ignition source were between 350-500 °C, with the rate of temperature rise being in the order of 100-200 °C/min. Thermocouples placed at the top of the switch did not show consistent temperature rises, if any temperature rise was recorded at all.

3.2.2 Smoke Obscuration and High Sensitivity Smoke Detector Results

Smoke obscuration above the switch gear bay reached 100% within seconds of the activation of the Nichrome ribbon. The Analaser, when used, went into alarm immediately after the Nichrome ribbon was switched on. When the nozzles were placed at the top of the bay, the smoke obscuration fell markedly upon activation of the spray.

3.2.3 Hydrogen Chloride Analysis

The concentration of hydrogen chloride never rose above 10 ppm in any of the experiments conducted, with no HCl detected in the majority of tests.

3.2.4 Pressure Measurement

Pressure measurement at the nozzle manifold enabled the pressure drop between the bottle and nozzles to be determined and hence allowed the accurate calculation of flow rates based on manufacturer's data.

3.3 Suppression Results

Fire tests conducted with nozzle manifolds mounted at the top of the switch revealed that single fluid, full cone and narrow discharge angle nozzles operating at high pressures were the most efficient types. The high velocity fogs produced by these nozzles could repeatedly extinguish a test fire within 2 seconds using less than 1 L of water.

High water flow rate, low pressure, coarse (sprinkler like) sprays used more water and gave longer extinguishment times than the high velocity fogs. In addition, low water flow rate, low pressure, fine sprays used in recent studies [5] consumed more water and gave longer extinguishment times than the high velocity fog.

Air atomising nozzles gave good results for small scale test fires. However, if a fire was of greater intensity, these nozzles resulted in longer extinguishing times and used more water than the high pressure single fluid nozzle combination.

The high pressure single fluid nozzle combination was also found to give the best results when mounted at the bottom of the switch, although their performance was not as good as when they were placed at the top of the bay.

Wide cone angle single fluid nozzles operating at high pressures gave good results when mounted at the front of the switch.

Remote room fogging experiments proved to be far less effective than the in-cabinet arrays.

3.4 Discharge Tests on Live Switch Gear

The different types of switch gear were all powered using a 50 V (DC) battery charger. Tap or distilled water was discharged onto the switch using a frontal nozzle array. As soon as water was in direct contact with the PCBs, the trips contained were activated, cutting off power to the switch. All the switch gear bays became fully operational when dry.

Some PCBs were connected to the mains 110 V supply. Circuit breaks were activated upon the application of water. Again, the boards became fully operational when dry.

3.5 Suppression Tests in Live Switch Gear

Fire suppression tests were conducted on live switch gear. The trips contained in the switch gear bay were activated when water fog was incident. Occasionally, smoke from the fire activated trips prior to suppressant discharge.

Fire characteristics were not different from those in unpowered switch gear. The fires were extinguished in under 2 seconds using the optimum top-mounted, single fluid nozzle, high pressure array.

The switch became fully operational when dry (except for the fire damaged cards). The long term effect of the exposure of PCBs to smoke, fire and water is being examined by GTE.

3.6 Leakage Current Measurement

Leakage currents between two parallel tracks on a PCB surface were measured using the apparatus described in Section 2.3.8. The leakage currents for distilled water, tap water and the condensed material from smoke were 18, 45 and 56 μA respectively with resistances of 1.80, 0.21 and 0.20 MOhm respectively.

4. DISCUSSION

4.1 Unsuppressed Fire Test

The damage caused by a fire in a switch gear bay is extensive. The PCBs directly affected by the fire are rendered completely unusable. The IR output and thermocouple measurements of the fire reach maximum values in about 10-12 minutes with temperatures high enough at the peak of combustion to melt some of the solder and aluminium components contained on the PCBs. The combustible-rich smoke plume leads to flames reaching 2-4 m above the switch gear bay.

The lateral spread of the fire, coupled with the flames in the smoke plume and high temperatures, means that the chances of the fire remaining contained in a single switch gear bay if unchecked are minimal. The cables usually present above the bay would be easily ignited by flames in the smoke plume, and the proximity to other switch gear bays in normal operation means neighbouring bays are also likely to burn.

4.2 Suppression Tests

The high velocity fogs produced by single fluid nozzles at high pressures proved to be the most efficient fire suppressing combination when placed either at the top, bottom or front of the switch. In addition to the other benefits of fine sprays, the high velocity fog is able to negotiate obstacles and penetrate to the seat of a fire.

When placed at the top or bottom of the switch, narrow cone angled sprays concentrate the water inside the bay, leading to rapid extinguishment. Figure 7 shows the temperature profile at the core of the test fire and shows a dramatic reduction in temperature after the activation of the water fog.

Although air atomising nozzles produce high velocity fogs, the amounts of water used were too low to extinguish efficiently a test fire.

Coarse sprays in common with those used in a recent telecommunication fire suppression study [8] and 'sprinkler like' sprays were not effective against this fire challenge. These large droplet size, low thrust sprays were unable to negotiate obstacles and penetrate to the seat of the fire.

Room fogging experiments were less successful than the 'in-cabinet' tests as the concentration of water around the core of the fire was not high enough to bring about rapid extinguishment. Total flood water fog or sprinkler systems were not favoured by GTE in any case (vide supra).

Frontal nozzle arrays were effective as there was less obstruction to the spray. However, it is difficult to envisage the unobtrusive installation of such a manifold.

Experiments conducted on live switch gear showed that water fog did not damage the electrical equipment contained in the bay. The shock hazard associated with such equipment is low as the power was cut-off to the switch gear bays upon the activation of the fog. The switch gear bays became fully operational when dry. In addition, there was no reduction in performance of the optimum single fluid, high pressure nozzle array when suppressing a fire in a live switch relative to an unpowered bay.

The simple conductivity measurements revealed that the smoke produced by the burning circuit boards was more conductive than tap water, explaining why, in some experiments, trips were activated before the actuation of the water spray.

5. CONCLUSIONS

This study shows that the PCBs contained in the 2EAS switch gear were a substantial fire threat and if a fire occurred, the loss of revenue due to down time and salvage could be enormous.

As a potential candidate for fire suppression in these situations, 'in-cabinet' water fog has been found to be extremely effective, safe and non-destructive. Coupled with this, water is non-toxic, environmentally friendly and cheap.

There is no foreseeable problem in designing a fully integrated 'in-cabinet' system including 'double knock' (dual) activation of a clean, initially dry spray manifold. Therefore, the drawbacks of conventional water systems (large volumes of water, accidental discharge, leaks and impure water) have been addressed and negated.

6. CURRENT TEST WORK

It is recognised that these trials are confined to one particular type of telecommunication cabinet and that more work is required on different types of electronic equipment before a 'universal' protection system is available.

A recent visit to Mercury Communications premises in central London showed there to be a variety of systems hardware of differing function and geometry where direct impingement of water fog was not possible. In addition, the fire threat associated with bundles of coaxial cables laid in metal trays positioned above the cabinets would have to be addressed.

Links have been forged between Mercury Communications with a view to further testing of 'in cabinet' water spray. An on-going project using Mercury Communications electronic cabinets has shown water fog to be versatile. Mercury's fully-enclosed cabinets usually contained PCBs; however, many different types of equipment are also contained, making direct impingement of water fog from either the top or bottom impossible.

Figures 8 and 9 show diagrams of Mercury equipment and the fire challenge tackled in the current test program. Results so far show that obscured fires can be extinguished by water fog produced by nozzles placed inside the cabinet using less than 1 L of water. These test fires are believed to be extinguished by the cooling effect of entrained water fog and the inerting effect of water vapour. Although this testing is in its early stages, it is envisaged that the 'in cabinet fogging' system may be successfully applied to a wide variety of telecommunication and other electronic installations.

7. ACKNOWLEDGEMENT

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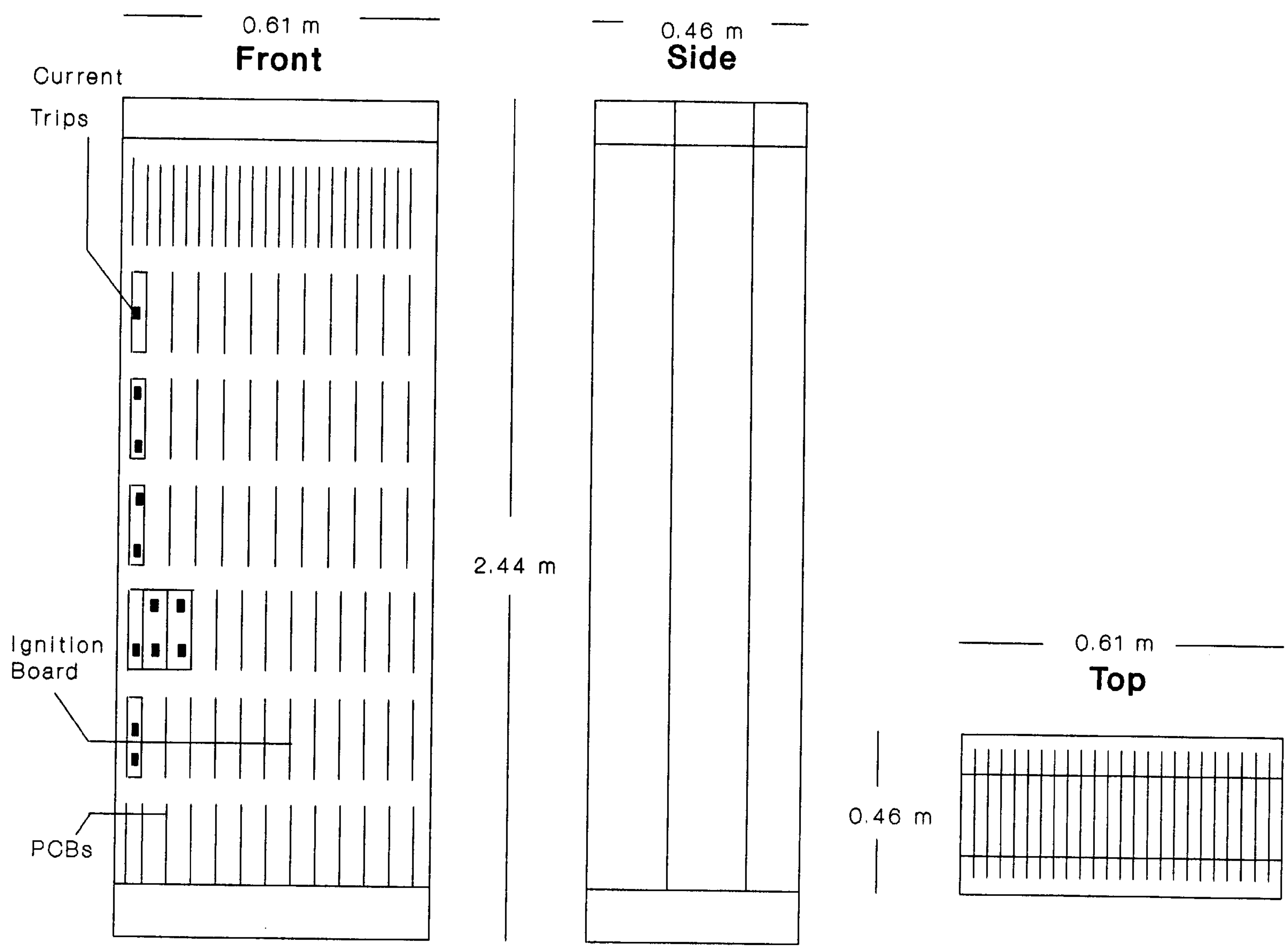


Figure 1: A Typical Switch Gear Bay and Position of the Ignition Board

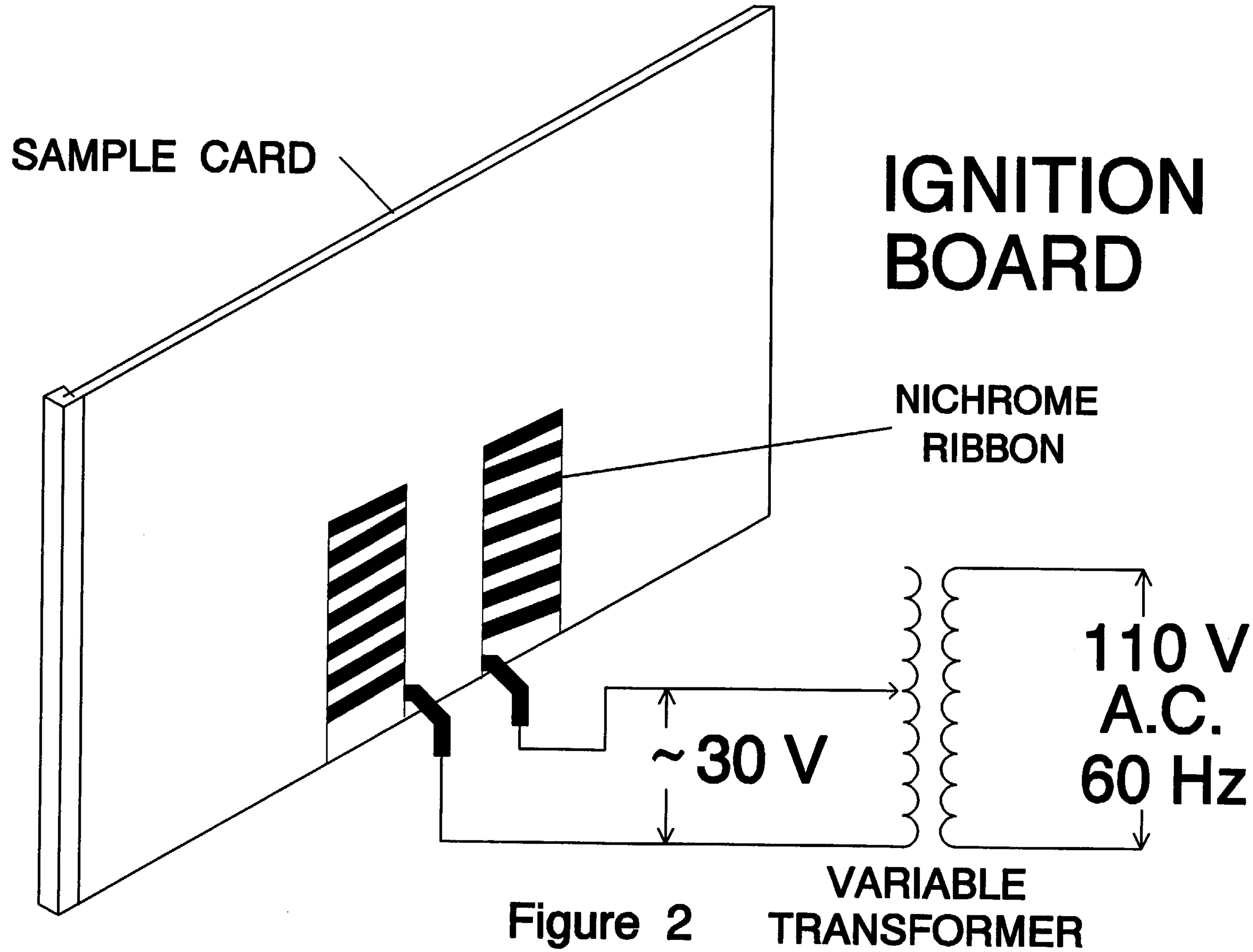

SAMPLE CARD
IGNITION BOARD
NICHROME RIBBON
~30 V
110 V
A.C.
60 Hz
VARIABLE TRANSFORMER

Figure 2

THERMOCOUPLE POSITIONS

TESTS 2 - 18, 22, 28 - 34.

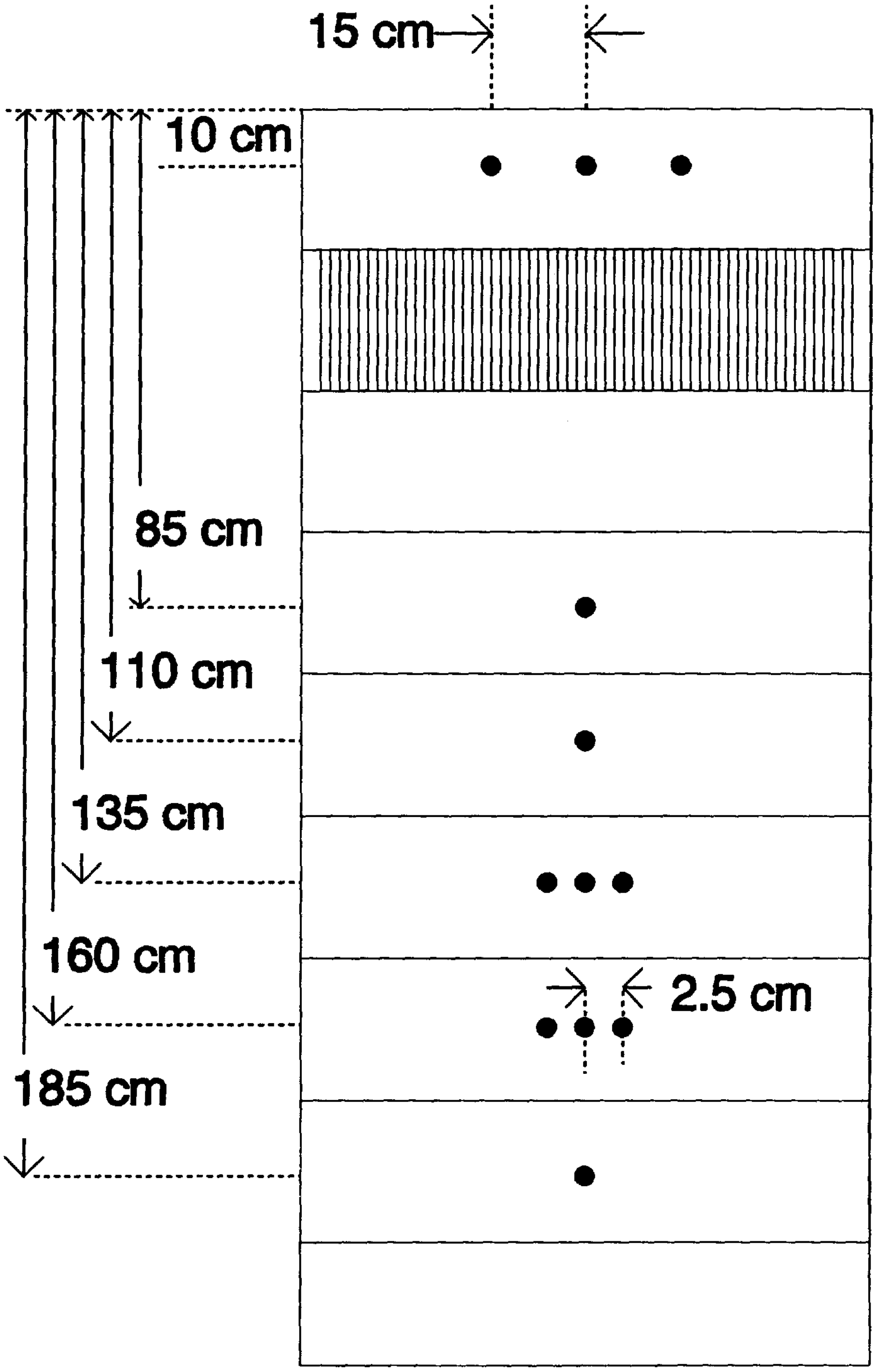


Figure 3

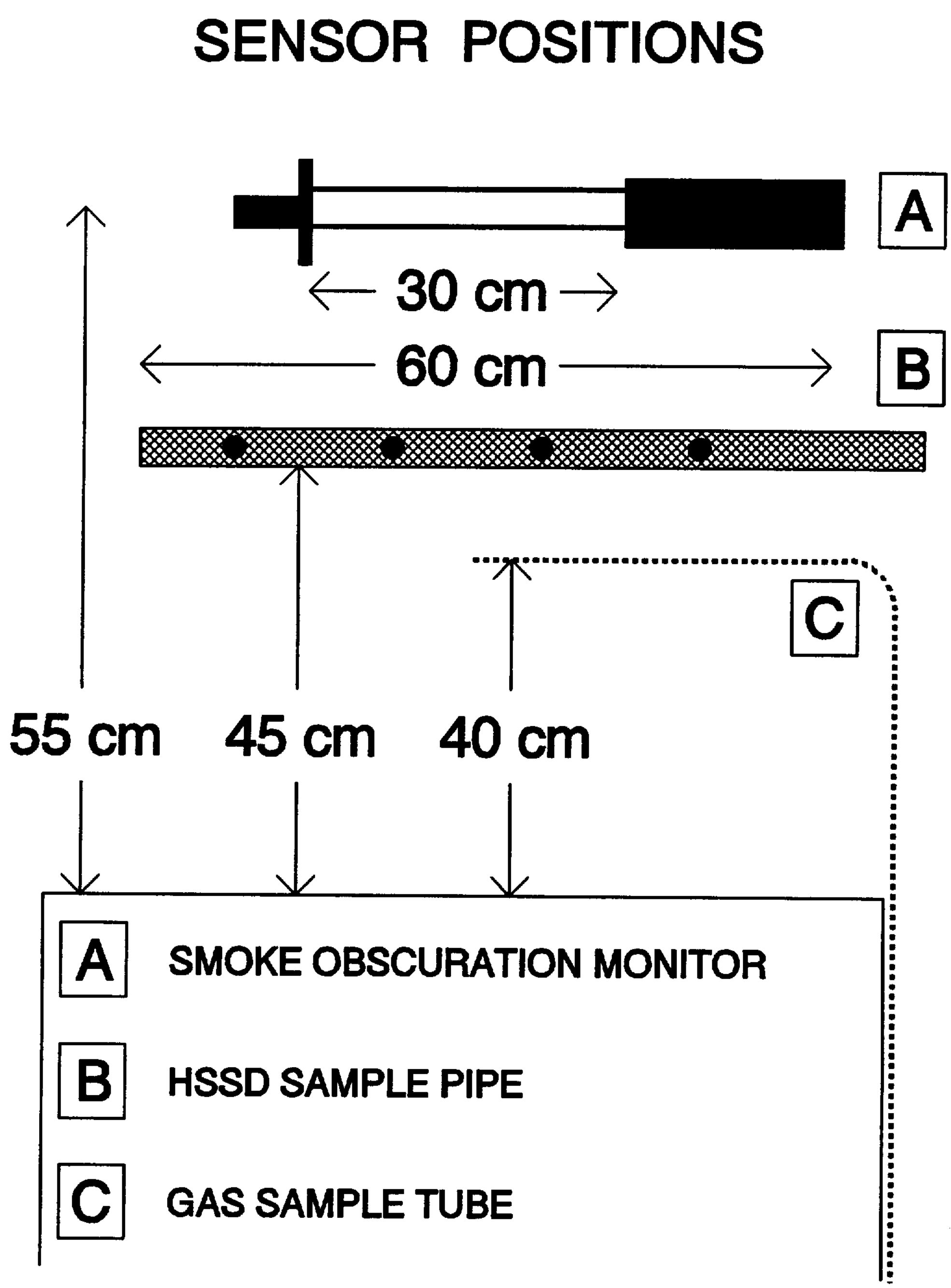

SENSOR POSITIONS
A
30 cm
60 cm
B
C
55 cm
45 cm
40 cm
A SMOKE OBSCURATION MONITOR
B HSSD SAMPLE PIPE
C GAS SAMPLE TUBE

Figure 4

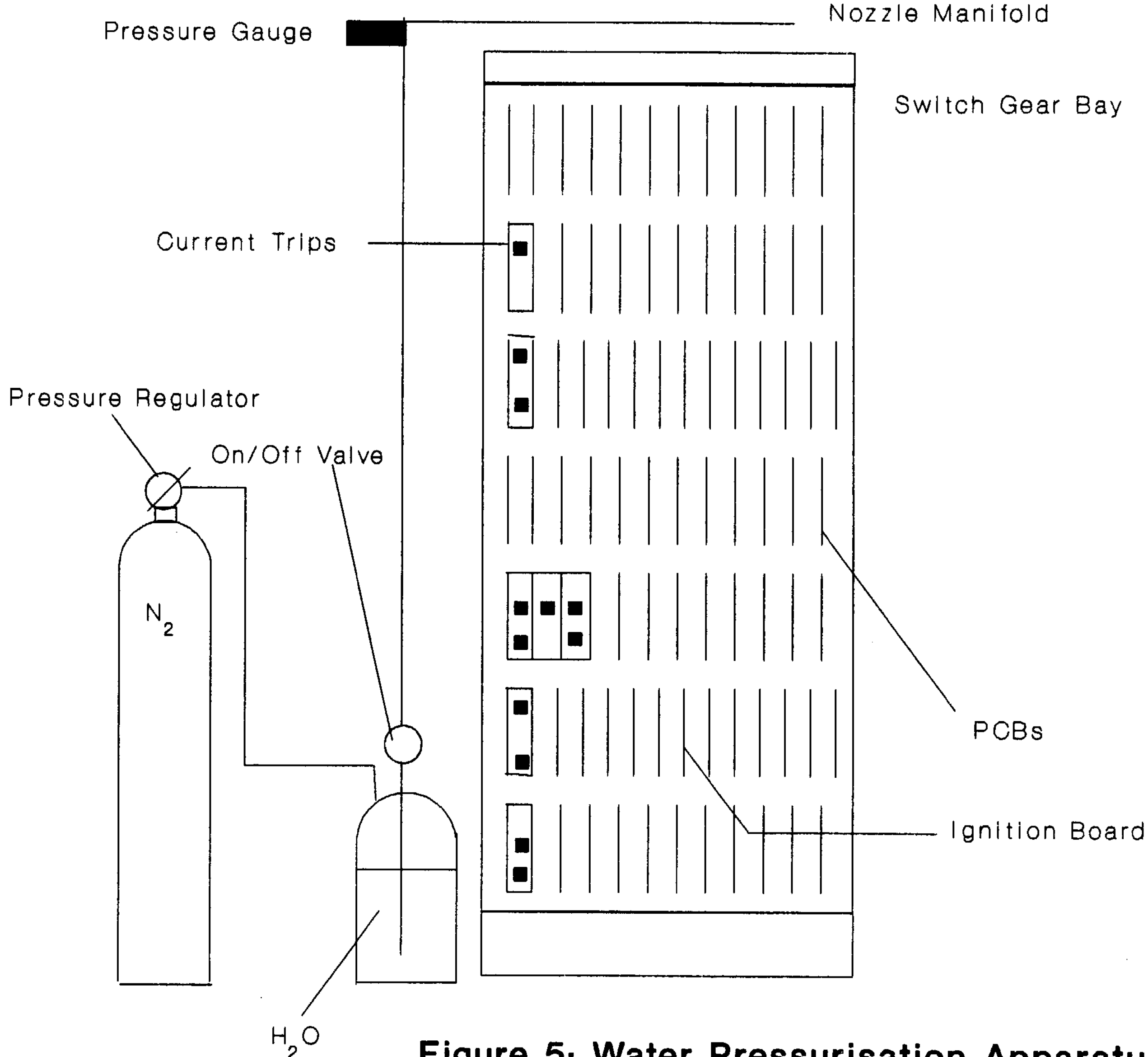


Figure 5: Water Pressurisation Apparatus

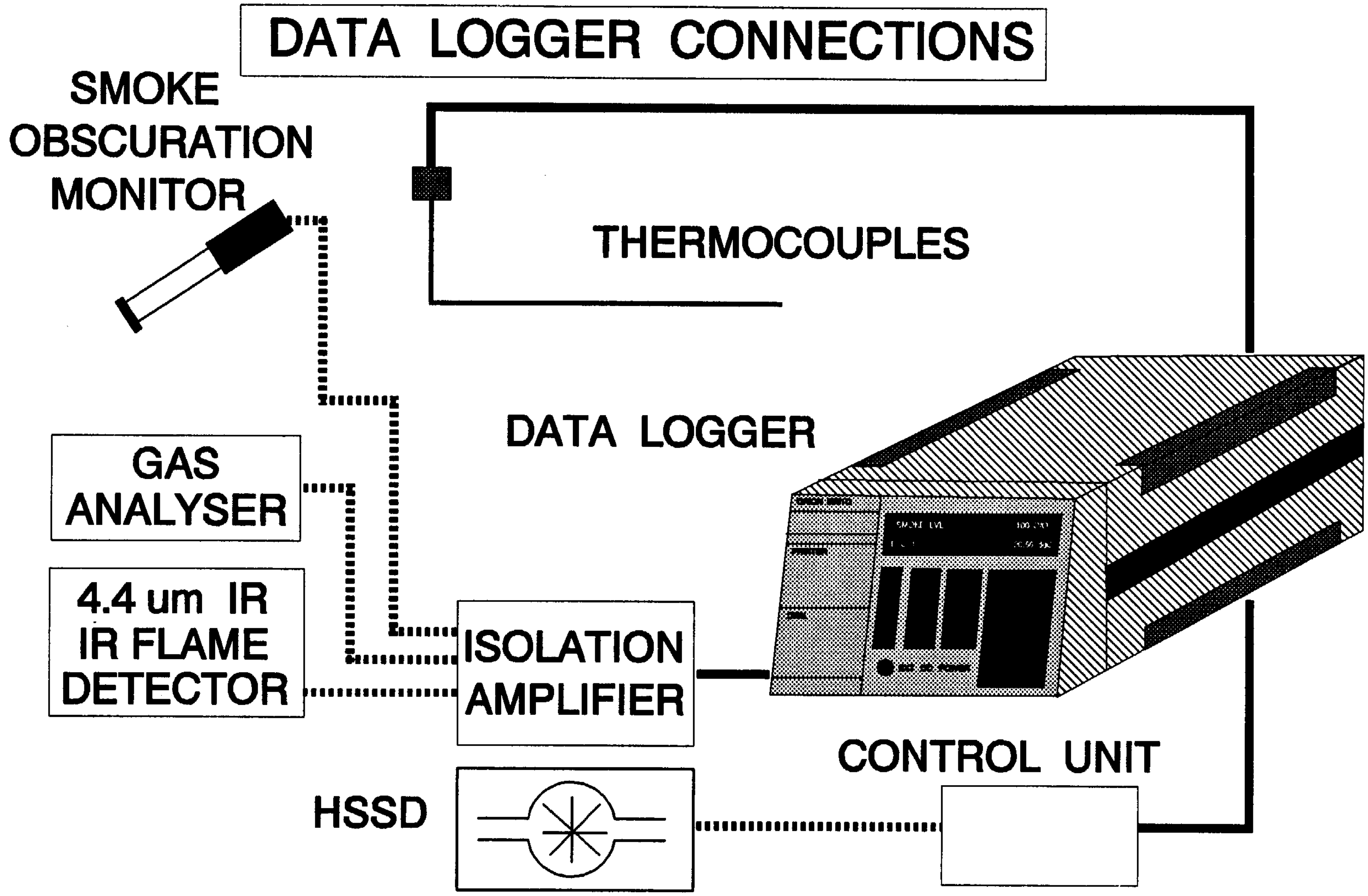

DATA LOGGER CONNECTIONS
SMOKE OBSCURATION MONITOR
THERMOCOUPLES
DATA LOGGER
GAS ANALYSER
4.4 um IR IR FLAME DETECTOR
ISOLATION AMPLIFIER
CONTROL UNIT
HSSD

Figure 6

FIGURE 7

TEMPERATURE PROFILE FOR EXTINGUISHMENT BY HIGH VELOCITY FOG

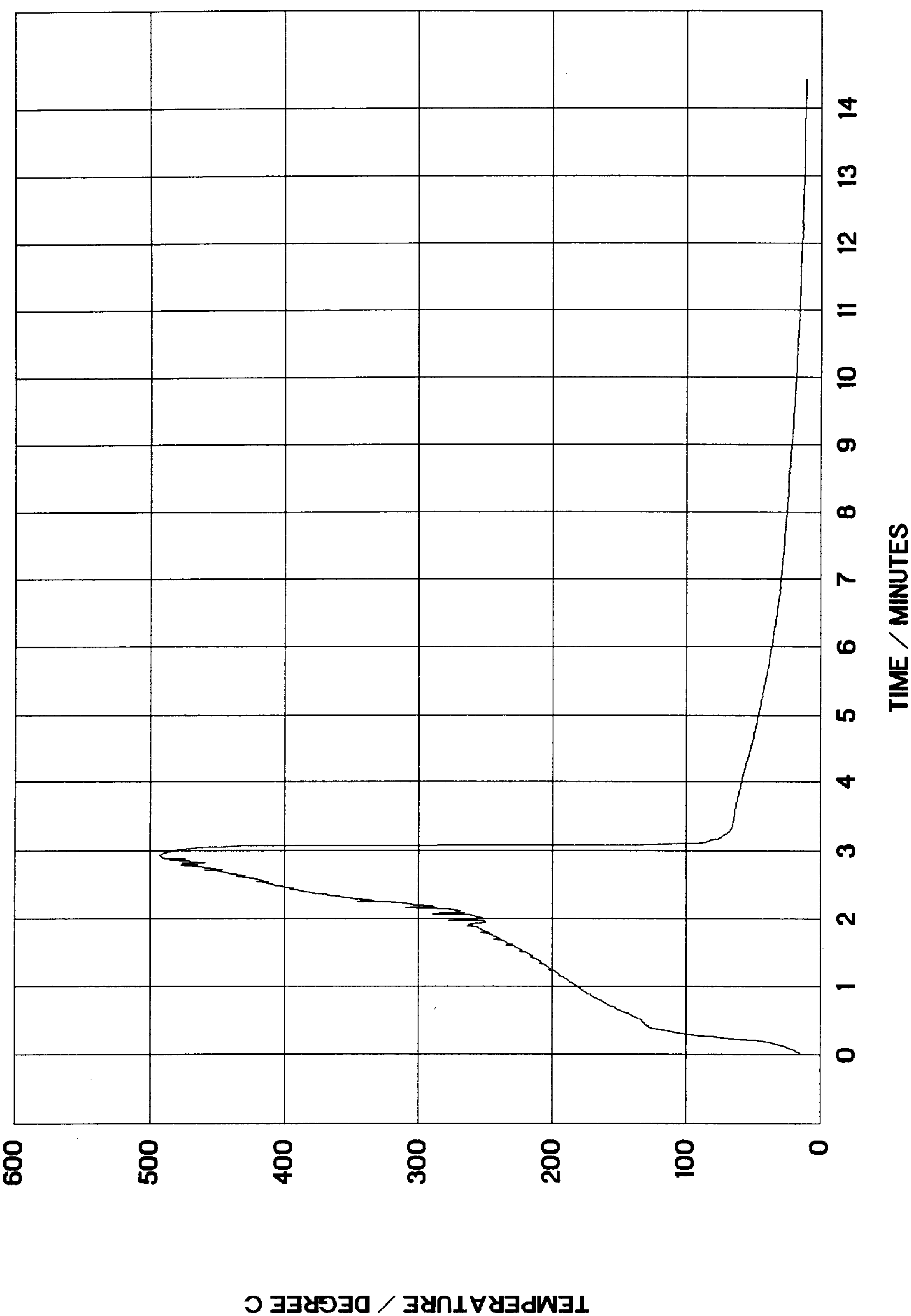


Figure 8: External features of an enclosed telecommunication cabinet

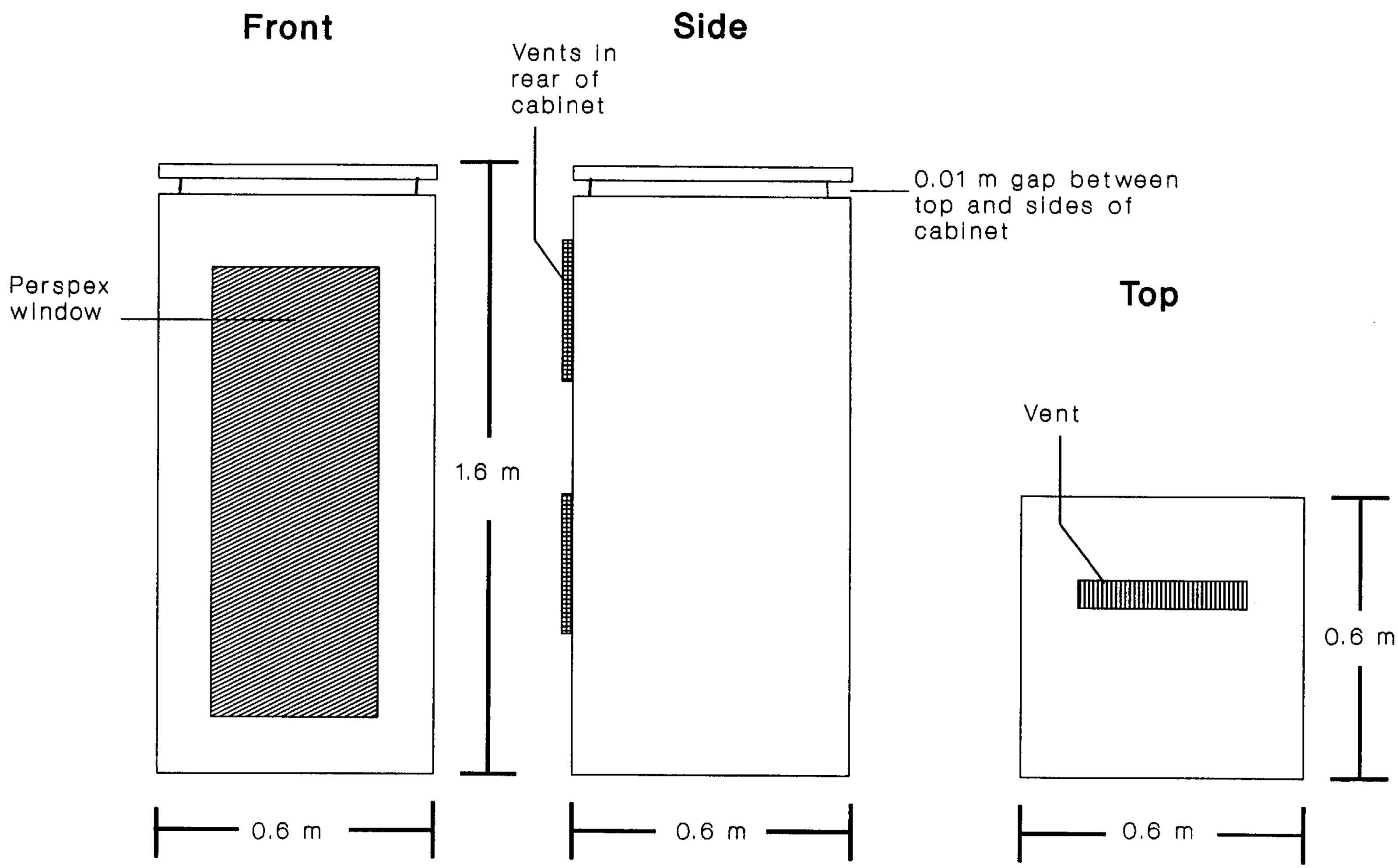
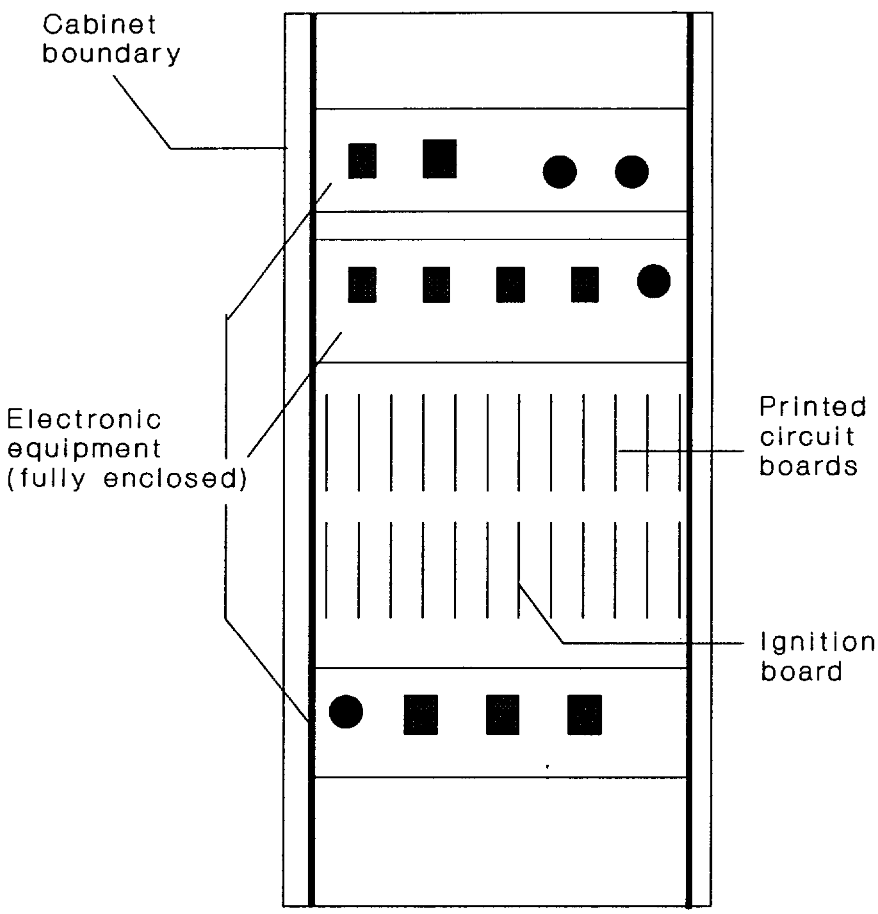


Figure 9: Fire challenge inside an enclosed telecommunication cabinet



5.0 LIST OF PARTICIPANTS

Kathy A. Notarianni
Workshop Chair

Nora H. Jason
Workshop Coordinator

Ronald Alpert
Factory Mutual Research
Box 9102
Norwood, MA 02062-5082

Rebecca Anderson
Johnson & Higgins
1215 Fourth Ave.
Seattle, WA 98161

Donald Anderson
Notifier Co.
12 Clintonville Rd.
Northford, CT 06472

William Anderson
Mobil Oil Corp.
Pennington-Rocky Hill Rd.,
Bldg. 16
Pennington, NJ 08543

William Bachalo
Aerometrics, Inc.
550 Del Rey Ave.
Sunnyvale, CA 94086

Jerry Back
Hughes Assoc.
6770 Oak Hill Lane
Suite 125
Columbia, MD 21045

Charles Barnett
Figgie Fire Protection
1000 E. Edgerton Rd.
Cleveland, OH 44141

Richard Bielen
National Fire Protection Res.
1 Batterymarch Park
Quincy, MA 02269

Robert Bill
Factory Mutual Research
1151 Boston Providence
Norwood, MA 02062

William Blazek
General Services Admin.
18th F Sts., NW
Rm. No. 4308
Washington, DC 20405

Leonard Blum
Reliable Automatic Sprinkler Co.
525 N. MacQuesten Pkwy.
Mt. Vernon, NY 10552

James W. Bowman
DuPont Company
P.O. Box 6090
Newark, DE 19714

Edward Budnick
Hughes Associates, Inc.
6770 Oak Hall Ln.
Suite 125
Columbia, MD 21045

Jay Cannon
Allendale Mutual Insurance
101 Merritt 7, Second Floor
Main Ave.
Norwalk, CT 06851

Bill Carey
Underwriters Laboratories
333 Pfingsten Rd.
FP-Bldg. 5A
Northbrook, IL 60062

David Catchpole
BP Exploration (Alaska) Inc.
900 E Benson
P.O. Box 196612
Anchorage, AK 99519-6612

Marv Charney
Kidde-Fenwal, Inc.
400 Main St.
Ashland, MA 01501

Salvatore A. Chines
Industrial Risk Insurers
85 Woodland St.
P.O. Box 5010
Hartford, CT 06102-5010

W. Mark Cummings
U.S. Coast Guard
1082 Shennecossett Rd.
Fire Res. Branch
Groton, CT 06340-6096

Jean DeHaai
Delavan Inc.
811-4th St.
West Des Moines, IA 50265

Paul DeSipio
Naval Air Warfare Ctr
P.O. Box 5152
Code 6013
Warminster, PA 18974

Philip DiNenno
Hughes Associates
6770 Oak Hall Ln., Suite 125
Columbia, MD 21045

Kevin Dolan
Viking Corporation
210 N. Industrial Park Rd.
Hastings, MI 49058

Bruce Downie
Rutgers University
P.O. Box 909
Piscataway, NJ 08855-0909

Thor Eklund
DOT/FAA Technical Center
Atlantic City International Airport
ACD-240
Atlantic City, NJ 08405

Francis Fendell
TRW Space & Electronics
One Space Park, Bldg. R-1/Rm.1062
Redondo Beach, CA 90278

Dan Filicicchia
Spraying Systems Co.
North Ave. at Schmale Rd.
Wheaton, IL 60189-7900

Russell P. Fleming
National Fire Sprinkler Assn.
4 Robin Hill Park Rd.
P.O. Box 1000
Patterson, NY 12563

Joseph Foehrkolb
Fireline Corp.
4506 Hollins Ferry
Baltimore, MD 21227

John Foreacre
The St. Paul Co.
500 W. Madison, Suite 2600
Chicago, IL 60661

William Fries
Liberty Mutual Insurance Co.
175 Berkeley St.
P.O. Box 140
Boston, MA 02117-0140

Victor Gameiro
Securiplex Technologies Inc.
549 Meloche Ave.
Dorval, Quebec H9P 2W2
Canada

Richard Gann
NIST/BFRL
Bldg. 224, Rm. B250
Gaithersburg, MD 20899

Harvey Goranson
Professional Loss Control Inc.
One Locomotive Drive
P.O. Box 585
Kingston, TN 37763

Casey Grant
NFPA
1 Batterymarch Park
P.O. Box 9101
Quincy, MA 02269-9101

William Grosshandler
NIST/BFRL
Bldg. 224, Rm. B356
Gaithersburg, MD 20899

Alankar Gupta
Boeing Commercial Airplane Grp.
P.O. Box 3707
GU-HP
Seattle, WA 98124

Matthew Gustafson
U.S. Coast Guard
2100 Second St., SW
G-MTH-4, Rm. 1304
Washington, DC 20593

Ian Hanson
I.E.I. (AUST) Pty.Ltd
Unit 7, 192 Kings Grove Rd.
Kings Grove, N.S.W. 2208
Australia

Paul Haugsjaa
GTE Laboratories
40 Sylvan Rd., MS 18
Waltham, MA 02254

Richard Hill
DOT/FAA Technical Center
Atlantic City International Airport
ACD-240 Atlantic City, NJ 08405

Richard Hobbs
Central Sprinkler Co.
451 N. Cannon Ave.
Lansdale, PA 19946

Haukur Ingason
Swedish National Testing
& Research Inst.
Box 857 Brinellgatan 4
50115 Boras
Sweden

Nora H. Jason
NIST/BFRL
Bldg. 224, Rm. A252
Gaithersburg, MD 20899

George Laverick
Underwriters Laboratories
333 Pfingsten Rd.
FP-Bldg. 5A
Northbrook, IL 60062

James Maddry
SAIC
360 Bay St., Suite 200
Augusta, GA 30901

Dan Madrzykowski
NIST/BFRL
Bldg. 224, Rm. A345
Gaithersburg, MD 20899

Timothy Marker
DOT/FAA Technical Center
Atlantic City International Airport
ACD-240
Atlantic City, NJ 08405

Paul Marttila
HI-Fog Fire Prot.
56E Uwchlan Ave.
Rm. 303
Exton, PA 19341

Larry Maruskin
U.S. Fire Administration
16825 S. Seton Avenue
Emmitsburg, MD 21727

Jack Mawhinney
National Research Council
National Fire Lab. M59
Ottawa, Ontario K1A0R6
Canada

Michelle Maynard
NASA
SI-FSD-3
Kennedy Space Ctr, FL 32899

Tillman McCarson
New Mexico Eng. Res. Inst.
901 University Blvd., SE
Albuquerque, NM 87106-4339

Lawrence A. McKenna
AT&T
131 Morristown Rd.
Rm. B2223
Basking Ridge, NJ 07920

Jim Milke
Univ. of Maryland
Dept. of Fire Protection
Rm. 0151
College Park, MD 20742

Dan Mooney
Boeing
1700 N. Moore St.
Suite 2000
Arlintton, VA 22209

Scott Nichols
Northern Fire & Safety
1235 Rt. 23
P.O. Box 833
Butler, NJ 07405

Kathy Notarianni
NIST/BFRL
Bldg. 224, Rm. A252
Gaithersburg, MD 20899

John W. O'Rourke
AT&T
225 Schilling Circle
Cookeysville, MD 21057

Howard W. Packer
El Dupont De Nemours & Co., Inc.
Louviers 33E106
P.O. Box 6090
Newark, DE 19714-6090

Gene Parsons
Marriott Corp.
1 Marriott Dr.
Washington, DC 20058

Costas Polymeropoulos
Rutgers University
P.O. Box 909
Piscataway, NJ 08855
Kent Porter
Boeing Commerical Airplane Grp.
MS 7X-EA - P.O. Box 3707
Seattle, WA 98124

John Ramsey
The Viking Corporation
210 N. Industrial Park
Hastings, MI 49058

Martin Reiss
Cerberus Technolgies
51 Sawyer Rd., Suite 150
Waltham, MA 02154

Hollis Rulon
Atlas Fire Equipment, Inc.
1035 Jersey Ave.
P.O. Box 330
Gloucester City, NJ 08030

Constantine Sarkos
DOT/FAA Technical Center
Atlantic City International Airport
ACD-240
Atlantic City, NJ 08405

William Satterfield
Hartford Steam Boiler
One State St.
Hartford, CT 06102

John Scarff
Marriott Corp.
1 Marriott Dr.
Dept. 924.36
Washington, DC 20058

James R. Schacht
Ansul Fire Protection
One Stanton St.
Research & Development
Marinette, WI 54143

Rick Schartel
Pennsylvania Power & Light
2 N. 9th St., N-5
Allentown, PA 18101

Carmine Schiavone
Central Sprinkler Co.
451 N. Cannon Ave.
Lansdale, PA 19446

Michael Seradiglia
AT&T
131 Morristown Rd., Rm. B2245
Basking Ridge, NJ 07920

Bob Shoemaker
Delavan Inc. 811-4th St.
West Des Moines, IA 50265

John Sileo
Johnson and Higgins
6 Stanford Forum
Stanford, CT 06904

Terence Simpson
FSI Research
Mill House, Poyle Rd.
Colnbrook
Slough, SL3 OHB
England

Stephanie Skaggs
New Mexico Eng. Res. Inst.
901 University Blvd., SE
Albuquerque, NM 87106-4339

Jack Snell
NIST/BFRL
Bldg. 226, Rm. B216
Gaithersburg, MD 20899

James D. Soden
Texaco Inc.
P.O. Box 1404
Rm. 4239 THP
Houston, TX 77251

Patricia Tatem
Naval Research Lab.
455 Overlook Ave., SW
Code 6180
Washington, DC 20375

Antony Turner
Marioff Hi-Fog
14 Stanley Crescent
London W11 2NA
England

Daniel Verdonik
HQ Army Materiel Command
5001 Eisenhower Ave.
Alexandria, VA 22333

Kathy Vernot
Reliable Automatic Sprinkler Co.
525 North MacQuesten Pkwy.
Mt.Vernon, NY 10552

William Webb
Rolf Jensens Associates Inc.
1751 Lake Cook Rd.
Suite 400
Deerfield, IL 60015-5294

Joseph Wolfe
Naval Air Warfare Ctr.
P.O. Box 5157
Code 6014
Warminster, PA 18974

Richard Wright
NIST/BFRL
Bldg. 226, Rm. B216
Gaithersburg, MD 20899

Steven Younis
Ocean City Research Corp.
4805-B Eisenhower Ave.
Alexandria, VA 22304

Bob Zalosh
Worcester Polytechnic Institute
Center for Firesafety Studies
Worcester, MA 01609

Tom Ziegler
GTE
One Stamford Forum
Stamford, CT 06904

Doron Zilbershtein
Underwater Services
600 Northeast 185 St.
Miami, FL 33179

Shlomo Ziv
Underwater Services
600 Northeast 185 St.
Miami, FL 33179

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The water mist fire suppression workshop was organized to facilitate the commercialization of water mist technology in the United States. The imminent lack of availability of halon fire suppressants has sparked worldwide efforts in developing alternative fire fighting agents and delivery systems. Water mist systems are potential replacements in many industrial uses, as well as in new markets, such as commercial passenger aircraft. Speakers presented state-of-the-art papers on the incentives of using misting sprays, the advances in spray drop size measurement and the engineering criteria for water mist fire suppression systems. Three papers discussed projects demonstrating the use of water mist systems in aircraft, marine, and telecommunications applications. With this background the speakers and attendees were divided into three panels: research needs, end use criteria, and marketing. The purpose of the panel sessions was to identify the areas of concern relating to the commercialization of water mist systems. The proceedings bring together the recommendations of each panel and the individual technical papers.

KEY WORDS (MAXIMUM 9 KEY WORDS; 28 CHARACTERS AND SPACES EACH; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES)

fire suppression; water fog; water mist; water sprays; fire research; droplets; drop sizes; fire extinguishment; sprinklers; aircraft; electronic facilities; marine transportation

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