NISTIR 6527

Measurement Needs for Fire Safety: Proceedings of an International Workshop

Thomas J. Ohlemiller
Erik L. Johnsson
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NIST
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

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June 2000

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Measurement Needs for Fire Safety: Proceedings of an International Workshop

Thomas J. Ohlemiller, Erik L. Johnsson and Richard G. Gann

I. Introduction

At the twelfth meeting of the FORUM for International Cooperation in Fire Research, held in Garston, England, the members agreed to convene a workshop focused on improving their capabilities in science-based fire measurements. Such measurements are at the heart of what the member organizations of the FORUM do. Whether they be inputs for fire models, fire characterization parameters for model validation, material or product fire performance, each requires careful quantification as a basis for further progress in this field.

The potential benefits of collaboration among members have long been recognized, but the complexities of transferring funds across national boundaries have proven to be a hindrance. Thus, with this Workshop, members agreed to seek an area of collaboration where each could devote internal funds toward specific mutual goals in the area of fire measurements. The Workshop was convened April 4-6, 2000 to review needs and establish common interests, thereby to converge on one or more specific inter-laboratory projects. The attendees are listed in Appendix A.

The conveners recognized that the subject of fire measurements covers a broad territory. Thus experts from various laboratories were asked to summarize their views on the needs of specific areas, including the capabilities and requirements of fire models (compartment and burning object models) and the measurements implicit in product tests and in quantifying the internal parameters of fires (heat flux, temperature, flow velocities and species concentrations). Appendix B shows the Workshop program, including the names of the invited speakers. Appendix C comprises copies of the visual aids from the invited presentations.

In the following pages, we have summarized the sense of the presentations in the various sessions of the Workshop and also the range of ideas which arose in the discussions following the presentations. Ultimately, the participants voted on the areas of primary interest for collaboration. As discussed below, heat flux measurements emerged as the main candidate.

II. Session on Capabilities of Fire Models

Tokiyoshi Yamada presented a summary of input requirements of zone-type compartment fire models and the measurement needs for model validation. Such models require initial conditions (defining the building configuration and vertical temperature profiles) and boundary conditions (wall thermal properties, the imposed heat release rate and species generation rates that mimic the burning item of interest, natural and forced ventilation flows and, in some cases, exterior wind or pressure conditions). From these inputs the models predict smoke layer height, average layer temperature and average layer species concentrations, as well as static pressure differences

between the building exterior and interior. Dr. Yamada presented desired uncertainties in all of these variables both for smoke filling modeling and smoke control design.

George Hadjisophocleous focused on fire models based on computational fluid dynamics. In general, the input requirements for initial and boundary conditions are similar to those of zone models but, if the information is available, may be more complete. For example, the complete velocity distribution at a compartment air flow inlet is desirable. In principle, these models can handle a complete computation of the test fire as well, but this is very difficult for real products of interest. Also, product yields obtained in free burn conditions and used as model inputs may not be correct in the reduced oxygen conditions of a large compartment fire. The model solutions yield complete descriptions of the space and time distributions of such variables as temperature, flow velocities and species concentrations. Because of the wealth of detail in the model output, it can be difficult to determine the extent of detailed agreement with experiment, especially if the overall character of a fire is captured but its exact behavior is not.

Vytenis Babrauskas addressed the issue of burning rate models for specific items to be found within a compartment. He first addressed items for which some correlation or approximate computational formula was available. These ranged from liquid pools to Christmas trees. Upholstered furniture models were reviewed in some detail but the point was made that these fires get geometrically very complex before they reach their peak heat release rate, making accurate modeling unlikely. Wall and ceiling-lining fire growth models have received extensive attention but appear to need further work; none has been included in a compartment fire model. For a wide variety of other real products, there are no computational formulae. The SFPE Handbook of Fire Protection Engineering **[1]** does include sample heat release rate data for a variety of such products; this list will expand in the revised edition now in preparation. Dr. Babrauskas called for greater attention to the spread of fire among multiple items in a room environment.

The discussion was then opened to all participants to address the most urgent measurement needs for model input, output or validation. The discussion was allowed to range rather widely with no particular attempt at convergence of opinion on measurement needs. We summarize here some of the more prominent ideas which did emerge in the discussion.

- It can be useful to insert into a fire model a sub-model of the type of sensor(s) being used in validation experiments. An example would be a sub-model of each thermocouple that includes its time response and radiation influences. This could aid the comparisons between model and experiment, but it is useful only if the sensor model is accurate.

- There is a need for an internationally accepted (and thus thoroughly validated) set of fire test data which could serve the role of model validation.

- There is room for a more thorough effort in both modeling and experimental validation. The impact of combined model input uncertainties on the model outputs has not been studied

sufficiently. Similarly, the repeatability of experiments used for model validation is not well established.

- Since all measurements contain errors, it would be useful to do a sufficient number to examine overall mass, energy and species balances, as a check on the internal consistency of the measurements.

There was also a generalized focus on species generation, reaction and transport and the need for multi-point measurements, notably in such difficult situations as a doorway after flashover. Similarly, there was general interest in heat flux prediction and measurement.

III. Session on Product Tests

Kristen Opstad discussed product tests, with a focus on those being adopted by the European Union. The tests range from a non-combustibility test whose main purpose is to define this term, i.e., when a material is subjected to an intense furnace exposure, it does not evolve a measurable amount of heat. Such a test does not provide data for fire modelers. Other tests include heat of combustion in a bomb calorimeter which provides an upper limit on the heat to be seen in a real fire. The single burning item test is used for wall or ceiling lining materials. It provides measures of heat release rate, smoke production, flame spread and tendency to produce burning droplets. The heat release rate results are cast in terms of an index based on the peak heat release rate and the time to this peak. Six classes of behavior are then defined, using fire behavior of materials in ISO 9705 as a reference. This provides some guidelines for fire protection engineers in applying the results of this test. There are also eleven new tests dealing with fire resistance. A notable addition to these is the use of a plate thermometer to measure and program furnace temperature.

Pravin Gandhi discussed product tests used in North America. There is a very wide variety of such tests whose results are used in voluntary safety standards or in building code compliance. Most are highly product-specific and do not yield outputs that a fire modeler could use in a predictive manner. In addition to tests for ignitability, combustibility and flame propagation, Dr. Gandhi discussed tests for fire detection sensitivity, for fire resistance of a wide variety of industrial fire control products and for fire suppression.

In discussing product tests in Asia, Yuji Hasemi noted that there has been no movement as yet toward regional harmonization of fire performance requirements. However, in the face of a growing fire problem in parts of the region, there is an increasing interest in applying ISO fire test standards. In most of the region there is little experience with performance-oriented tests. Japan, however, is in the midst of adopting a performance-based code for buildings. For room lining materials, this may be based on ISO 9705, with two smaller scale test alternatives under consideration: a reduced-scale enclosure test and the Cone Calorimeter. The focus of the enclosure test is likely to be toxicity assessment, however, rather than prediction of larger scale flashover potential.

In the discussion section, participants were invited to address whether they wanted to focus on a measurement method for a product or on how an existing product test method could be modified to produce data for fire models or performance-based codes. The discussion instead ranged more broadly, starting from questions and comments evoked by the morning's presentations. A few of the more prominent points made were as follows:

- There have been some large inconsistencies among various facilities in the measurement of heat fluxes, particularly in the context of fire resistance testing. There is a distinct need for a set of guidelines that would improve lab-to-lab consistency and accuracy.

- Reduced-size "room" tests results do not predict full-scale behavior because not all of the scaling parameters can be matched. The result can be qualitative differences in fire growth behavior.

There was some discussion of the toxicity of fire gases and how best to measure them, plus a call for better means to measure them in the context of a fire. It was pointed out that the Cone Calorimeter has been shown to yield quite low levels of carbon monoxide, making it a poor candidate platform for such measurements. The high levels of CO in post-flashover fire gases are evidently the result of quenched combustion chemistry, not simply low ambient oxygen levels.

IV. Session on Fire Parameter Measurements

Ned Keltner focused his presentation on temperature and heat flux issues in the context of large furnaces used for fire resistance measurements. Experience has shown that the instantaneous temperatures in different test furnaces can vary by 100 °C or more and the instantaneous heat flux can vary by a factor of two. Even thermocouples at the same location, oriented differently with respect to the heat source, can disagree by 100 °C. An extensively instrumented "furnace characterization unit" was substituted into the sample position in the furnace to provide redundant measures of heat flux to a sample. Dr. Keltner suggested that this redundant heat flux measurement approach be adapted to other, smaller fire test apparatuses.

William Grosshandler presented an overview of gas flow and gas velocity measurement issues. Duct flows are at the heart of such measurements as heat release rate. The non-spatially-resolved flow measurements typically applied to these have an uncertainty of the order of 5 %. Spatially resolved measurements are needed for validation of field model predictions of fire-induced flows. A number of traditional techniques for point flow measurement are not well adapted to fire. Particle imaging velocimetry is useful but limited in the spatial area it can measure. A related technique applies to the tracking of particles in sprinkler sprays. The areas in most need of improved flow measurements include those through openings into a compartment fire and flows near a fire plume. Optical techniques for this need hardening and larger area coverage capabilities.

William Pitts addressed the problem of temperature measurements in fires. Radiation-based methods were briefly mentioned but the primary focus was thermocouples. Errors in thermocouple measurements of local gas temperatures can be considerable, especially in compartment fires where the radiation field is highly asymmetric. Aspirated thermocouples, which are much less convenient to use, can reduce these errors substantially but not eliminate them. The use of three unshielded thermocouples of different diameters to permit extrapolation to results for zero size yields anomalies when applied to rapidly fluctuating conditions since the thermocouples have differing response times. There is a continuing need for better means to estimate the errors and uncertainties of temperature measurements in fire environments.

The ensuing discussion ranged over these three classes of measurements and the desirability of making each the focus of a collaborative effort. The issue of the time response of thermocouples and the desirability of modeling it received some discussion in light of the anomalous behavior observed by Dr. Pitts. Heat flux measurements received more interest and again the point was made that it is necessary to know the relationship between the heat flux to the burning surface in small scale tests (e.g., the Cone Calorimeter) and full-scale fire tests of real products. One or two participants pressed for further efforts on velocity measurements but there was no consensus in this direction.

It was pointed out that what regulators seek in a product test differs from what fire researchers seek. The former want consistency in the test results; the latter want information that can be generalized to predict product behavior in new situations. This arose in the context of discussions as to where the collaborative efforts should focus - on improvements in fundamental parameter measurements or on product performance factors more immediately of interest to regulatory personnel.

V. Session on Heat Release Rate and Species Measurements

Marc Janssens gave an overview of the measurement of heat release rate from burning objects. Methods based on sensible enthalpy measurement were briefly reviewed but the main focus was on oxygen consumption calorimetry. Small, medium and large-scale applications were briefly reviewed. Available uncertainty analyses were summarized. In a single laboratory, using a single well-defined fuel, uncertainty varies from ± 5 % for the Cone Calorimeter to ± 7 % for large-scale heat release rate measurements. Round robin tests among laboratories at various scales show substantially larger uncertainties. It was pointed out that one possible source of this variability among laboratories is differences in the time response of the calorimeters. This issue of time response and how it affects observed values of peak heat release rate has received little attention.

Per Blomqvist discussed extractive methods of gas analyses in fires. Gas sampling via probes inserted into a fire offers some advantages over optical methods which are degraded by soot but, at the same time, the probe disturbs the fire and one has to be sure that the sample entering the probe emerges unchanged at the other end. Analysis methods for permanent gases and less volatile species were briefly reviewed and the talk then focused on Fourier Transform Infrared

spectroscopy (FTIR). This technique has the advantage of sensitive quantitation of several species simultaneously with a response time on the order of several seconds. Response time is degraded as sensitivity is increased.

Linda Blevins surveyed several non-invasive optical techniques for species concentration determination. Unfortunately, most of these techniques, such as spontaneous Raman scattering or laser-induced fluorescence, are seriously degraded by the presence of soot, especially the heavy soot typical of real room fires. The use of tunable diode lasers is more promising and is the subject of a current NIST research project. These are used for absorption spectroscopy and, as such, are somewhat invasive since localized species absorption measurements require the introduction into the fire environment of a platform having the diode laser and a detection cell. The technique offers promise of detection of a wide variety of species but some significant technical challenges remain.

George Mulholland discussed smoke aerosol measurements. Such measurements are needed for improved detection of fires, product characterization, validation of smoke dispersion models and for sub-grid modeling of flame radiation. Typical uncertainty levels (95 % confidence limits) for smoke concentration when sampled from a duct are ± 10 % but no time resolution is obtained. Time-resolved smoke yield measurements require a technique like optical extinction. As applied in the new NIST Furniture Calorimeter, such a smoke meter is capable of an expanded uncertainty (2 σ) of about ± 20 %. Smoke sampling in flames is more complex, spatial gradients are large and uncertainty levels for various available techniques have not been assessed. There remains a need for a round robin on soot measurement using a standard generator.

VI. Selection of a Topic for Collaborative Work Among FORUM Members

With the completion of the prepared presentations, the discussion turned to the selection of the one (or more) topic(s) of greatest opportunity for collaborative work. All attendees were asked to state their preference as to the single topic area that they viewed as being most needed and most promising in this regard. Polling of the attendees elicited subjects from CO measurements in room fire conditions to velocity measurements in fire plumes or at room openings to measurements of the yield of respirable aerosol particles. There was considerable discussion of whether any collaborative effort should focus on the same overall test environment (e.g., the ISO 9705 room) with differing measurands at each lab or whether all labs should focus on the same measurand within such a room context.

The latter approach prevailed. The most frequently mentioned needs were improvements in measurement of:

- Heat flux to the surface of a burning sample
- Gas velocity over spatial areas in a room fire environment
- Temperature over areas in a room fire environment
- Heat release rate from full-scale burning objects
- Smoke characteristics

When the attendees were asked to vote for their preference on the above list (with the understanding that their laboratory would likely participate in an effort in the expressed area of interest), heat flux emerged as the top choice.

Heat flux is at the heart of burning rate and fire growth in a compartment environment. It is thus of primary importance. The measurement challenge ranges from the mainly radiant fluxes at floor level, to combined radiant and convective fluxes during fire growth and, finally, during burning. In this last area, particularly, it is essential to demonstrate that the sample surface is subject to the same heat fluxes in bench scale tests as seen in full-scale room fires. There were repeated suggestions that multiple methods of heat flux measurement be applied to these problems but no clear consensus on this issue emerged. There was repeated emphasis by several participants on making a room corner test configuration the focal point of heat flux measurements.

The group then discussed a set of goals for the proposed joint measurement effort. The three general goals which emerged are:

- To quantify the level of uncertainty in such measurements as well as the sensitivity of the measurements to the parameters known to affect them,

- To reduce these uncertainties to a point where there is general agreement as to the value and usefulness of the measurements,

- To harmonize the best procedures for such heat flux measurements; this would be expressed in the form of a set of written guidelines.

The need now is for a detailed plan of action toward achieving these goals. It is to include a set of specific tasks and the laboratories responsible for each. The first meeting of the personnel from each laboratory who will be most directly involved in the work has been tentatively scheduled to take place in London in a late July time frame.

There was also interest in pursuing collaborative efforts on two of the other topics mentioned above. Marc Janssens will take the lead in the next steps on improvement of the measurement of heat release rate from room fires. Tokiyoshi Yamada will take the lead on velocity field measurements. No champion emerged in the topic area of temperature distribution measurements.

Acknowledgments

FORUM members kindly consented to providing a venue for the organization of a workshop on collaborative fire measurements. Richard Bukowski of NIST helped move this issue to the forefront of international interaction. Richard Gann served as discussion leader throughout this Workshop.

References

[1] SFPE Handbook of Fire Protection Engineering. 2nd Edition. National Fire Protection Assoc., Quincy, MA, DiNenno, P. J.; Beyler, C. L.; Custer, R. L. P.; Walton, W. D., Editor(s), 1202 p., 1995.

Appendix A - FORUM Workshop Attendance List

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APPENDIX B. Schedule of FORUM Workshop on Measurement Needs for Fire Safety

Day	A.M. (9:00-12:30)	P.M. (1:30-5:00)
Tue, Apr 4		**1:00-4:30 Tuesday only** Welcoming remarks (J. Snell, NIST – United States) Opening remarks (R. Gann, NIST – United States) Presentations on capabilities of Fire Models: Zone Models (T. Yamada, National Research Institute of Fire and Disaster –Japan) CFD Models (G. Hadjisophocleous, National Research Council of Canada) Burning Item Models (V. Babrauskas, Fire Science and Technology, Inc. - United States) [Group discussion of key measurements needed for (a) input and (b) validation, the accuracy and spatial/temporal resolution desired]
Wed, Apr 5	Presentations on product tests: Europe (K. Opstad, SINTEF Civil and Environmental Engineering – Norway) North America (P. Gandhi, Underwriters Laboratories, Inc. – United States) Asia (Y. Hasemi, Building Research Institute – Japan) [Group discussion of the potential of existing pass/fail test methods to provide additional product performance information]	Presentations on property measurements (accuracy, spatial & temporal resolution): Heat Flux (N. Keltner, Ktech Corporation – United States) Flow/Velocity (W. Grosshandler, NIST – United States) Temperature (W. Pitts, NIST – United States) [Group discussion to identify those types of information that are most desirable to characterize product and/or model performance]
Thu, Apr 6	Presentations on species measurements (accuracy, spatial & temporal resolution): Heat Release Rate (M. Janssens, Southwest Research Institute – United States) Gases – extractive (P. Blomqvist, SP Swedish National Testing and Research Institute – Sweden) Gases – In-situ (L. Blevins, NIST – United States) Aerosols (G. Mulholland, NIST – United States) [Group identifies those types of information that are most desirable to characterize product and/or model performance]	Identification of core measurements and best subject(s) for initial development. Identification of small Working Group of people from organizations that would perform the research

APPENDIX C:

FORUM WORKSHOP PRESENTATIONS

Appendix C: FORUM Workshop Presentations

SESSION I.

CAPABILITIES OF FIRE MODELS

ZONE MODEL

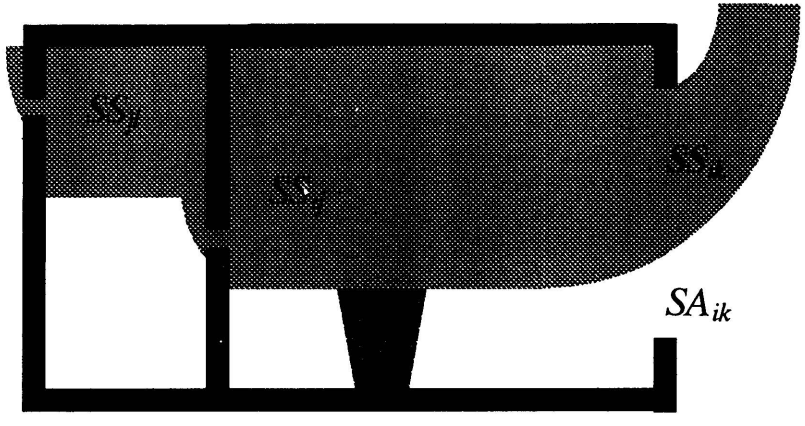
- I/O and required Measurements for Model Validation

FORUM WORKSHOP
at NIST
April,2000

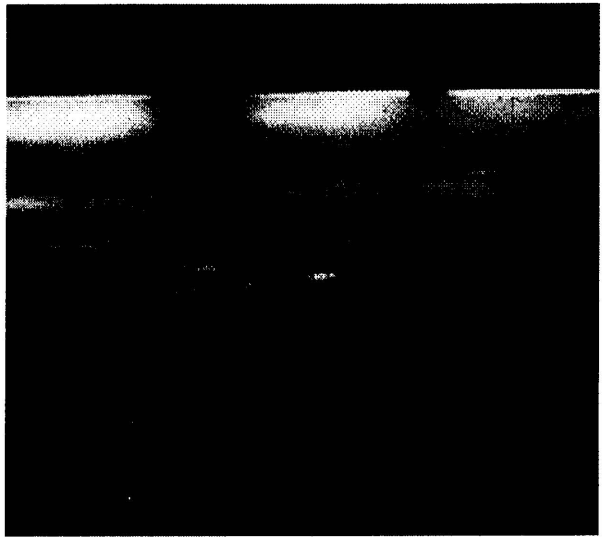
Tokiyoshi YAMADA
(tyamada@fri.go.jp)
National Research Institute of Fire and Disaster
Fire and Disaster Management Agency,
Ministry of Home Affairs
Tokyo JAPAN

What is Zone Model ?

- Fire phenomena characterized by small numbers of zone, which are of uniform temperature and yields of product species (usually 2 zones)
- A set of physical models to reconstruct macroscopic fire phenomena



What is essential for fires being predicted by Zone Model ?



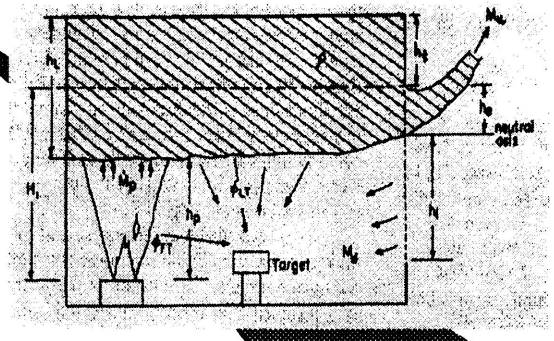
- *For predicting with good accuracy*

  The target phenomena in fires are expected to be characterized by well-mixed and/or layered

Zone model developed (example)

USA

- Harvard Computer Fire Code, FIRST
- CFAST, CCFM, FAST
- ACOS(network), ASET, FPETOOL



JAPAN

- BRI2(T), SMKFLOW(net work model)
- various kind of Code developed by Construction Company (based on BRI2)

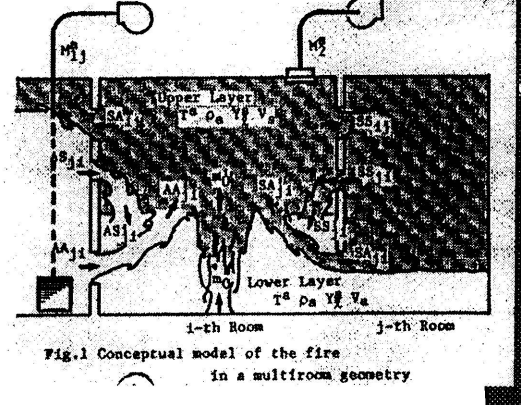


Fig.1 Conceptual model of the fire in a multiroom geometry

AUSTRALIA

- FIRECALC

What are Zone models used for and by whom ?

Very Popular

- **Building Fire Safety Deign by engineering designers**
  - **A. Smoke filling model for large space (atrium, stadium)**
  - **B. Smoke control design (especially pressurization)**

Inexperienced (in Japan)

- **Reconstruction of real fires by attorneys or investigators for court, administrative issues**
- **Education and Fire Fighters Training by Instructors**

A. Smoke Filing model for large space

- **Design Policy**

Use large volume as a smoke reservoir and extend egress available time.

Smoke Filing model for large space

- **Important information required by zone model**

Life safety point of view

1) When will the smoke layer fall down to e[illegible]pe level ?

If it falls down earlier than egress completion, then

2) How large vent is necessary to keep the clear h[illegible]
for evacuation and fire brigade operation ?

3) How hot or contaminated is the smoke layer ?

Building Property damage prevention

4) Can the glass roof in the atrium break by the exposure to the smoke layer?
5) Can the column collapse by the compartment fire?

● Input Data and Its data range, accuracy required

1. Initial Conditions

(a) Building Configulation

Rooms (Width, Depth, Height)

magnitude: $10 \sim 10^2$ m in order

- **Horizontal Section Area on =*f* (Heig**

in real situation : measurable accuracy i 1m (2%)

Opening (Size : Width, Height(top, bottom))

(Location: Orientation, Connection between room

magnitude: $1 \sim 10^2$ m in order

- Flow coefficient α should be specified.(0.7 to 0.85)

The accuracy is almost 5% or little less.

(b) Ambient Temperatures: Inside and outside of the building.

- **Vertical temperature profile =T (Height)**

spatial resolution corresponds to the steepness of temperature,

temporal : a couple of minutes is enough.

- **Input Data and Its data range, accuracy required**

2. Boundary Condition

(a) Thermal Property of Surroundings of large space (Time independent)

κ (Thermal conductivity), ρ (density), c(specific heat) of materials of large area, i.e. ceiling.

- Adequate convective heat transfer α is more important.

(b) Fire Heat Source (Time dependent)

Model fire for design.

Heat release rate: ranging from 3 to 25 MW

Fire Area :0.5 m^2 to 17 m^2

Real Fire: (*discuss in burning Item models in detail)*

Generaly adopt pool fire of methanol.

Heat release rate: estimated by total mass devided by burning time duration. Accuracy is less than 5% empirically.

- Fire area data give much effect on Plume volume.

● Input Data and Its data range, accuracy required

2. Boundary Conditions

(c) Outdoor Conditions of Winds :. *Not well discussed and considered*

Average wind velocity and coefficient of winds pressure are estimated by using reference velocity measurement at the roof top.

Design level : Statistic of the meteorological is utilized.
Most frequent direction and intensity of winds are referenced

Experiment Level: Temporal resolution is 1sec. to 1 min. and 10 to 20 min averaged data are used.
Measuring point is only one base point and various spatial data are estimated as input data for ventilation.

(d) Mechanical Ventilations:

Design level : Only specific exhaust rates are defined.

Experiment Level : *Just trust product specification*

For large space, Indoor static pressure is supposed to be ambient . So mechanical property of "pressure – volume" dose not give much effects on exhaust rate.

Output & Exp. Data required for Model Validation (1)
- Smoke Layer Information (1/2) -

- **Layer Height and the Time Curve**

1)Prediction

Temporal resolution : less than 5 sec. (1 s ideal)
(for evaluating egre)

Spatial resolution : less than 0.5 m in some ight.
(interface of smoke laye us)

- **The required resolution seems to be time & space-dep**
In early stage, smoke layer falls down rapidly, so fine res
preferable for both temporal and spatial features.

2) Measurements required for model validation

Temperature profile (N% method)
Temperature rise, smoke meter , observation

Output & Exp. Data required for Model Validation (2)
- Smoke Layer Information (2/2) -

- **Average Temperature**

  1)Prediction

  Temporal resolution : less than [illegible]sec. (1 sec is ideal)
  Accuracy of Temperature : less than [illegible] for evacuation
  less than 20 [illegible]roperty)

  2) Measurements required for model validation

  Temporal : (same as prediction)
  Spatial : At least 3 thermocouple trees in vertical
  each of them having more than 10 vertic[illegible]

- **Combustion Products**

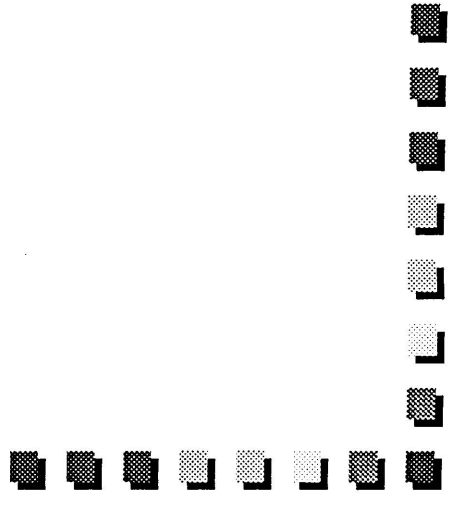
  Temporal resolution : less than 5 sec. cm
  Spatial resolution : one or two base point inside smoke laye[illegible]
  (usually the gas yield is well mixed and unifo[illegible]

FORUM Workshop: Product Tests in North America

Pravinray D. Gandhi, Ph. D., P.E.
Underwriters Laboratories Inc.
333 Pfingsten Rd. Northbrook, IL 60062, USA

Presentation

- Product Testing
- Measurement



Product Testing and Measurements

- Product Testing in the USA
  - Code requirements
  - Voluntary safety standards

Product Testing and Measurements

- Measurements
  - Diverse range of measurements required dependent upon fire performance objectives and product tested
  - Relevant to
    - Test parameters
    - Test results
    - Acceptance criteria

Product Testing and Measurements

- Examples
  - Ignition Property
  - Combustibility and Flame Propagation
  - Fire Detection
  - Fire Resistance
  - Fire Suppression

Ignition Property

- Building construction products and materials
- Interior finish materials
- Plastics insulation
- Specialty materials (e.g., wet-bench plastics)
- Others

Ignition Property

- Some test standards:
  - ASTM E136 - small-scale
  - ASTM E1929 - small-scale
  - ASTM E1354 - small-scale

Ignition Property

- Measurements:
  - Time
  - Total heat flux
  - Temperature
  - Air flow rate
  - Weight loss

Combustibility and Flame Propagation

- Materials, Products and assemblies
  - Insulation plastics
  - Interior finish
  - Furnishings
  - Wire and cable
  - Roofing materials
  - Others

Combustibility and Flame Propagation

- Some test standards:
  - UL 94 - small-scale
  - ASTM E1354, ASTM E1317 - small-scale
  - UL 1715 - full-scale
  - ASTM E84, UL910/NFPA 262, UL 1056, UL 900, ASTM E108 - product scale

Combustibility and Flame Propagation

- Measurements:
  - Time
  - Velocity
  - Temperature
  - Smoke obscuration
  - Weight loss
  - Gas flow rate
  - Flame propagation
  - Gases
  - Radiant and total heat fluxes

Fire Detection

- Products
  - Smoke detectors
  - Smoke detection systems
  - Heat detectors

Fire Detection

- Some test standards:
  - UL 268 - product-scale
  - UL 268A (air duct) - product-scale
- Measurements:
  - Smoke obscuration
  - Gases
  - Temperature

Fire Resistance

- Products and assemblies
  - Fire doors
  - Floor and ceiling assemblies
  - Structural members
  - Fire stop materials
  - Fire safes
  - etc.

Fire Resistance

- Some test standards:
  - ASTM E119, UL 263, UL 10B, UL 10C
- Measurements:
  - Temperature
  - Pressure difference
  - Gas flow rate
  - Radiant and total heat fluxes
  - Deflection

Fire Suppression

- Products and systems
  - Fire extinguishers
  - Foam agents
  - Sprinklers
  - Clean room systems
  - Misc. Hardware

Fire Suppression

- Some test standards:
  - UL 199 - product-scale,
  - NFPA 750 - product-scale
  - Large-scale fire tests

Fire Suppression

- Measurements:
  - Time
  - Water flow rate
  - Temperature
  - Water pressure
  - Gas analysis
  - Gas flow rates
  - Liquids flow rate
  - Foam-water proportioners
  - etc.

Summary of Measurements

- Time
- Temperature
- Length
- Weight
- Pressure
- Gases
- Smoke obscuration
- Velocity
- Gas flow rate
- Water flow rate
- Liquid flow rate
- Radiant heat flux
- Total heat flux
- Others

ASIA

Yuji Hasemi
Building Research Institute
Japan

- No movement toward Regional Harmonization
- Significant Increase of Fire Loss and Large Fires in NICS during 1990s
- Growing Interest in ISO
- Little Experience with Performance Oriented Fire Tests

HISTORY AND BACKGROUND

1982 - 1987	MOC R & D Program on Fire Safety Design Method
1986 - 1991	MOC R & D Program on Wooden Construction
1992	ISO Domestic Liaison Secretariat moved from JISC to I^2BH
1993 - 1998	MOC R & D Program on Fire Testing
1998 June	Revision of Building Standard Law(BSL) toward Performance-based Standard
2000	Liberalization of BSL Fire Safety Appraisal
2000 June	Revision of BSL Enforcement Orders Revised and New MOC Notifications

MOC Sopro Proposal for Reaction-to-Fire Test Framework

Reference

- ISO9705 Room Corner Test

Alternatives for limited fire scenarios and materials

- Revised Model Box Test

- ISO5660 Cone Calorimeter

BRI Proposal for the New Reaction-to-Fire Test Framework

- ISO9705 Room Corner Test
- Revised Model Box Test
- ISO5660 Cone Calorimeter

New BSL Reaction-to-Fire Test Framework

Successor of the Surface Test

- ISO5660 Cone Calorimeter
- Gas Toxicity Test ?

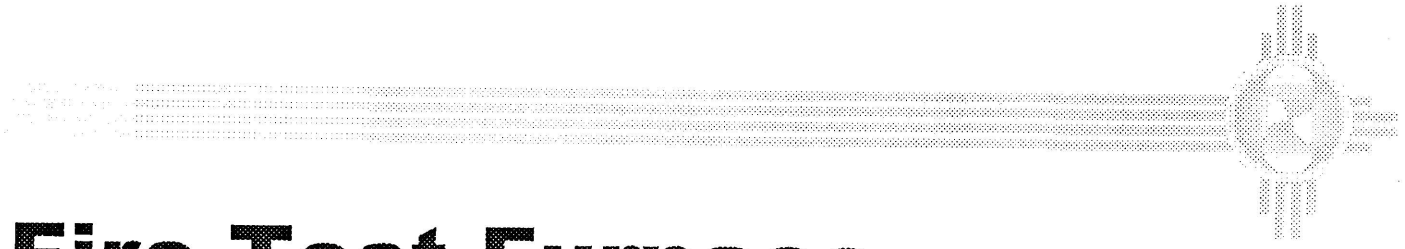
Evaluation of Design Solutions

- ISO9705 Room Corner Test?
- Revised Model Box Test?

Appendix C: FORUM Workshop Presentations

SESSION III.

PROPERTY MEASUREMENTS (ACCURACY, SPATIAL AND TEMPORAL RESOLUTION)



Fire Test Furnace Characterization Unit

U. S. Coast Guard R & D Center

Workshop - Measurement Needs for Fire Safety

National Institute for Standards and Technology

April 3-7, 2000

Ned Keltner - Ktech Corporation

project officer: Louis Nash - U. S. Coast Guard

program manager: Jesse Beitel - Hughes Associates

Fire Safety Science & Standardized Tests

Ktech CORP.

- Overall, fire safety science is making significant advances
  - ► Modeling - physical phenomena, zone models, field models
  - ► Test methods - harmonizing national standards
  - ► Measurements - small & intermediate scale tests
- Unfortunately, progress on large furnace tests has been slow
  - ► Current efforts to improve measurement & control techniques
  - ► Current efforts to measure heat transfer in furnaces

- U. S. Coast Guard sponsored work has two main goals
  - ► Characterize thermal exposure in furnaces with a representative device
  - ► Use the results as an aid to harmonizing exposure in different furnaces

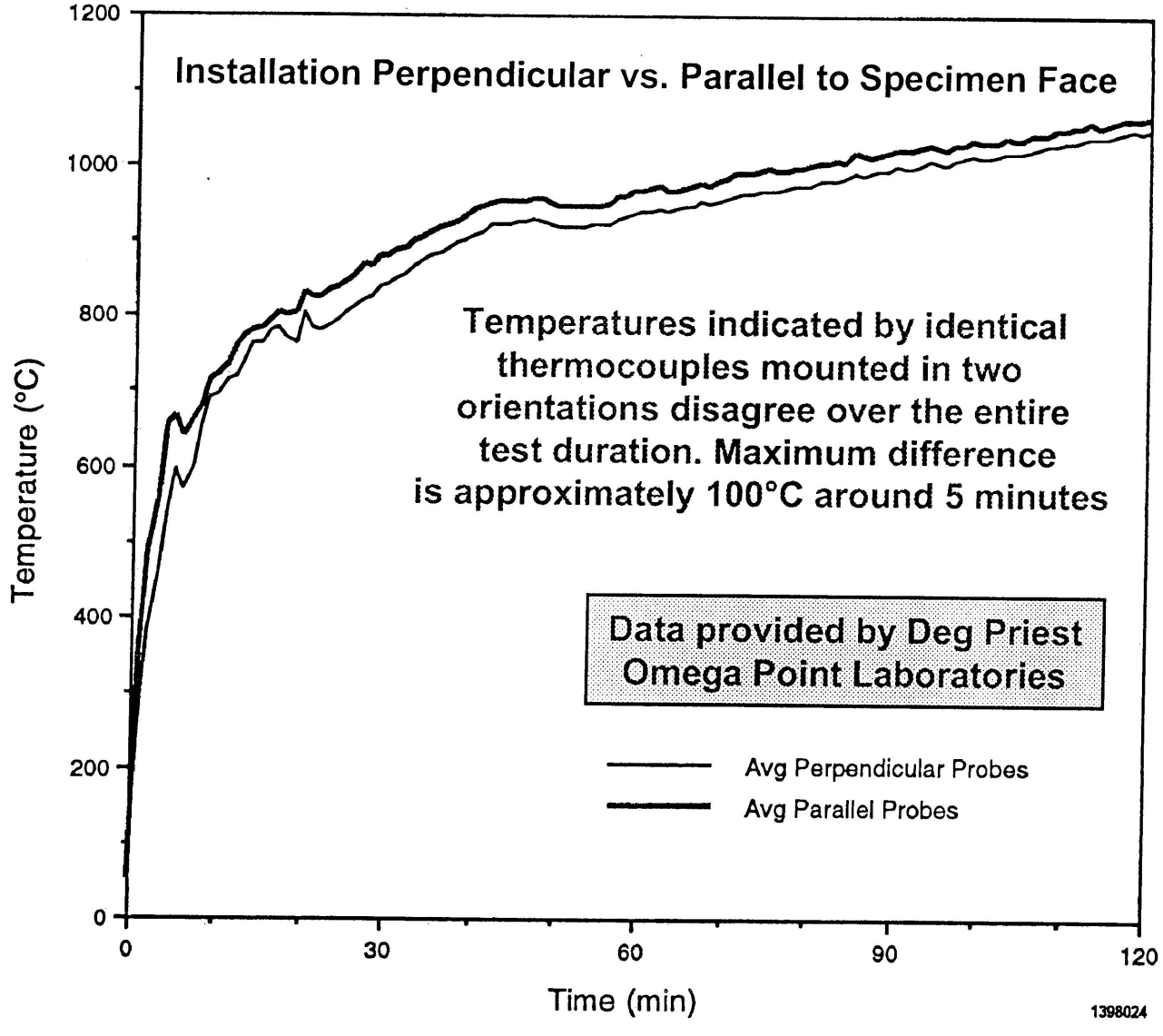
The Problem with Fire Safety Test Furnaces

Ktech CORP.

- U. S. Coast Guard fire safety test results vary significantly
  - ► Different furnaces produce different temperature histories (100°C or more at a given time) and different heat flux levels (up to 2X)
- Large variations are due to a number of factors including
  - ► Furnace size and lining
  - ► Furnace control thermocouple design, size, and installation
  - ► Fuel type (natural gas, propane, or fuel oil)
  - ► Test specimen properties
- A number of the causes have been studied and documented
  - ► Does the implicit assumption of $q = \varepsilon \cdot \sigma \cdot T^4$ work in furnace tests?
  - ► Analysis & Comparison of Marine Fire Testing Regulations & Procedures N. A. Wittasek - MS Thesis - Worcester Polytechnic Institute - 1996

Installation & Temperature Measurement Uncertainty ISO 834 Furnace Control Thermocouple Assemblies:

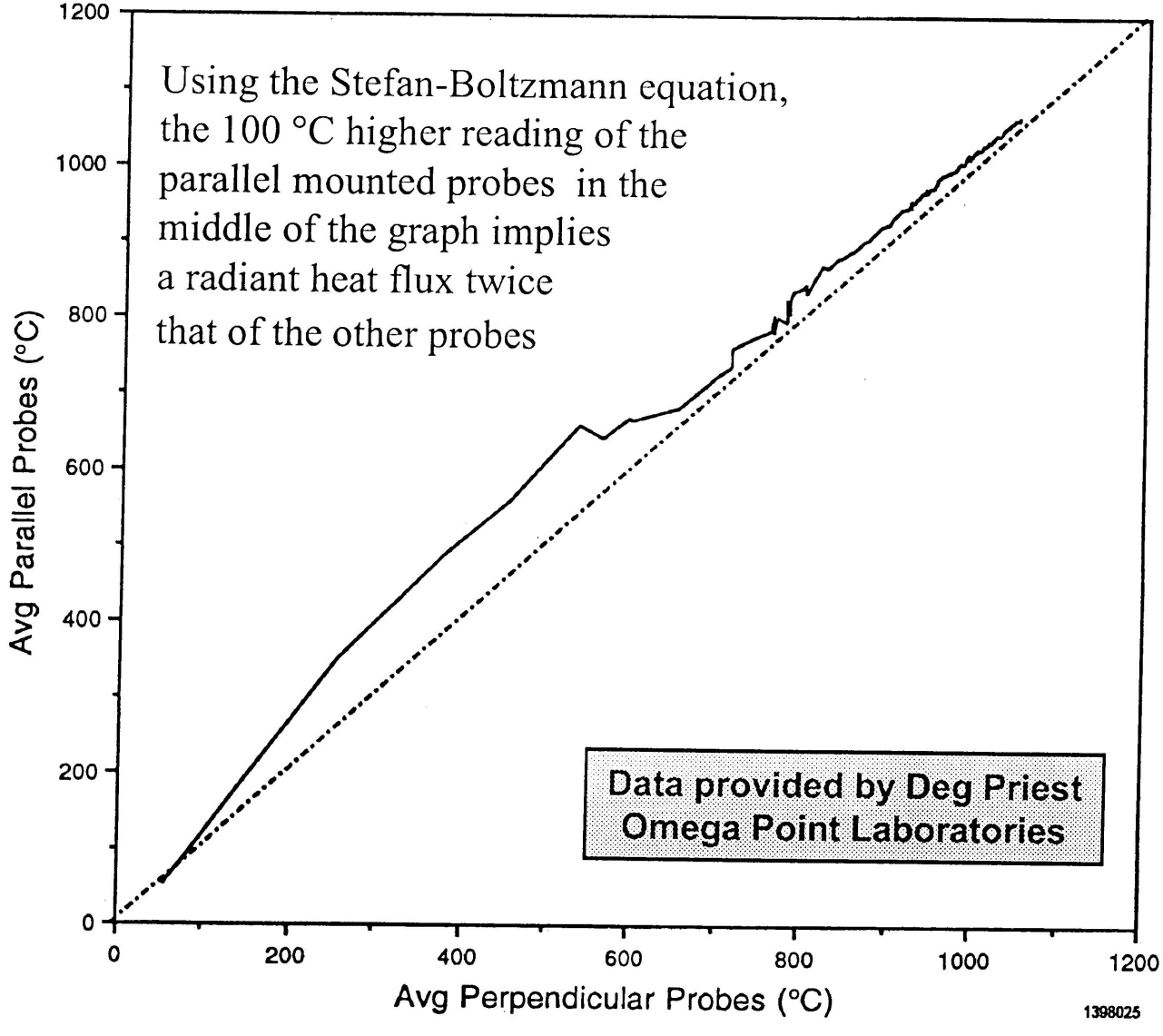
Ktech CORP.



Parallel vs Perpendicular ISO Furnace Probes

Radiant heat flux estimates vary with indicated temperature

Ktech CORP.



What Does & Doesn't a Thermocouple Measure?

Ktech CORP.

- Furnace temperature measurements re-emphasize well-known but often-forgotten points:
  - A thermocouple can only measure its own temperature
  - *Measured thermocouple temperature* is related to but is not the same as the *temperature of the process* in which you are interested
- Measurements using conventional thermocouple designs
  - Indication is the result of an energy balance
  - Provide insufficient information for calculating heat flux
- Measurements using directional flame thermometers (DFT)
  - Double sided design enables an energy balance
  - Transient (calorimetric) & steady (effective radiation temperature) data

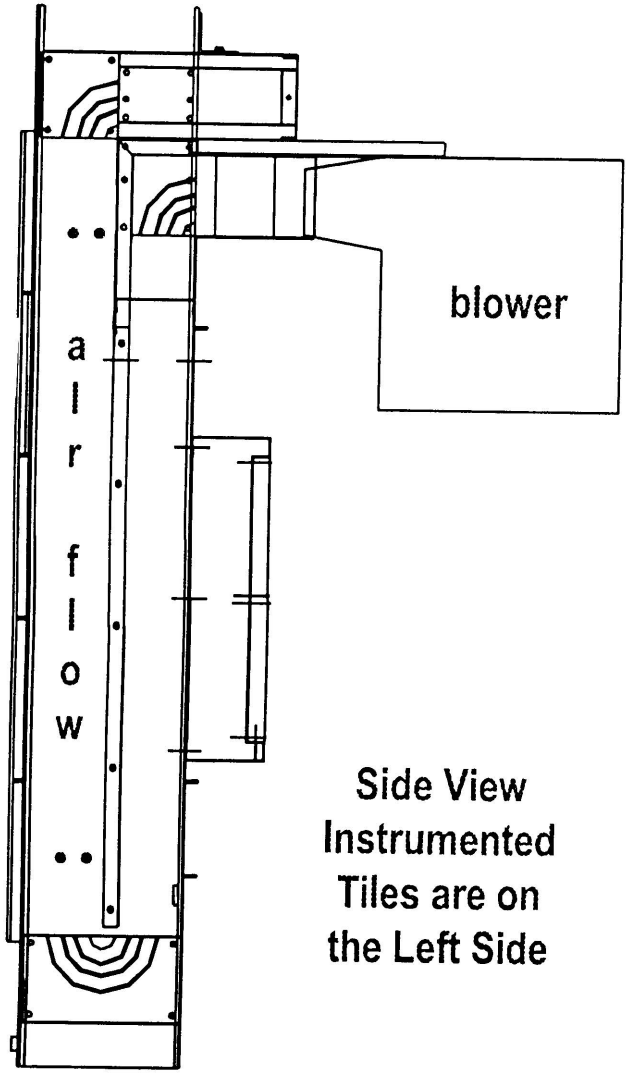
Furnace Characterization System Design

Ktech CORP.

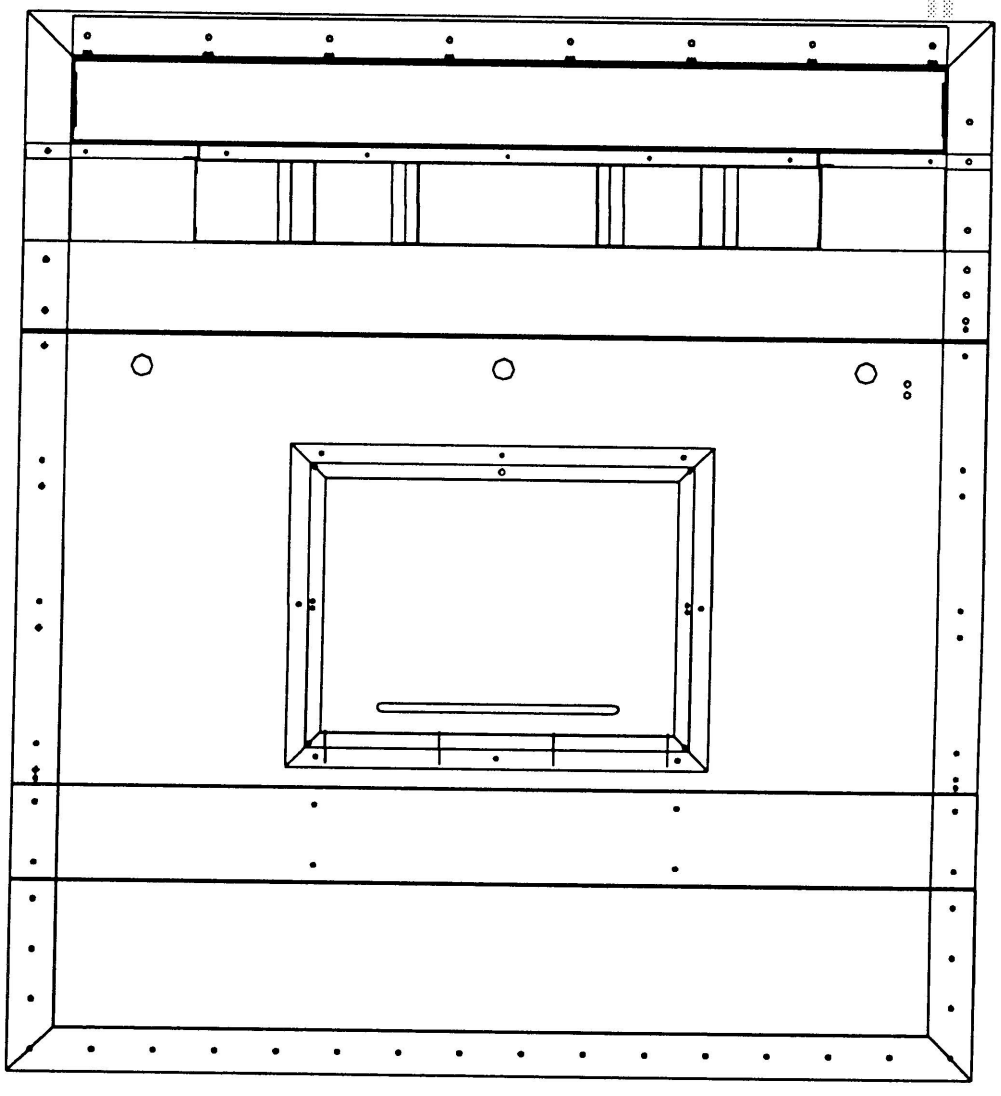
- U. S. Coast Guard R & D Center - initiated development of a system for characterizing temperatures and heat fluxes in fire safety test furnaces
- Design is an integrated measurement - acquisition - analysis package
  - ► Large size (1 m x 1m) with a multi-point sensor array
  - ► Digital data acquisition system & portable computer
  - ► Utilizes nonlinear parameter estimation and inverse heat conduction codes
- Features
  - ► All metal construction with thermal inertia similar to a marine bulkhead
  - ► High temperature capability — heated surface up to 1000°C
  - ► Redundant measurements of heat transfer
  - ► Uses both standard thermocouples and directional flame thermometers

Furnace Characterization Unit Layout

Ktech CORP.



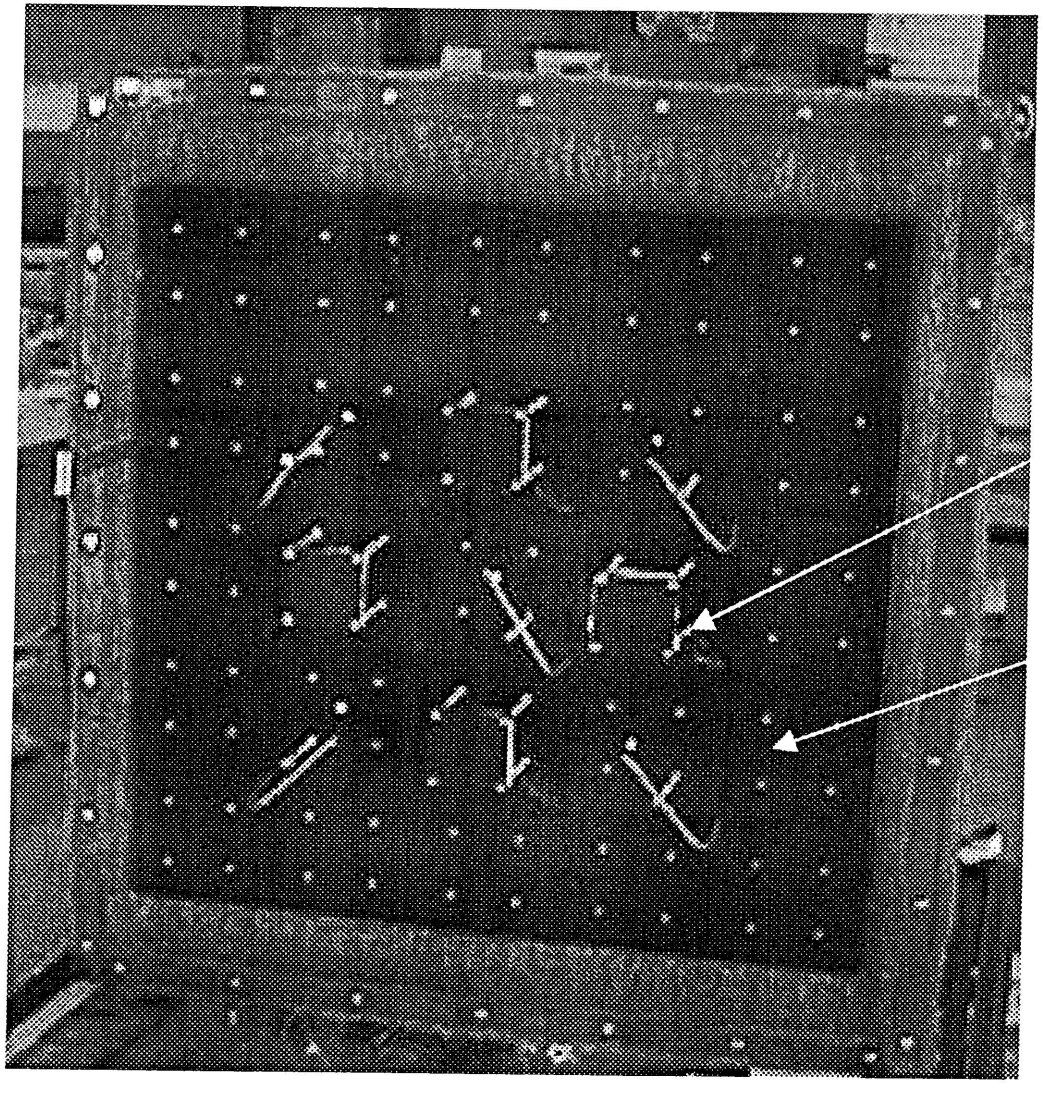
Side View
Instrumented
Tiles are on
the Left Side



1598026
FCU_talk—8

Exposed Surface of the Furnace Characterization Unit

Ktech CORP.



Directional Flame Thermometers

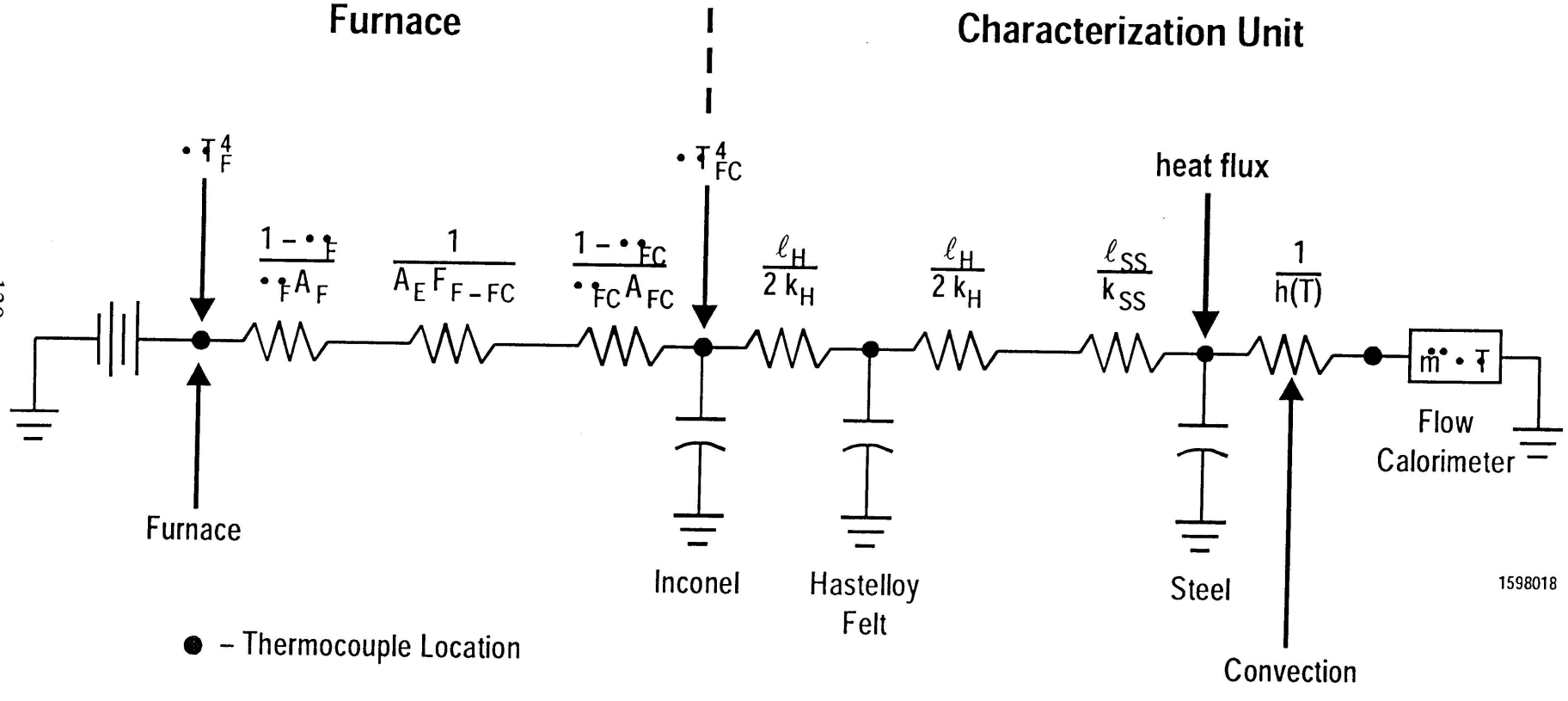
Inconel Tiles

Design Issue Tests - Four Tile Instrumented Array

Ktech CORP.

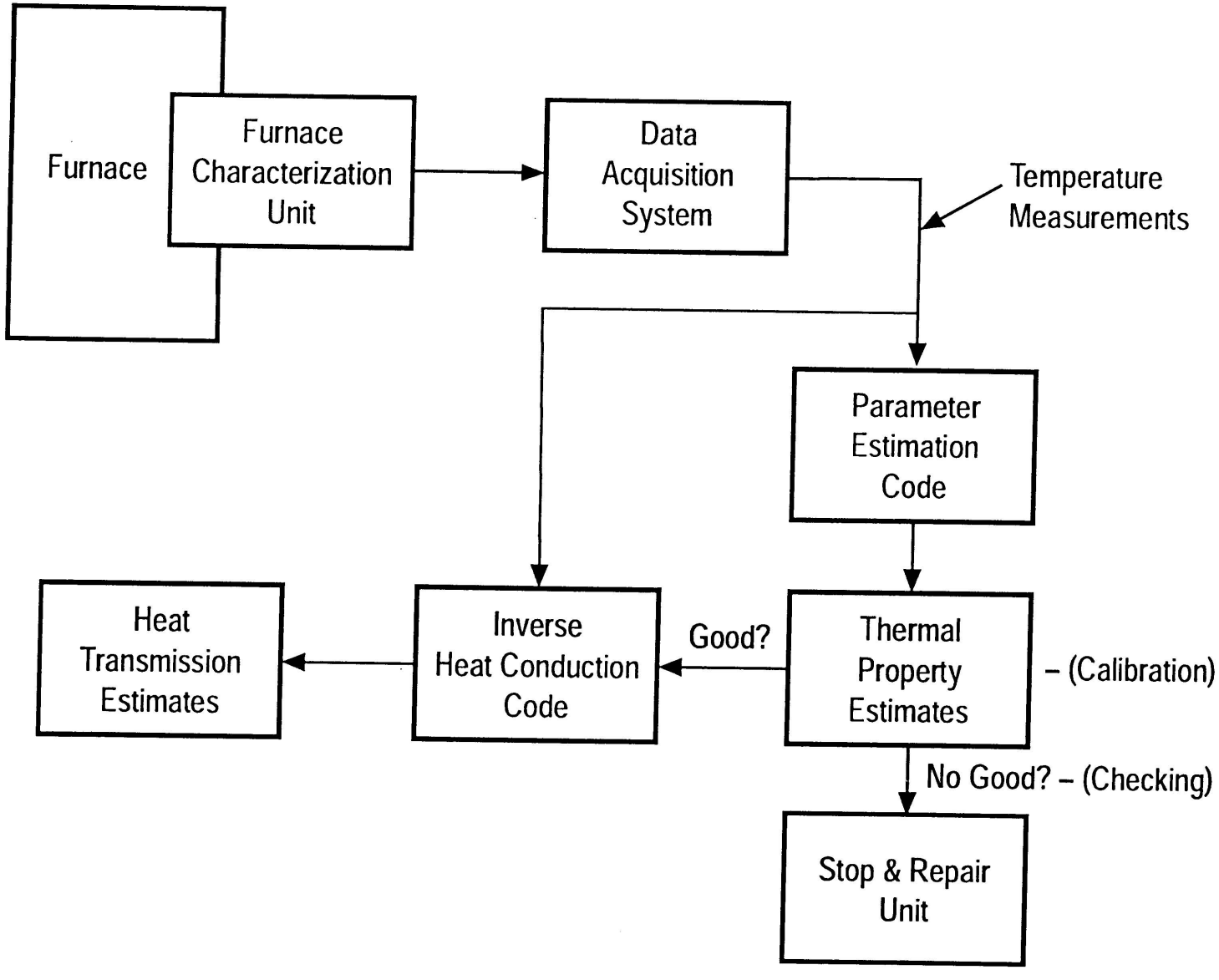
Simplified Thermal Model Used for Interpreting Test Data

Ktech CORP.



Furnace Characterization Unit Data Flow

Ktech CORP.



Numerical Techniques for Estimating Thermal Properties and Heat Transfer Rates

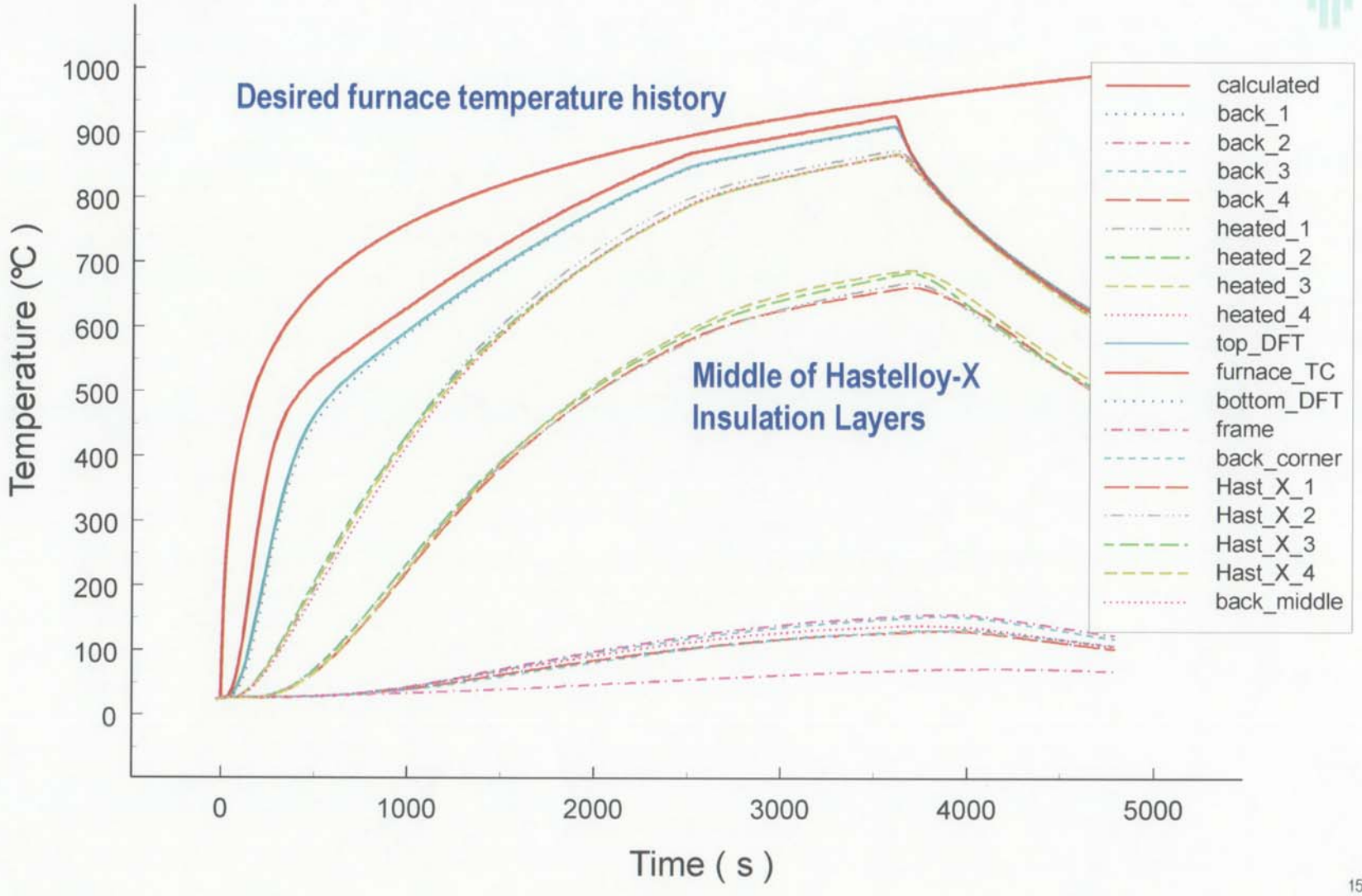
Ktech CORP.

- Parameter Estimation Code - (nonlinear - i.e., temperature dependent)
  - Multi-Layer Materials
    - If some material properties are known - calculate properties of unknown layers
    - Assumed the properties of Inconel 600, volumetric heat capacity of Hastelloy-X metal felt, and Steel Backface were known
  - Estimated Thermal Conductivity (values incorporate as-built variations)
    - Hastelloy X Metal Felt vs temperature and stainless steel wool
    - Used measured temperatures of Inconel, mid-plane of the Hastelloy-X, plus temperature and heat flux on Steel
- Nonlinear Direct & Inverse Heat Conduction
  - Direct Mode - Interior Temperatures for Defined Boundary Conditions
    - Most thermal analysis codes operate in this mode
  - Inverse Mode - Surface Heat Fluxes or Surface Heat Transfer Coefficients
    - Uses interior temperature histories with thermal properties estimated above

Design Issue Test Data 8-13-97

Showed good agreement between four tiles

Ktech CORP.



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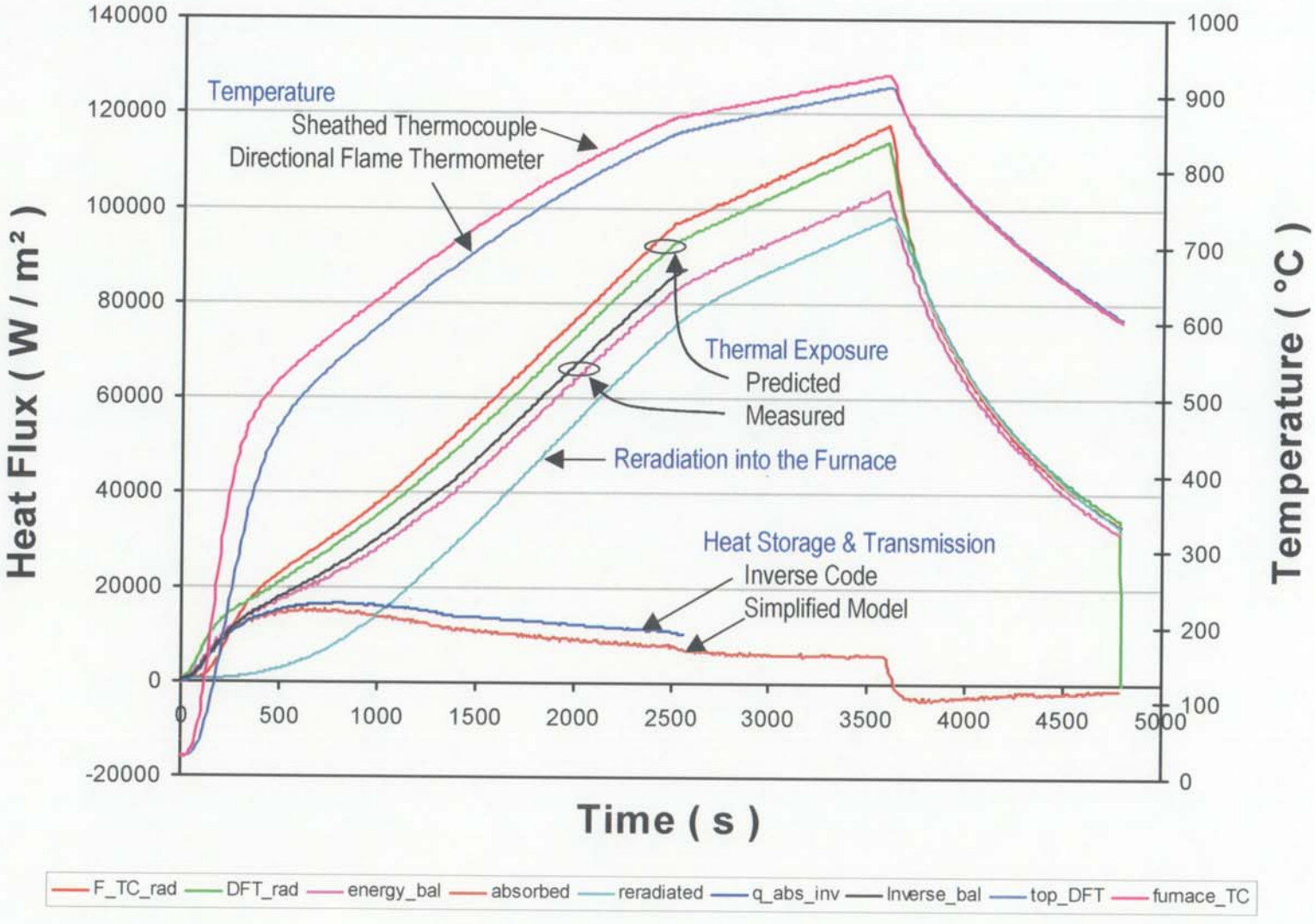
Simplified & Inverse Analyses of Data

Ktech CORP.



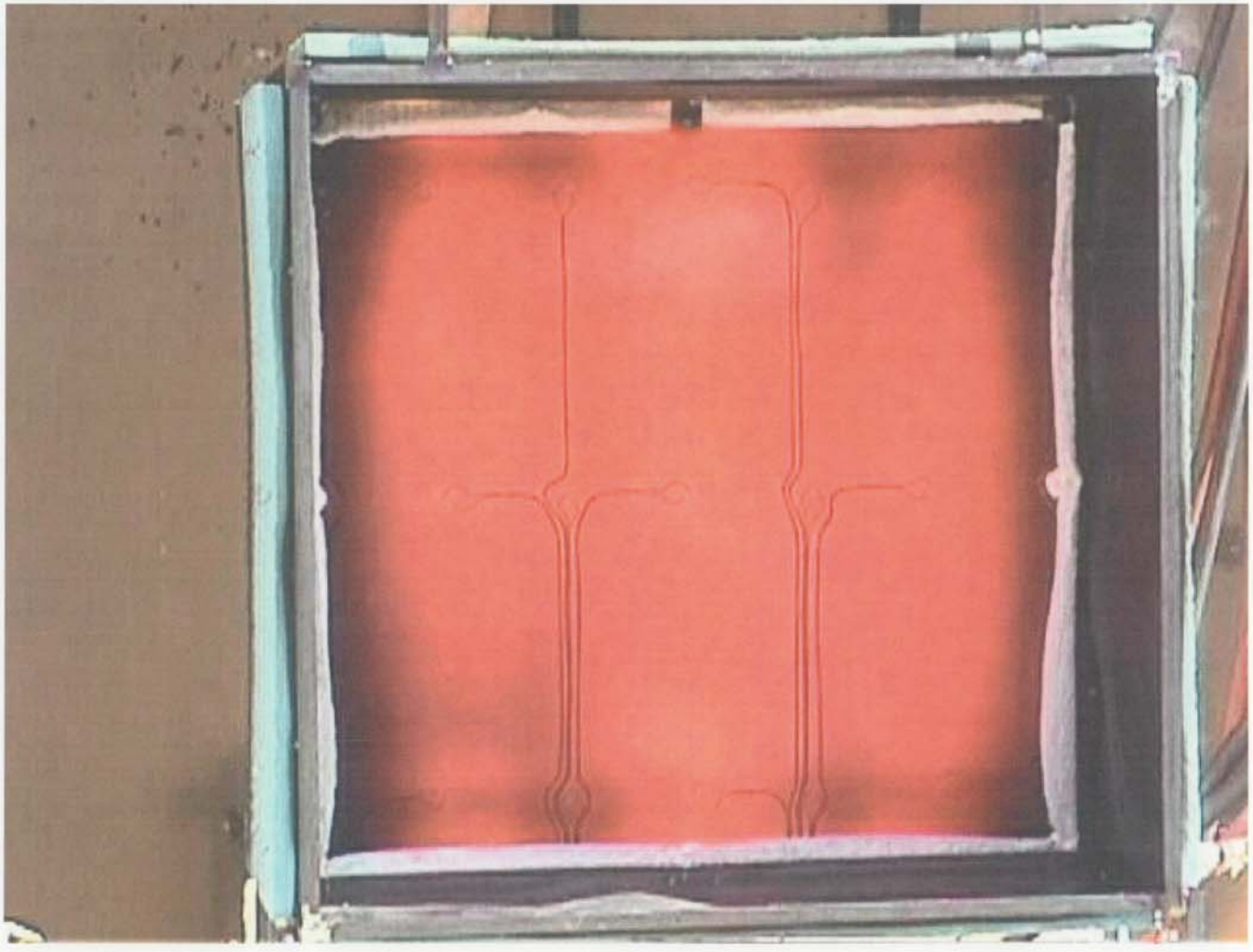
FCU Calibration Tests

Ktech CORP.

- Calibration Tests were run at Sandia National Laboratories
  - Tests used the Dial-a-Fire Fixture - a fast, programmable electric furnace
  - All six surfaces of the test enclosure were instrumented
  - Three tests followed the logarithmic time-temperature curve specified in International Maritime Organization Regulation A754
  - Three tests followed a stair-step time-temperature profile
- Heat Fluxes from the Logarithmic Curves
  - Peak absorbed heat fluxes were 20 - 25 kW / m^2
  - Peaks occurred at approximately 15 minutes
  - Repeatability in peak values between 3 tests - 3%
- Radiosity Analysis
  - Accurately predicted DFT temperatures (within 1%)

FCU Calibration Setup - Dial-a-Fire Heater Shroud

Ktech CORP.



Calibration Results - Logarithmic Time-Temperature Curve

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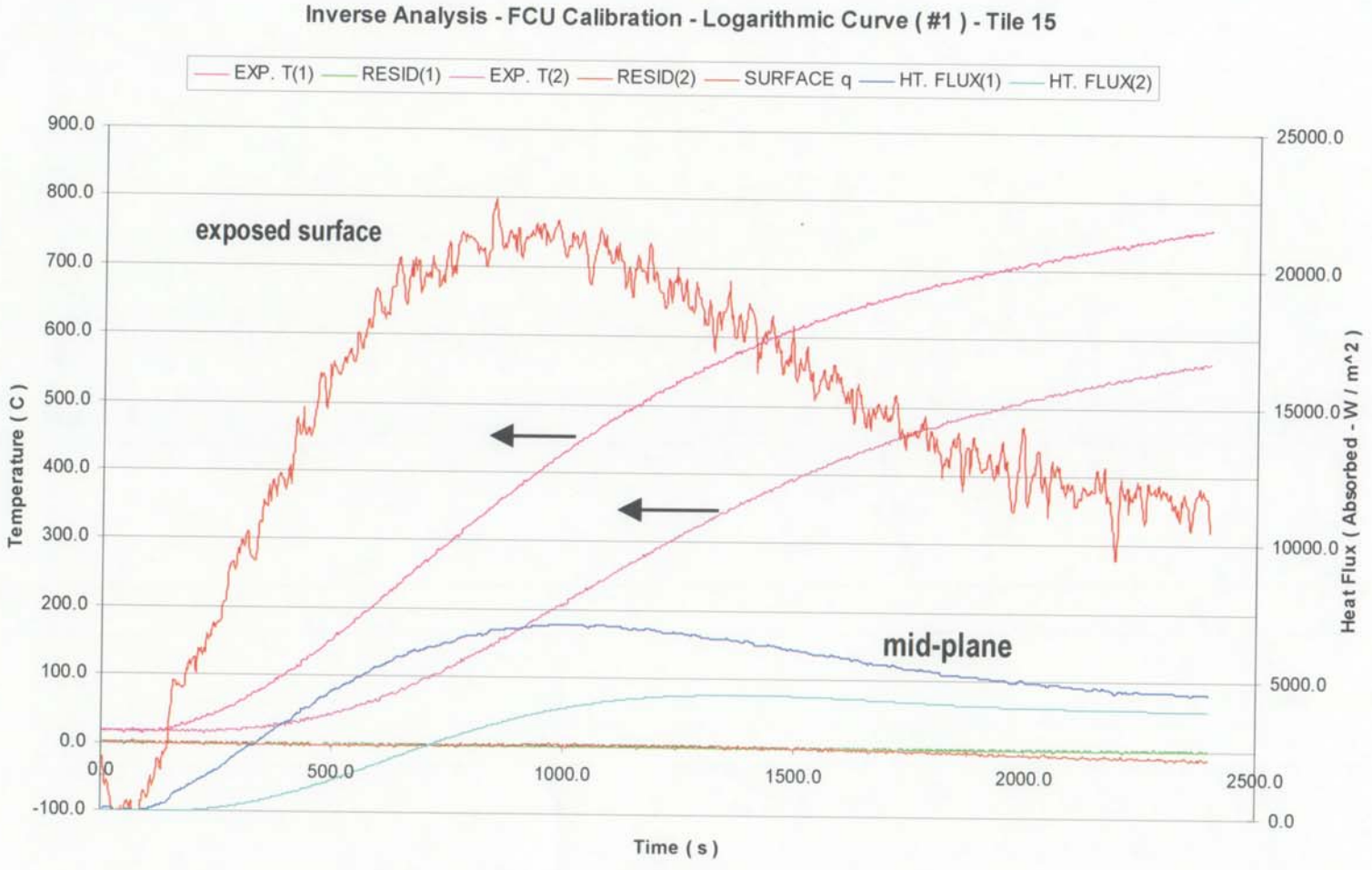
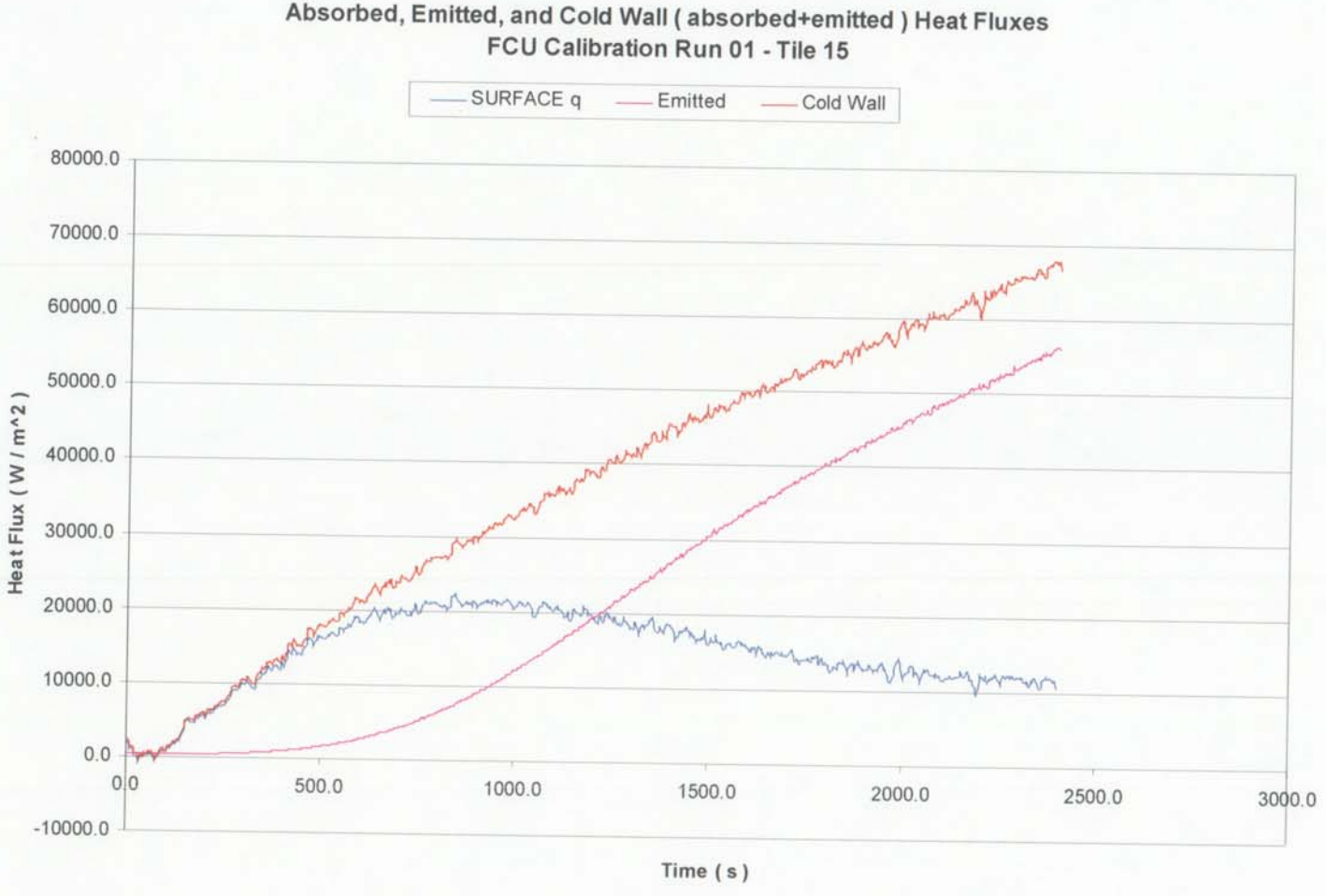


Calibration Results - Logarithmic Time-Temperature Curve

Ktech CORP.



Summary

Ktech CORP.

- U. S. Coast Guard R & D Center (Groton, CT) has developed a thermal measurement system for characterizing heat transfer in wall furnaces
- One meter square size fits small or full scale furnaces
- Thermal inertia similar to a marine bulkhead
- Operates hot – up to 1000°C
- Monitors furnace temperatures and heat transfer rates
- Redundant heat flux measurements
  - ► Self calibrating - using a nonlinear parameter estimation code
  - ► Heat transfer rates - calculated with an inverse heat conduction code

What's Next?

Ktech CORP.

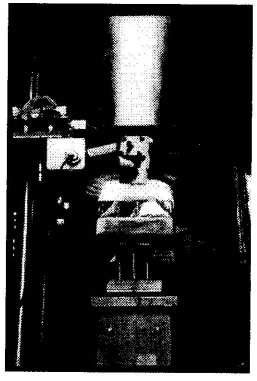
- Increase heat rejection capability to limit backface temperature rise
- Characterize thermal exposure in an actual furnace
- Compare exposure in different furnaces
  - ► Attempt correlation of furnace temperatures and heat fluxes
  - ► Use results as an aid in harmonizing exposures

- Adapt technique to intermediate scale tests
  - ► Intermediate Scale Calorimeter (ASTM)
  - ► Single Burning Item (Europe)
  - ► Room-Corner
- Adapt technique to column furnaces

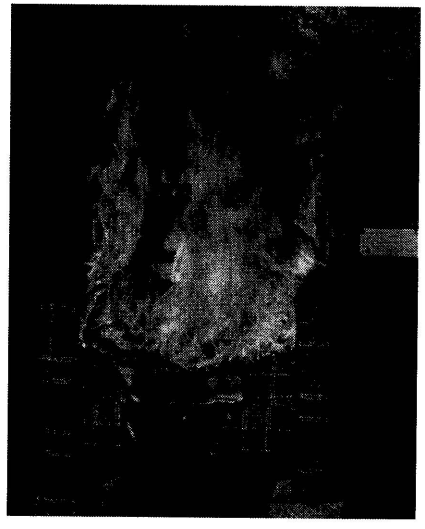
FORUM WORKSHOP:
Flow and Velocity Measurement Needs for Fire Safety

William Grosshandler
Building and Fire Research Laboratory
April 5, 2000

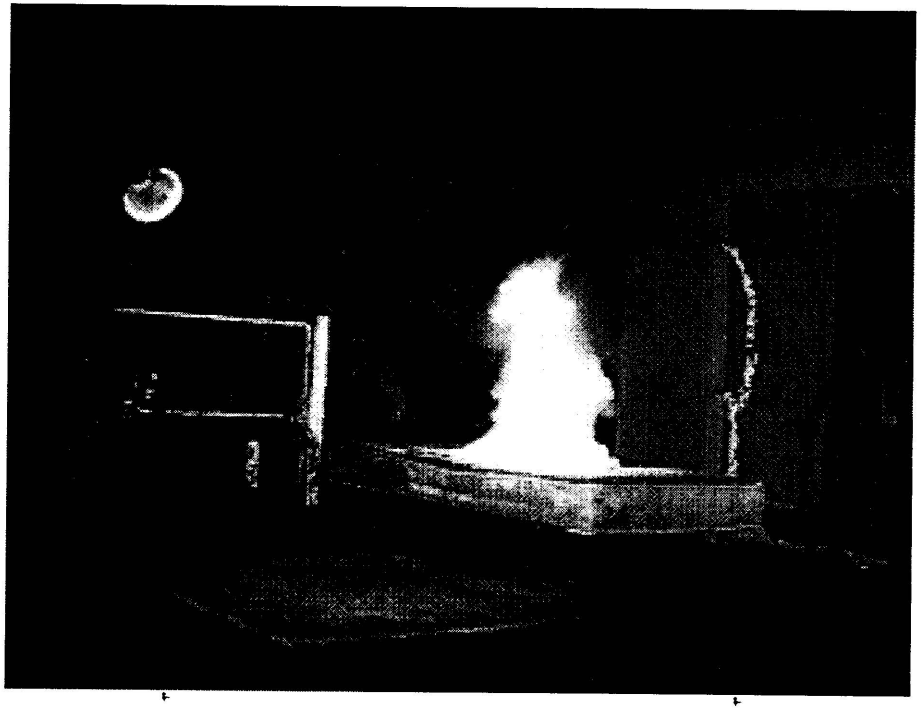
NIST
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce



cone
calorimeter



furniture
calorimeter



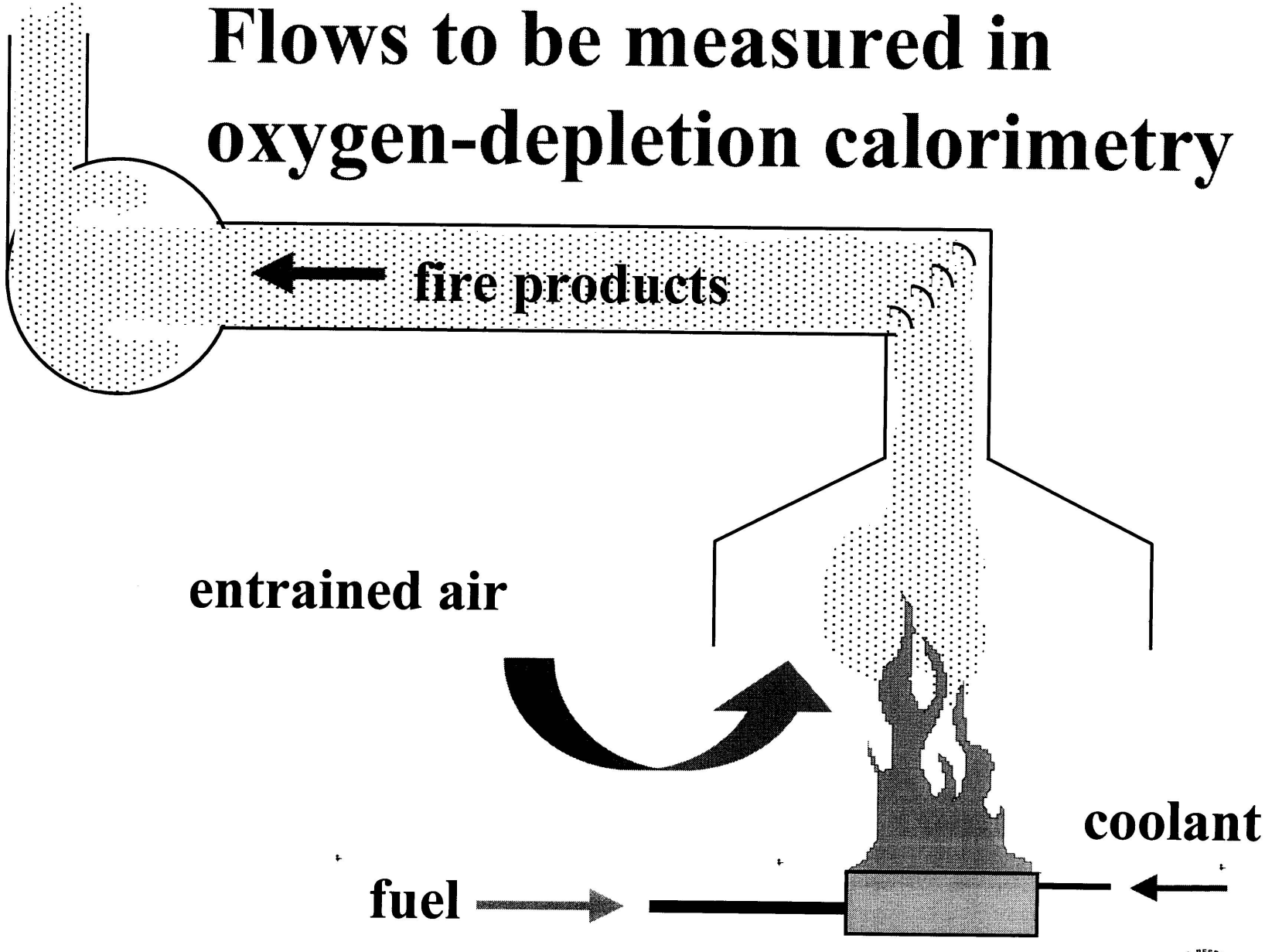
room-scale calorimeter

Oxygen depletion calorimetry

NIST
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

BUILDING AND FIRE RESEARCH LABORATORY

Flows to be measured in oxygen-depletion calorimetry



NIST
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

Volume average devices

APPLI-CATION	MEASUREMENT METHOD	ADVANTAGES	LIMITATIONS
fuel (gas)	dry/wet test meter	high flow rate	accuracy, low pressure
	rotameter	flexible, inexpensive	cal. req.
	metering orifice	accurate, high flow rates, no cal., fast response	pressure drop
	electronic mass flow meter	electrical readout, accurate, flow control	expensive, cal. req.
	bubble meter	high accuracy, for cal.	atm. pressure, low flows
fuel (liquid)	load cell/timer	electrical readout, accurate, no cal.	
	turbine meter	electrical readout	cal. req.
	rotameter	flexible, inexpensive	cal. req.
	sight gauge	simple, no cal., inexpensive	manual operation
coolant, suppres-sant	turbine meter	electrical readout	more expensive
	rotameter	flexible, fail-safe	
	bucket/stop watch	inexpensive	time average

Resolution & Uncertainty of Traditional Flow Meters

Spatial resolution: none, integrated across area

Time response: multiple seconds and slower

Uncertainty in flow:

5 % to 10 % (typical); < 5 % with care

Measurement issues: time response (transient operation only; e.g., flow of suppressant in pipe)

Exhaust duct flows

Bi-directional pitot probe:

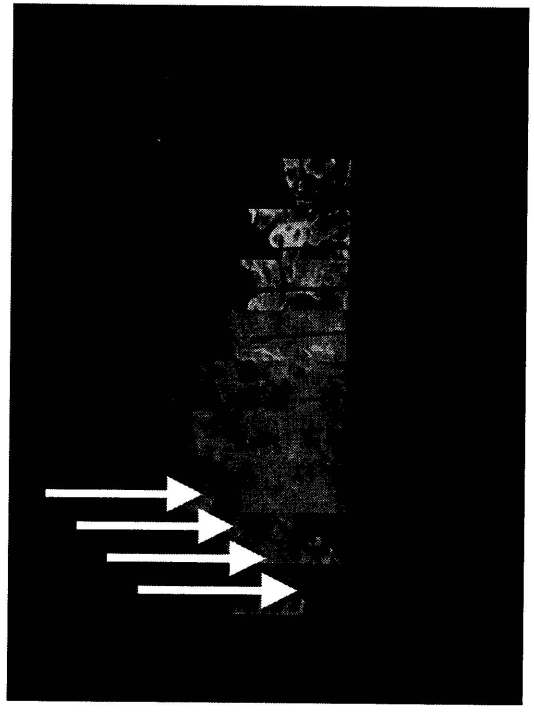
- **measures ΔP upstream vs. downstream**
- **relates point value to cross-stream average velocity**
- **0.1 to 1 s response time**

Accuracy limited by:

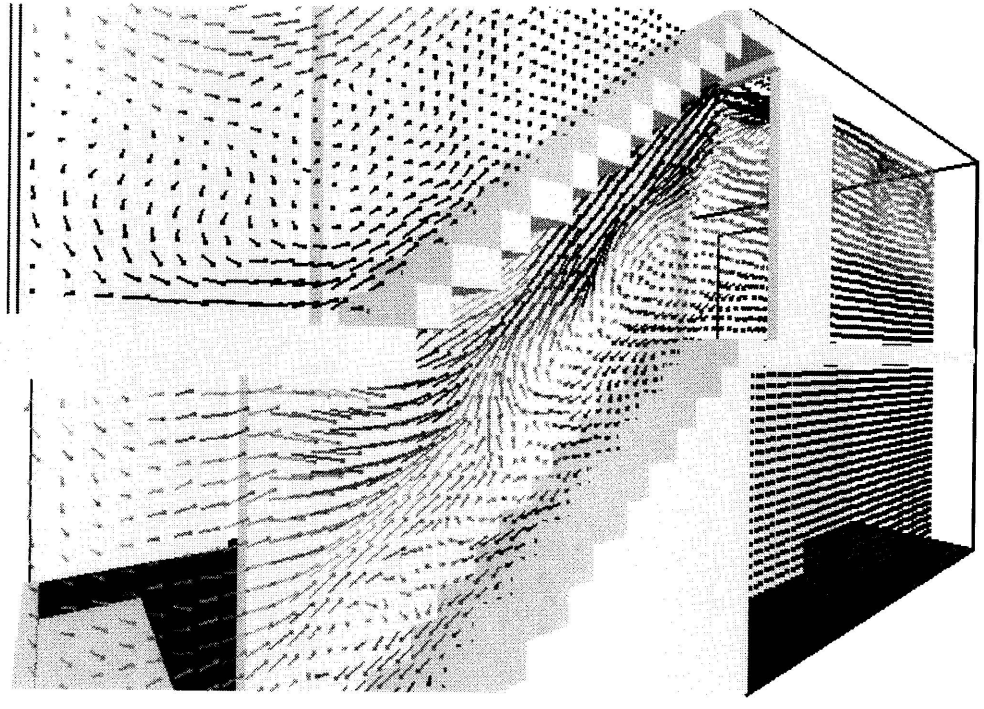
- **uncertainties in local properties**
- **shape of velocity profile**

Estimated relative std. uncertainty in flow: > 5 %

Buoyancy-induced velocity measurements for model validation



Door flows

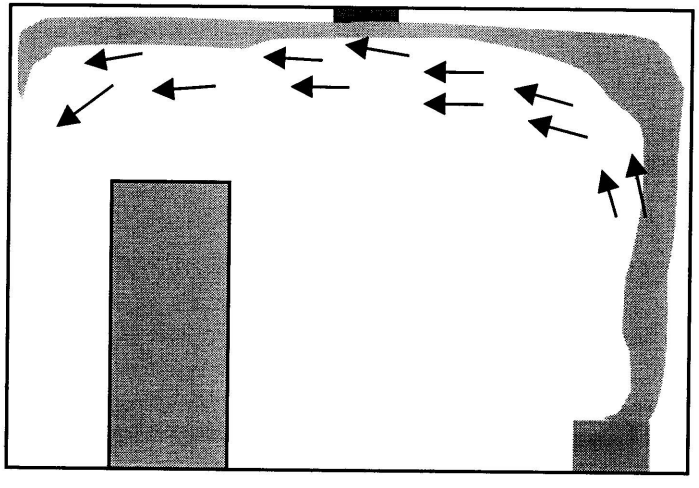


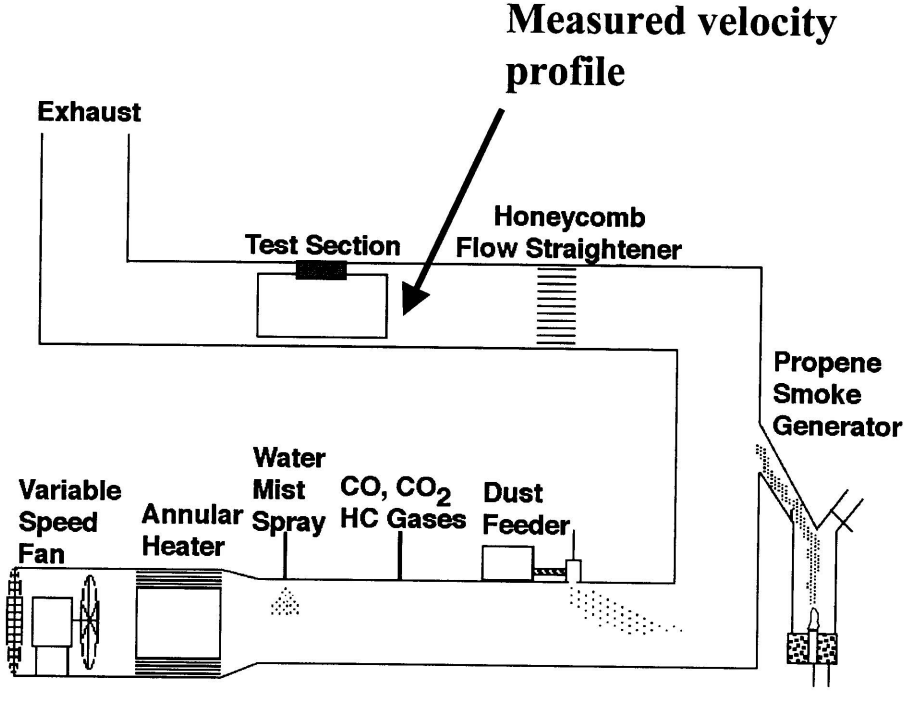
5 m/s →

Stair flow simulation

Smoke plume & fire detector flows

Full-scale detector testing



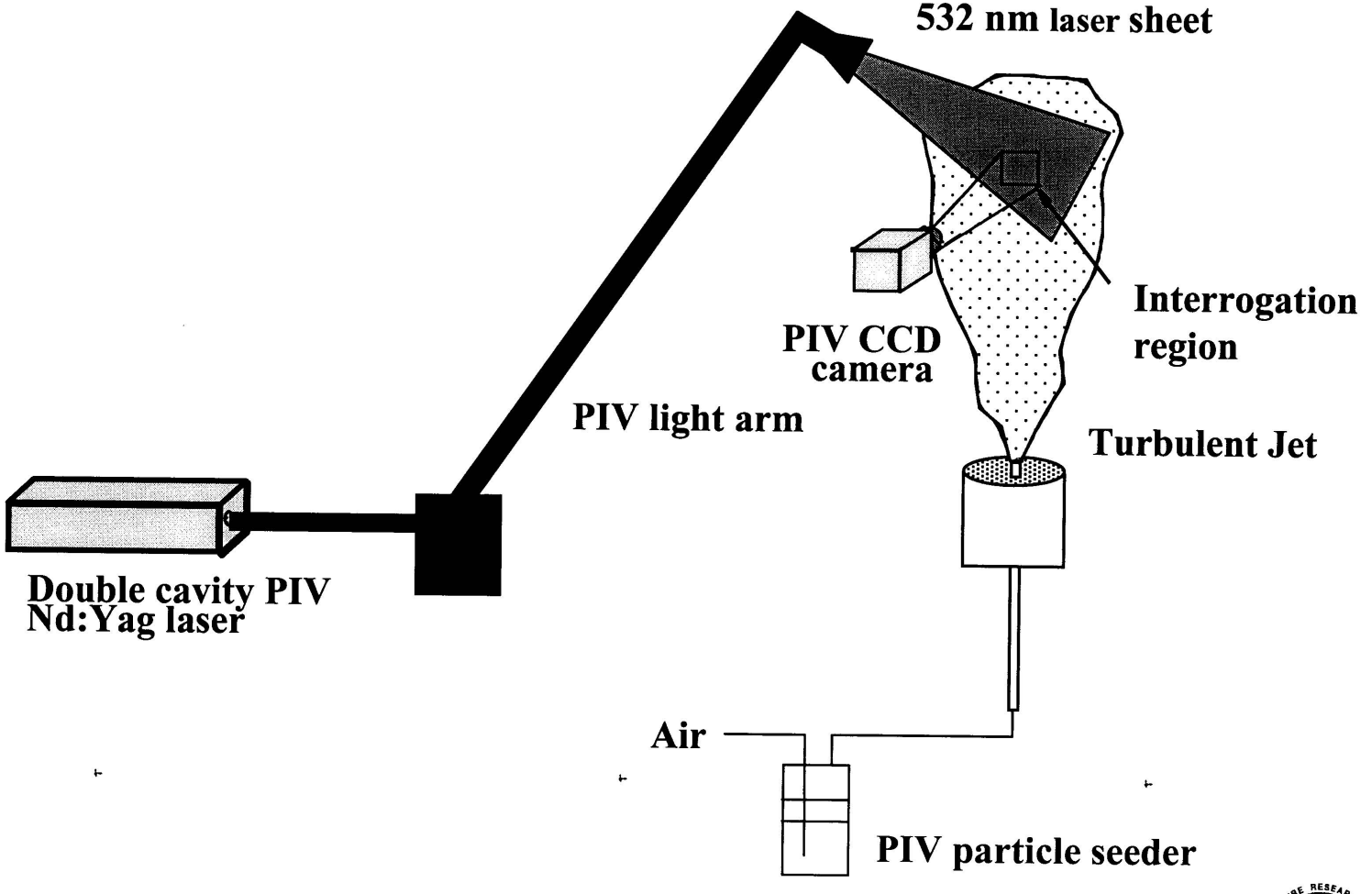


Fire-emulator/detector evaluator

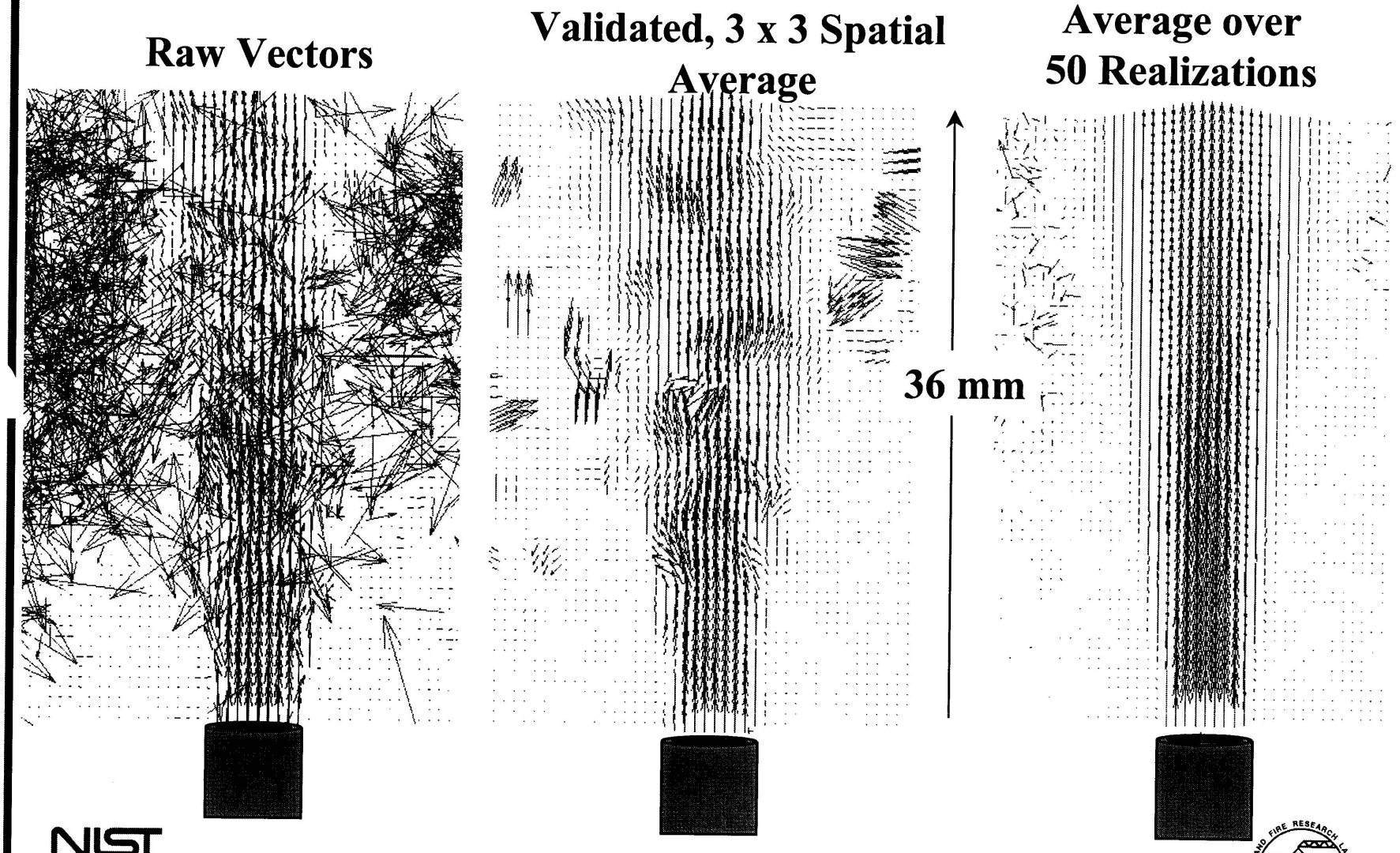
Unconfined gas flow measurement methods

PARAMETER	DEVICE	OPERATING PRINCIPLE
single velocity component	bi-directional probe	ΔP
	pitot tube	ΔP
	hot-wire anemometer	ΔT
	laser-Doppler anemometer (LDA)	scattered light
speed + direction	wind anemometer	aerodynamic forces
2-D velocity	cross-wire anemometer	ΔT
	2-D LDA	scattered light
	phase-Doppler particle analyzer (PDPA)	scattered light
	particle imaging velocimeter (PIV)	scattered light
2-D flow	laser sheet visualization	scattered light
3-D velocity	triple-wire anemometer	ΔT
	3-D LDA	scattered light

PIV experimental setup



PIV turbulent jet velocity vectors



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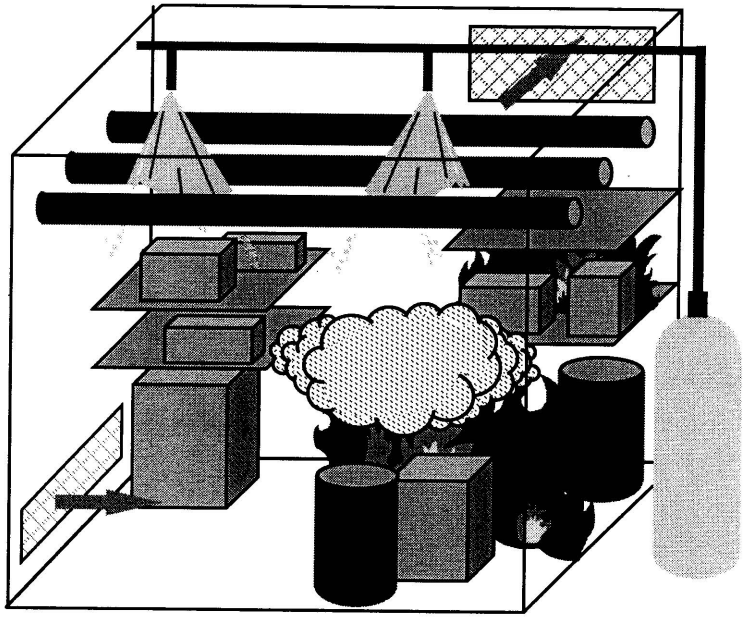
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

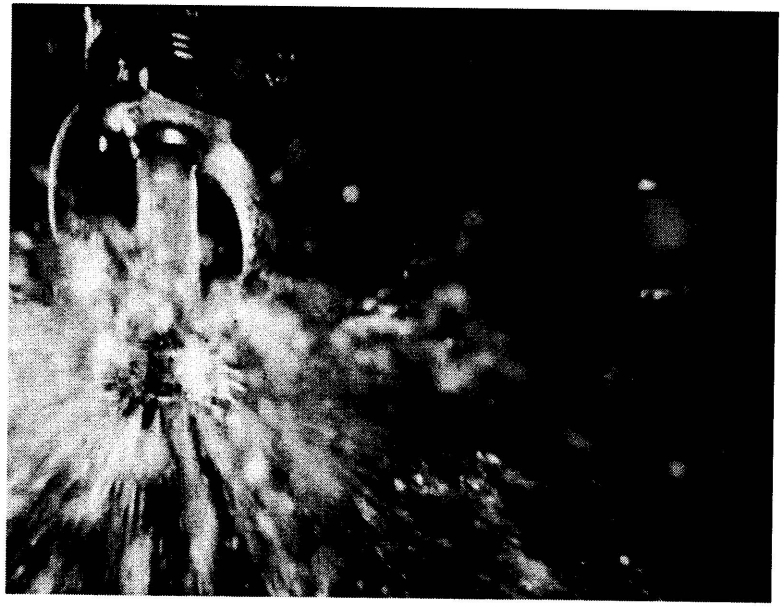
Resolution & Uncertainty of Velocity Measurements

METHOD	AREA	SPATIAL RESOLUTION	TIME RESPONSE	TYPICAL UNCERT.
hot wire probe	point	.1 to 1 mm	< 1 ms	< 2 %
LDA	point	.1 to 1 mm	1 ms to 10 s	< 4 %
pressure probe	point	1 to 10 mm	.1 to 1 s	< 10 %
wind anemometer	point	50 mm	5 s	< 20 %
PIV	1 x 1 cm to .3 x .3 m	.5 to 1 mm	1/30 s	< 5 %
particle tracking	10 x 10 cm to 1 x 1 m	1 to 5 mm	10 ms to 1 s	< 10 %

Droplet & spray flows



Halon replacement discharges

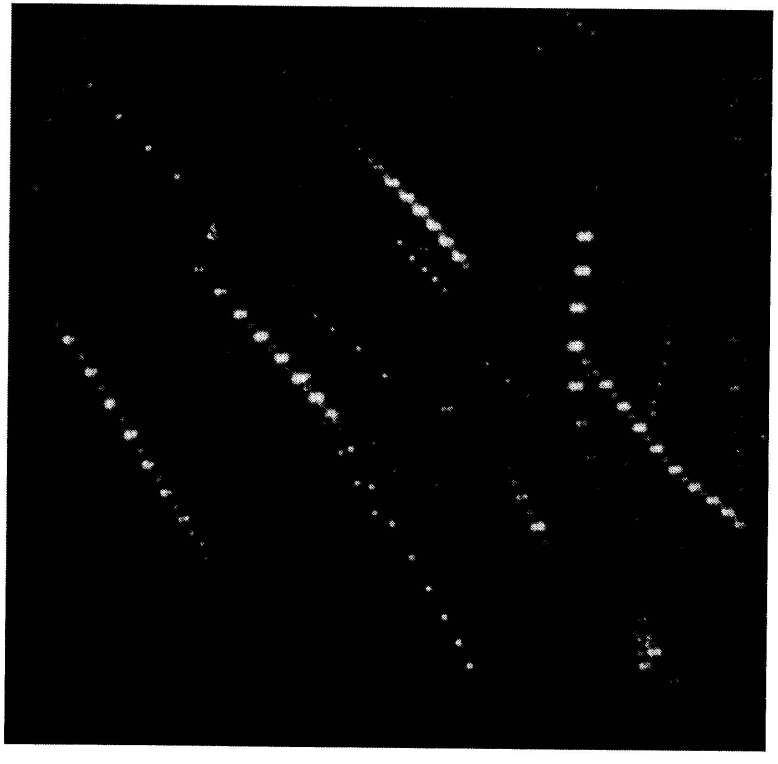


Sprinkler sprays

Droplet, particle flow measurement

- Buckets on floor (flow averaged over 10s of seconds and 10s of cm^2) $
- High speed movies/videos (2-D projection of flow, non-quantitative, insightful) $
- LDA (1, 2 or 3 velocity components at point) $$
- PDPA (LDA plus size) $$$
- PIV (2-D velocity vectors over area) $$$
- Particle Tracking (2-D velocity over area) $$

Laser sheet particle tracking



- Field model validation
- Sprinkler drop size and velocity
- Entrained air flow velocity
- Fire induced flows
- Non-intrusive
- 2-Dimensional plane
- High spatial resolution
- Method demonstrated at 0.25 m x 0.25 m
- Development of ability to measure 1 m by 1 m area

Summary

Traditional methods are adequate if good engineering practice followed:

- **use appropriate range (magnitude, environ.)**
- **calibrate**
- **apply realistic uncertainties**

Optical methods have significant limitations:

- **time response vs. velocity vs. seed particle number density (LDA and PDPA)**
- **particle size and shape (gas vs. droplet velocity)**
- **area vs. particle number, size and $ (PIV)**

Flow measurement challenges

1. Air flow through openings in fire room:
   - total area simultaneously
   - resolved to 10 cm^2
   - < 1 s time response
   - 2 components of velocity

2. Air entrainment into fire (same requirements)

3. Near-field in plume (same requirements)

4. Transient discharge of flashing suppressant

Focus research on:

- Developing/optimizing particle seeding
- Increasing area coverage
- Hardening optical methods and streamlining operation
- Developing appropriate controlled experiments to validate sub-models for simulations

Temperature Measurements in Fires

William M. Pitts

Building and Fire Research Laboratory

FORUM Workshop on Measurement Needs for Fire Safety

April 5, 2000

NIST
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

WHY MEASURE TEMPERATURE IN FIRES?

- High temperatures are a characteristic of combustion.
- High temperatures can generate large radiative fluxes which support fires (e.g., pyrolysis or vaporization of fuels, flame spread, flashover)
- Temperature is an indicator of the potential for damage.
- Temperature is an indirect indicator of heat release rate.
- Rates of chemical reactions are highly dependent on temperature.
  - e.g., reactions of solids, i.e., pyrolysis
  - gas-phase combustion
  - water-gas shift reaction
- Temperature is viewed as one of the easier to measure fire characteristics.

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WHAT ACCURACY IS "REQUIRED" FOR TEMPERATURE MEASUREMENTS IN FIRES?

- Very little guidance available in the literature.
- Little discussion of effects of uncertainty on models and/or correlations.
- It is clear that required accuracy depends on how the data will be used:
  - Estimate flashover time for compartment fire.
  - Determine air flow rate through doorway to $\pm 10\%$ by measuring velocity and density (ideal gas law) of incoming gas.
  - Validate temperature range where approach to thermodynamic equilibrium leads to a significant increase in carbon monoxide formation in rich high-temperature upper layers.

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WHAT TEMPORAL AND SPATIAL RESOLUTION ARE "REQUIRED" FOR TEMPERATURE MEASUREMENTS IN FIRES?

- Very little guidance available in the literature.
- Requirements depend strongly on fire dynamics and the design goals for the experiment.
- In general, experiments designed to test and/or validate field models should have higher spatial and temporal resolution than required for similar tests of zone models.
- Special measurements such as using two temperature signals for velocity measurement may require quite high temporal and spatial resolution.

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TEMPERATURE MEASUREMENT APPROACHES TO BE DISCUSSED

- Soot temperature based on resolving thermal radiation
- Holographic interferometry
- Infrared imaging of surfaces.
- Thermocouples
  - Bare Bead
  - Aspirated
  - Use of several variable-diameter probes

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SOOT TEMPERATURE MEASUREMENT

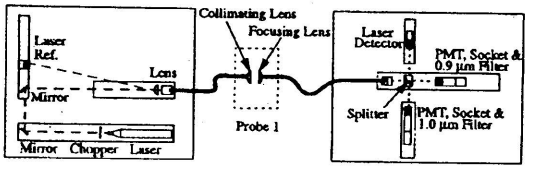

FIGURE 1 Multi-wavelength emission/absorption probe.

- Two-wavelength pyrometry, similar to probe used by Sivathanu and Faeth.
- Measurements recorded inside 6 m x 6 m square pool fire by Gritzo, Sivanthanu and Gill.
- Spectrally resolved thermal radiation at 1.0 and 0.9 μm.
- Two cm long sampling volume, data recorded at 250 Hz.
- Included error analysis, one of largest potential sources was uncertainty for the index of refraction for soot.

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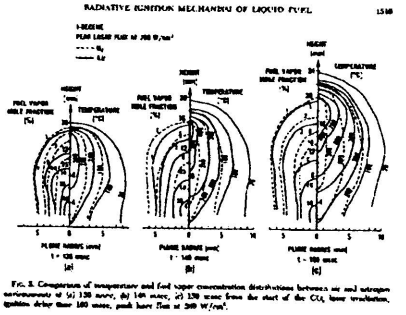
TEMPERATURE MEASUREMENT USING HOLOGRAPHY



- Coherent optical technique
- Used to study fuel vaporization (Kashiwagi et al.) and flame spread over solids (Ito et al.)
- Not widely employed, requires good optical access

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WALL TEMPERATURE MEASUREMENTS USING INFRARED IMAGING

- Technique developed by Arakawa, Saito, and Gruver.
- Records infrared radiation from wall using infrared camera during upward fire spread in a corner.
- Filter to observe radiation in window between 10 μm and 11 μm in order to minimize thermal radiation from heated gases.
- Estimate radiation from soot is much less than that from the walls.
- No detailed uncertainty analysis was provided

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"TYPICAL" THERMOCOUPLE MEASUREMENTS IN REAL-SCALE FIRE ENVIRONMENTS

- By far, the most numerous measurement made in fire tests
- Multiple bare-bead thermocouples positioned throughout test space
- Data recorded digitally with data rates on the order of a few seconds
- Variety of environments
- Generally employ thermocouples with diameters on the order of 0.25 mm
- Usually do not attempt to minimize possible errors in measurements

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WHAT IS THE PROBLEM?

A thermocouple, or any immersion device, can indicate only its own temperature. In general, this will not be equal to the gas temperature unless special precautions are taken. It is the responsibility of the investigator to determine the difference which exists, and to correct for it, or to design the probe such that the difference is acceptably small.

--R. J. Moffat, 1962

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WHY DOES A THERMOCOUPLE JUNCTION TEMPERATURE DIFFER FROM THE LOCAL GAS TEMPERATURE?

Answers

Heating or cooling effects due to:

- Radiation
- Conduction Along Thermocouple Wires
- Catalytic Heating Due to Surface Reaction
- Aerodynamic Heating at High Velocities

Time Response Limitations

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RADIATIVE HEAT TRANSFER TO A THERMOCOUPLE

$$q_{rad} = \sigma\epsilon\left(T_{sur}^4 - T_{tc}^4\right)$$

σ is the Stefan-Boltzmann constant and ϵ is thermocouple emissivity.

THERMOCOUPLE IN STEADY STATE

$$q_{con} = hA(T_g - T_{tc}) = -q_{rad}$$

Substitution gives:

$$T_g - T_{tc} = \frac{\sigma\epsilon\left(T_{tc}^4 - T_{sur}^4\right)}{k_g\left[\frac{0.24 + 0.56\left(\frac{U_o d_o}{\nu}\right)^{0.45}}{d_o}\right]}$$

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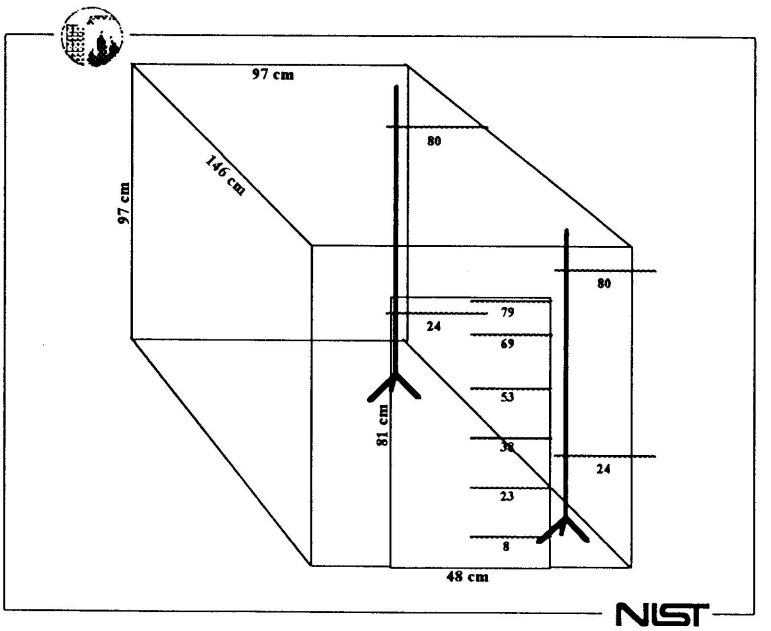

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Picture of Enclosure Fire

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ASPIRATED THERMOCOUPLES

- Adopted design from Glawe, Simmons, and Stickney based on it effectiveness and ease of construction
- Double shield design with flow over inner shield walls
- Both end and side opening versions were constructed
- Also tested much simpler design of Newman and Croce which uses a single shield and is most widely used design in fire testing
- Encountered a paradox: Newman and Croce recommended using an aspiration velocity of 7.7 m/s and claimed "aspirated temperature also appears to approach asymptotically a value which should correspond to the true gas temperature"; earlier literature on aspirated thermocouples indicated that thermocouple "efficiency" increases very slowly with aspiration velocity and recommended use of the highest velocity possible, values up to 150 m/s were employed

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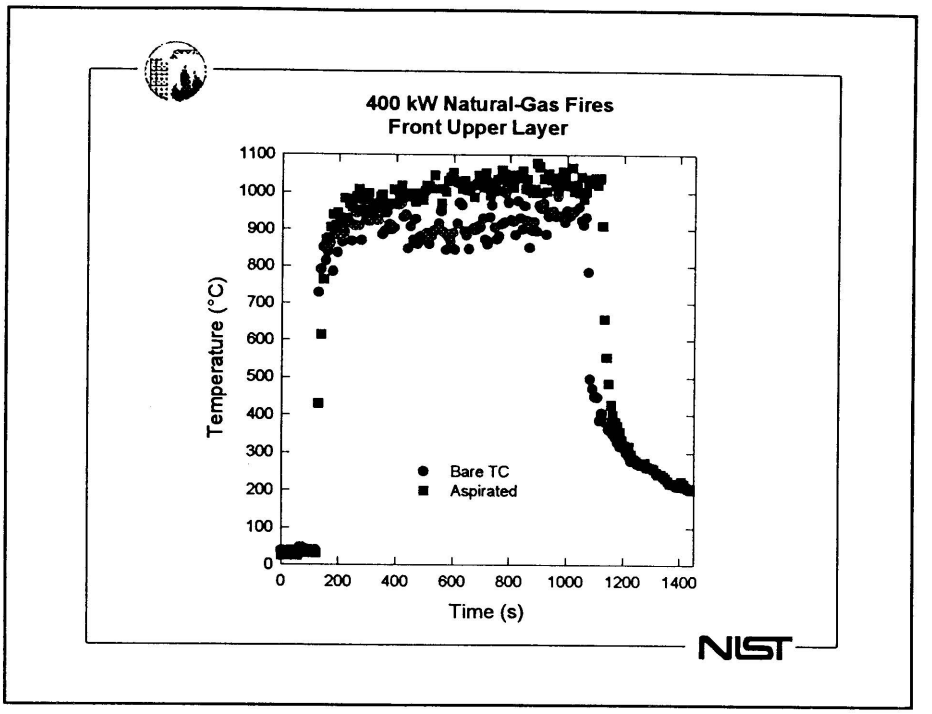
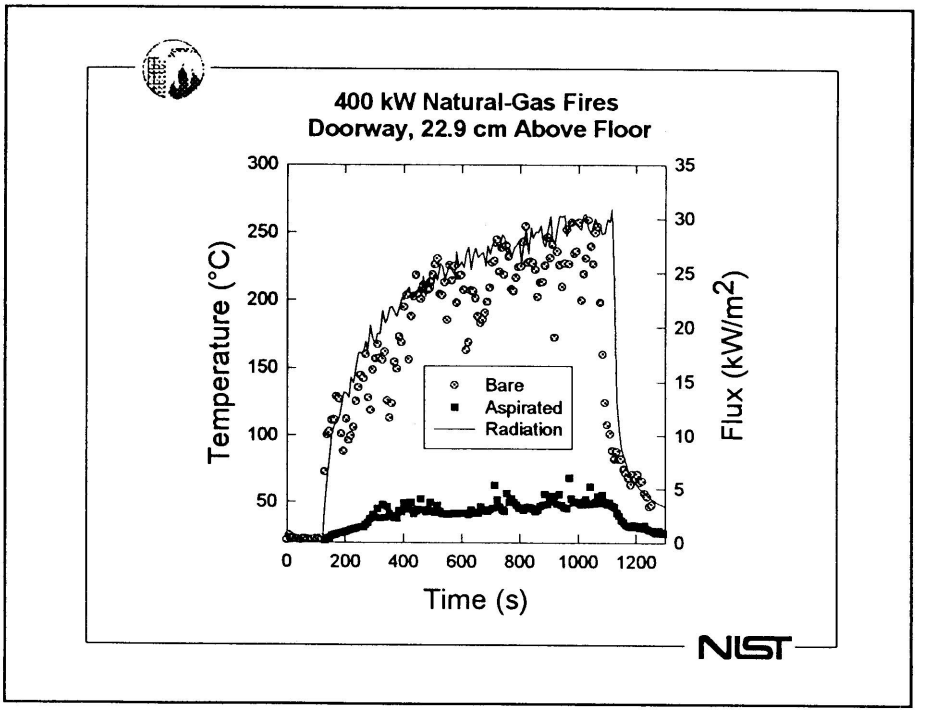
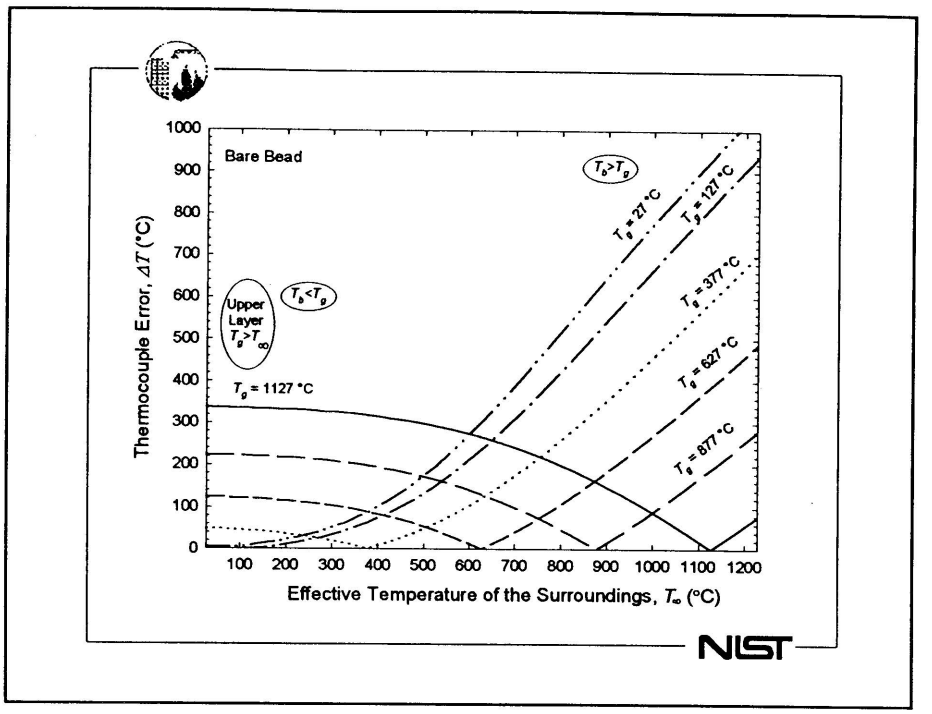
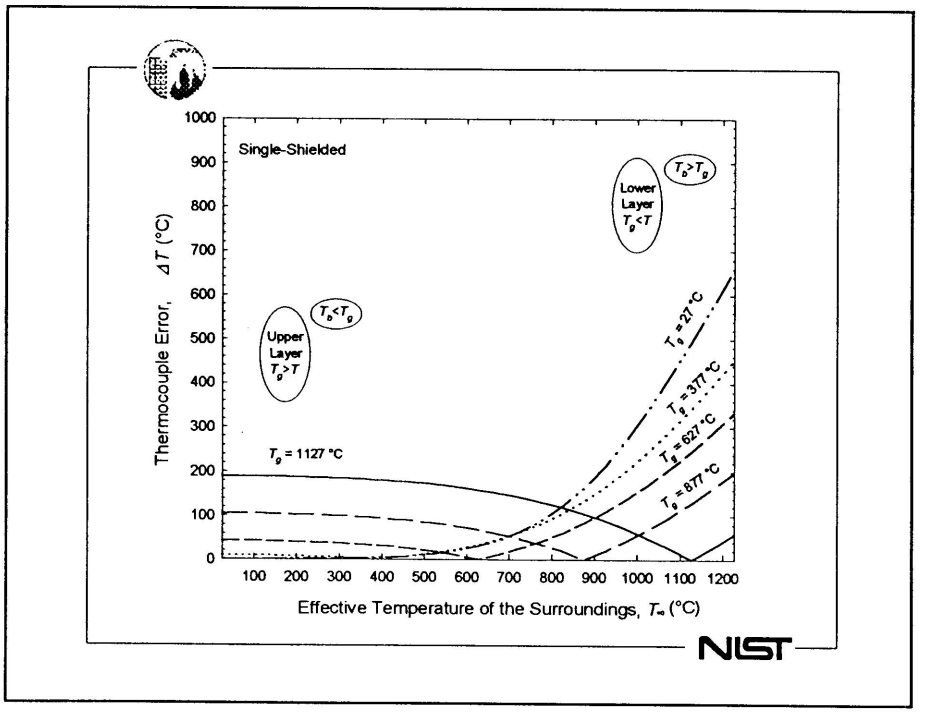
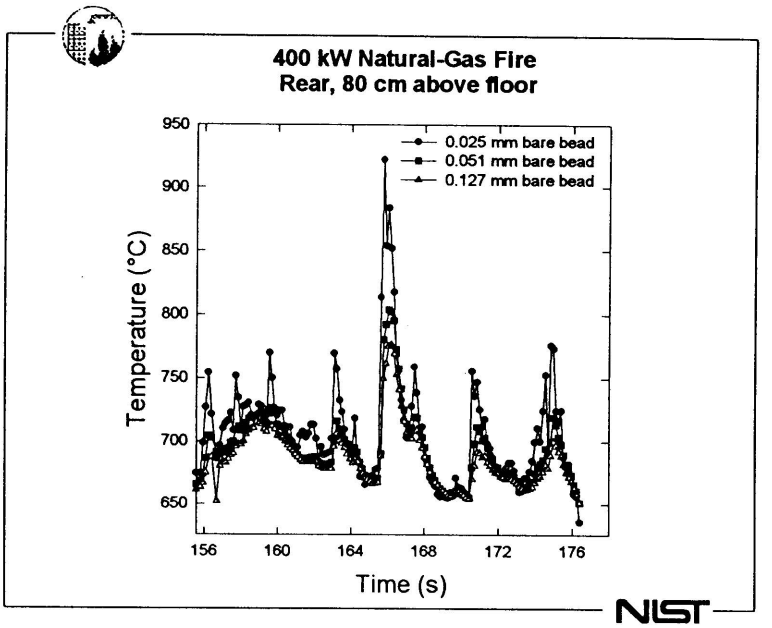
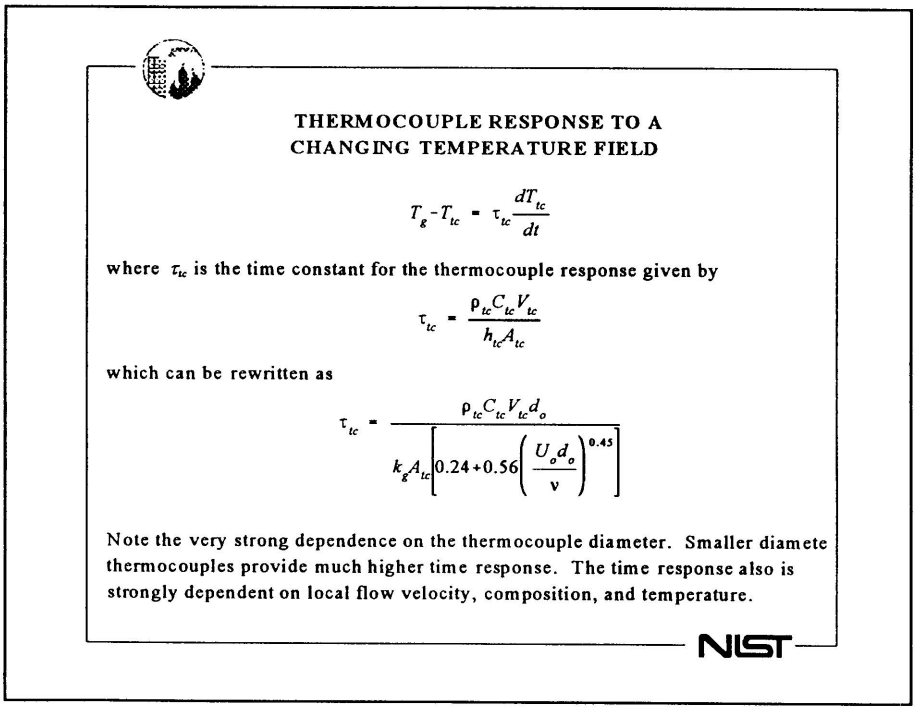

400 kW Natural-Gas Fires
Front Upper Layer
Temperature (°C)
Time (s)
Bare TC
Aspirated
NIST


400 kW Natural-Gas Fires
Doorway, 22.9 cm Above Floor
Temperature (°C)
Flux (kW/m2)
Time (s)
Bare
Aspirated
Radiation
NIST


Bare Bead
$T_b > T_g$
T_g = 27 °C
T_g = 127 °C
T_g = 377 °C
T_g = 627 °C
T_g = 877 °C
Upper Layer $T_g > T_\infty$
$T_b < T_g$
T_g = 1127 °C
Thermocouple Error, ΔT (°C)
Effective Temperature of the Surroundings, T_∞ (°C)
NIST


Single-Shielded
$T_b > T_g$
Lower Layer $T_g < T$
$T_b < T_g$
Upper Layer $T_g > T$
T_g = 27 °C
T_g = 377 °C
T_g = 627 °C
T_g = 877 °C
T_g = 1127 °C
Thermocouple Error, ΔT (°C)
Effective Temperature of the Surroundings, T_∞ (°C)
NIST


400 kW Natural-Gas Fire
Rear, 80 cm above floor
0.025 mm bare bead
0.051 mm bare bead
0.127 mm bare bead
Temperature (°C)
950
900
850
800
750
700
650
156
160
164
168
172
176
Time (s)
NIST


THERMOCOUPLE RESPONSE TO A
CHANGING TEMPERATURE FIELD
$T_g - T_{tc} = \tau_{tc} \frac{dT_{tc}}{dt}$
where τ_{tc} is the time constant for the thermocouple response given by
$\tau_{tc} = \frac{\rho_{tc} C_{tc} V_{tc}}{h_{tc} A_{tc}}$
which can be rewritten as
$\tau_{tc} = \frac{\rho_{tc} C_{tc} V_{tc} d_o}{k_g A_{tc} \left[0.24 + 0.56 \left(\frac{U_o d_o}{\nu} \right)^{0.45} \right]}$
Note the very strong dependence on the thermocouple diameter. Smaller diamete thermocouples provide much higher time response. The time response also is strongly dependent on local flow velocity, composition, and temperature.
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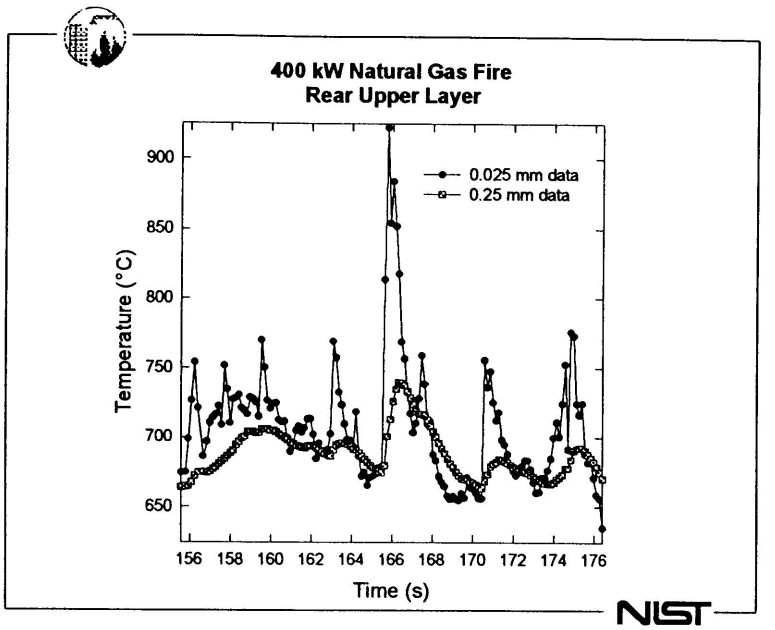

SPATIAL AND TEMPORAL RESOLUTION FOR THERMOCOUPLE MEASUREMENTS

- Time response for thermocouples typically used in fire experiments vary from few tenths of to greater than one second.
- Is tempting to define the spatial resolution of the probe as the effective size of the sampling area (e.g., bare thermocouple diameter plus boundary layer, volume of gas sampled by aspirated thermocouple).
- Most fire measurements are made in flow field. Effective spatial resolution is most often determined by response time of thermocouple. Consider thermocouple with 0.5 s response time in a flow of 1 m/s. Measurement is made over a length of roughly 0.5 s x 1 m/s = 0.5 m.

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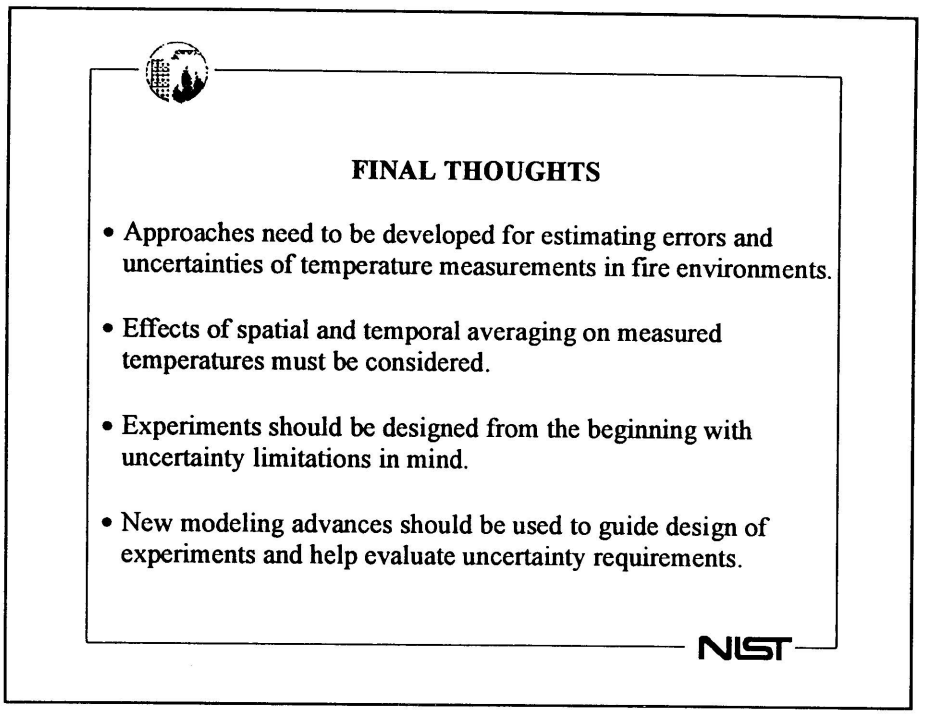
FINAL THOUGHTS
• Approaches need to be developed for estimating errors and uncertainties of temperature measurements in fire environments.
• Effects of spatial and temporal averaging on measured temperatures must be considered.
• Experiments should be designed from the beginning with uncertainty limitations in mind.
• New modeling advances should be used to guide design of experiments and help evaluate uncertainty requirements.
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Appendix C: FORUM Workshop Presentations

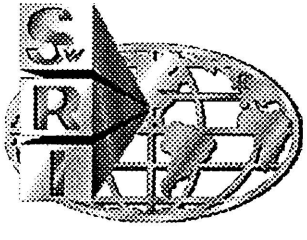
SESSION IV.

SPECIES MEASUREMENTS (ACCURACY, SPATIAL AND TEMPORAL RESOLUTION)

FORUM Workshop on Measurement Needs for Fire Safety
NIST, Gaithersburg, MD
April 4-7, 2000

Heat Release Rate (HRR)

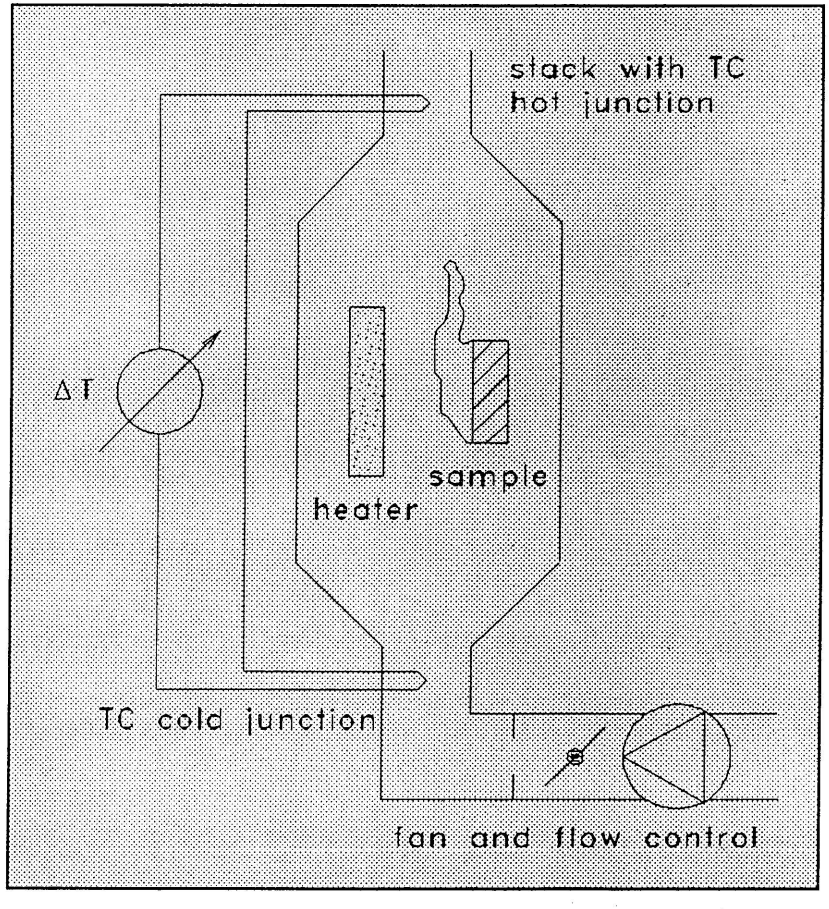
Marc L. Janssens, Ph.D.
Southwest Research Institute
San Antonio, Texas



Outline

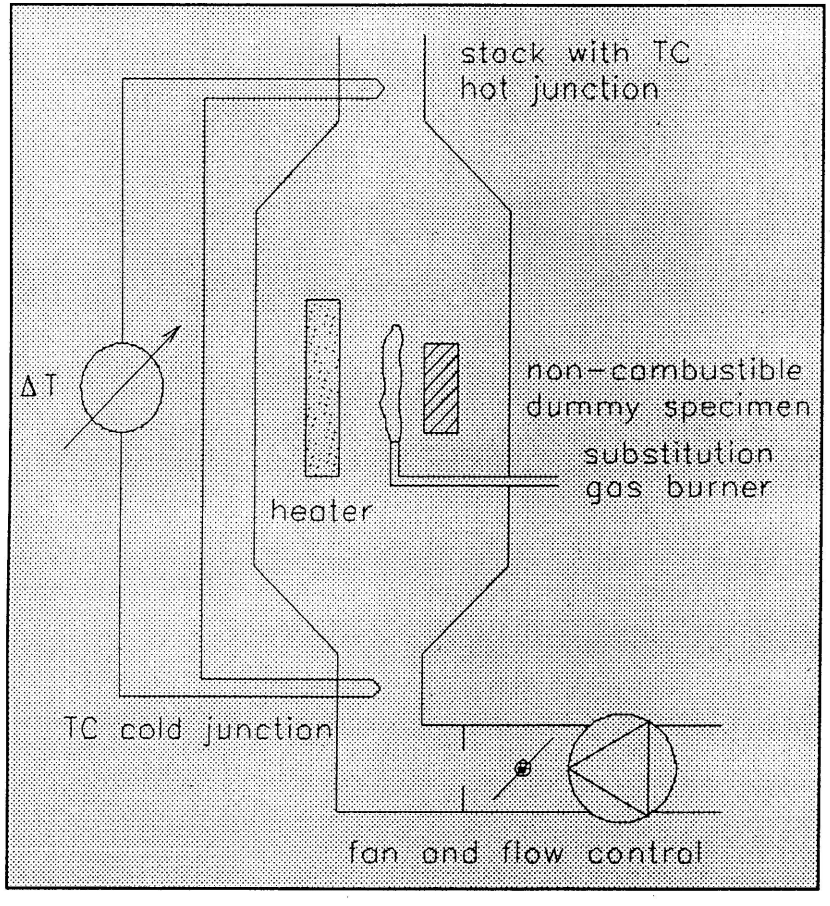
- Methods for measuring heat release rate
  - Sensible enthalpy rise method
  - Substitution method
  - Compensation method
  - Oxygen consumption method
- Heat release rate data and fire modeling
- Uncertainty Analysis
  - Terminology
  - Uncertainty of HRR measurements
- Conclusions

Sensible Enthalpy Rise Method



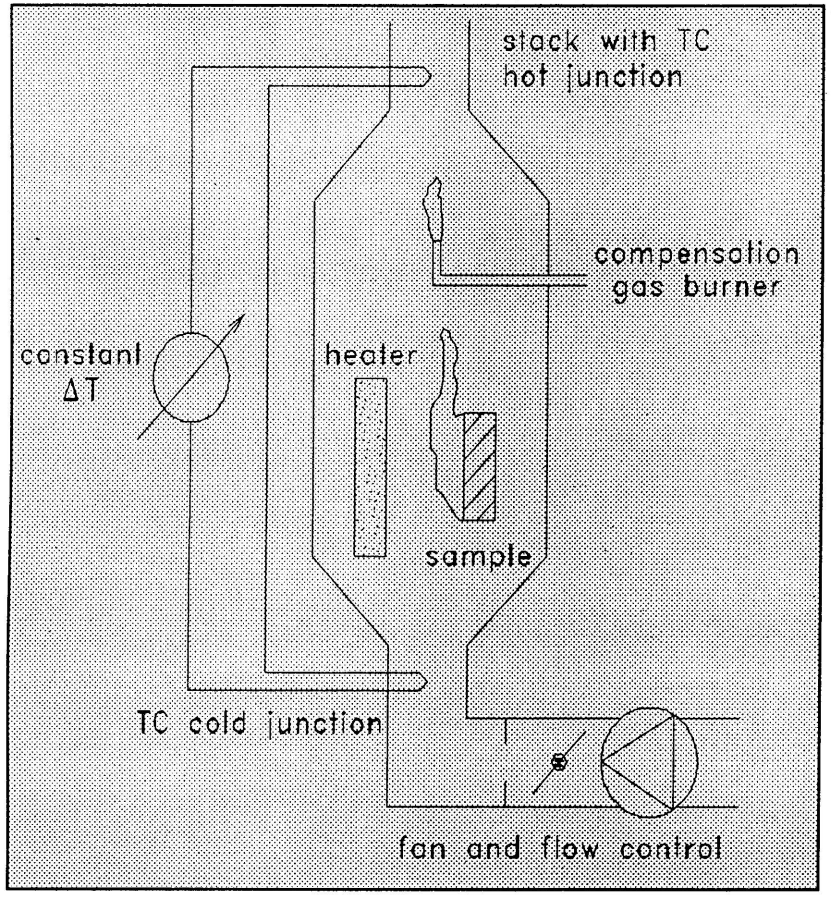
- **Examples**
  - Smith (OSU)
- **Advantages**
  - Simple
  - Inexpensive
- **Disadvantages**
  - Thermal lag
  - Radiative fraction

Substitution Method



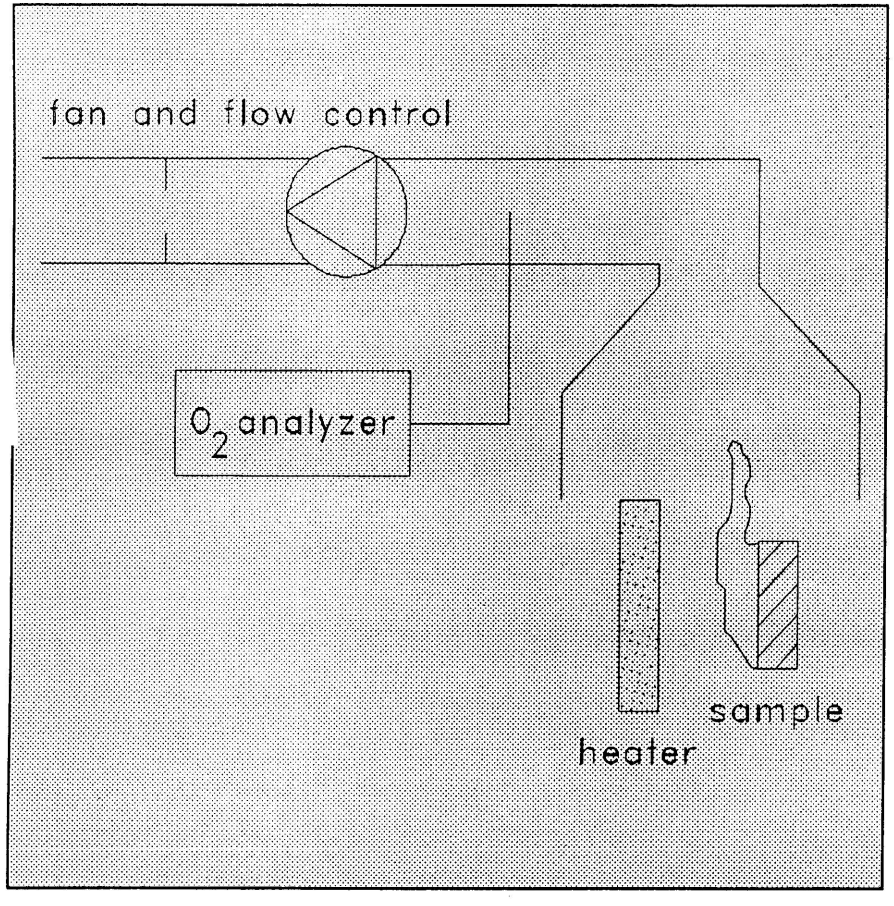
- **Examples**
  - ➢ Thompson/Cousins (FM)
  - ➢ Brenden (FPL)
- **Advantages**
  - ➢ No thermal lag problems
- **Disadvantages**
  - ➢ Complex control system
  - ➢ Double # of tests

Compensation Method



- **Examples**
  - Parker/Long (NBS)
  - Tordella (NBS)
- **Advantages**
  - No thermal lag
- **Disadvantages**
  - Very complex

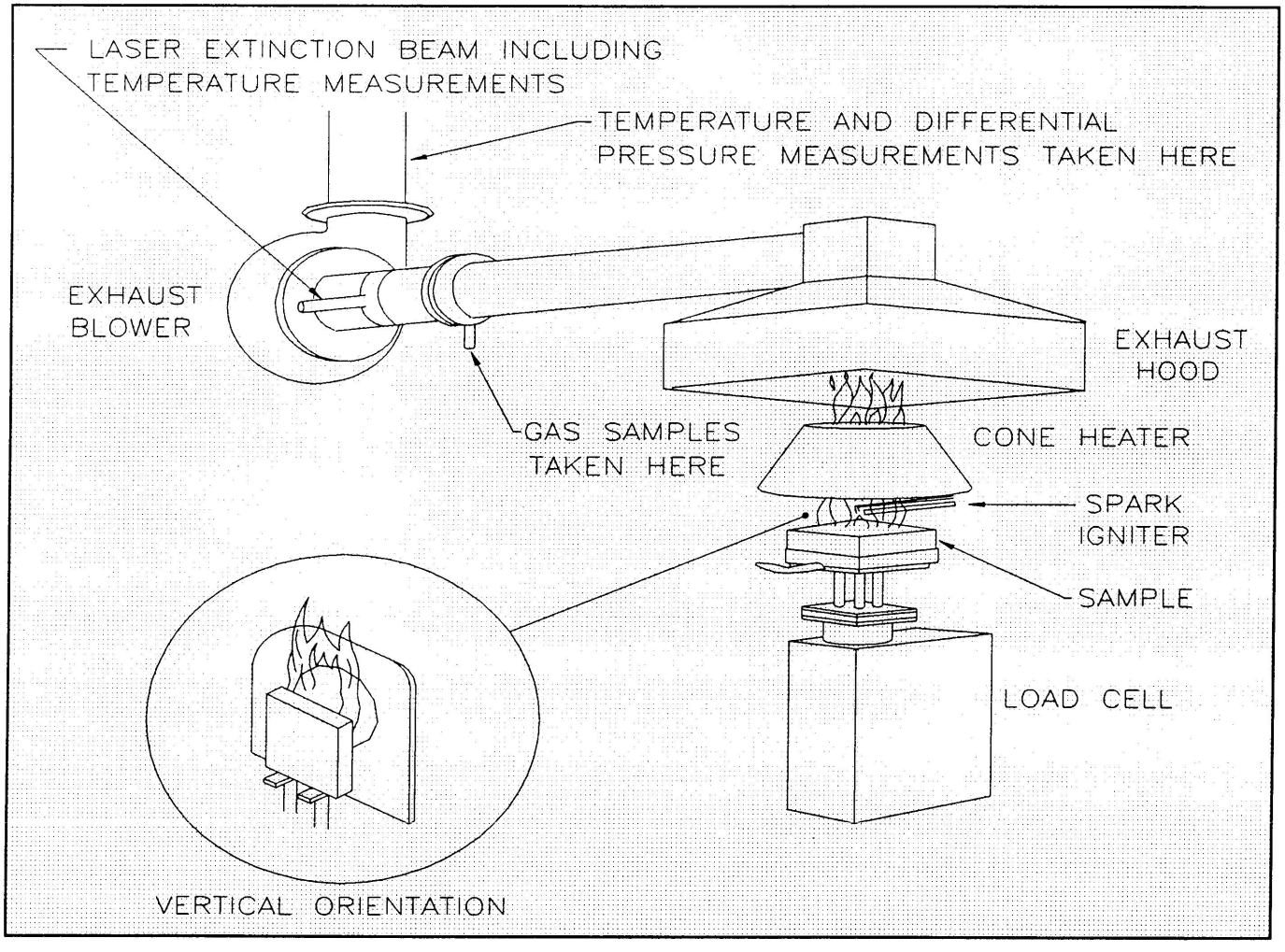
Oxygen Consumption Method



- **Examples**
  - Cone calorimeter
  - SBI
  - Room-corner test
  - Furniture calorimeter
  - ICAL
  - Large-Scale calorimeter
- **Advantages**
  - Practical
  - Accuracy
- **Disadvantages**
  - Instrumentation

Southwest Research Institute

Small-Scale HRR Testing



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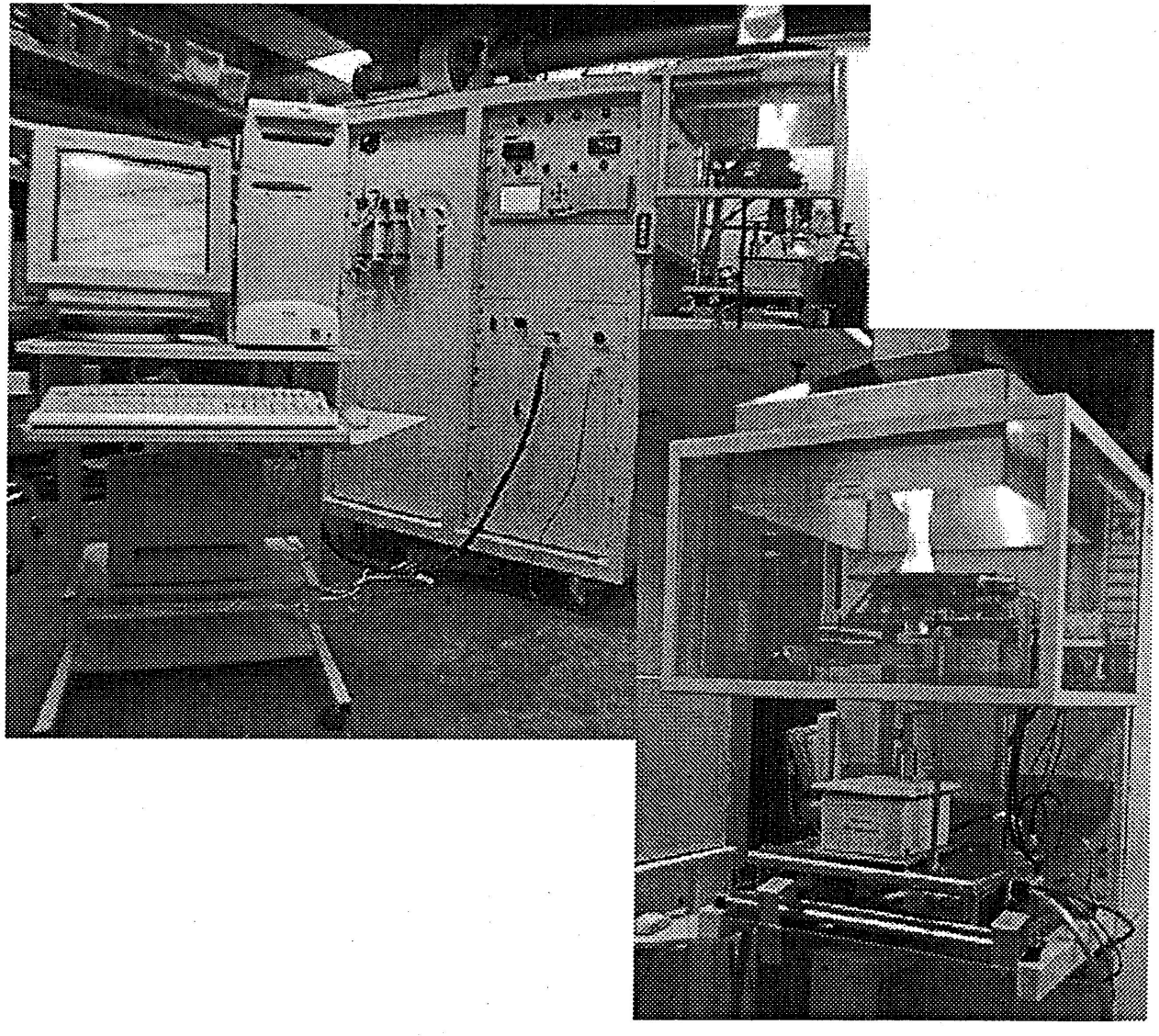
Small-Scale HRR Testing



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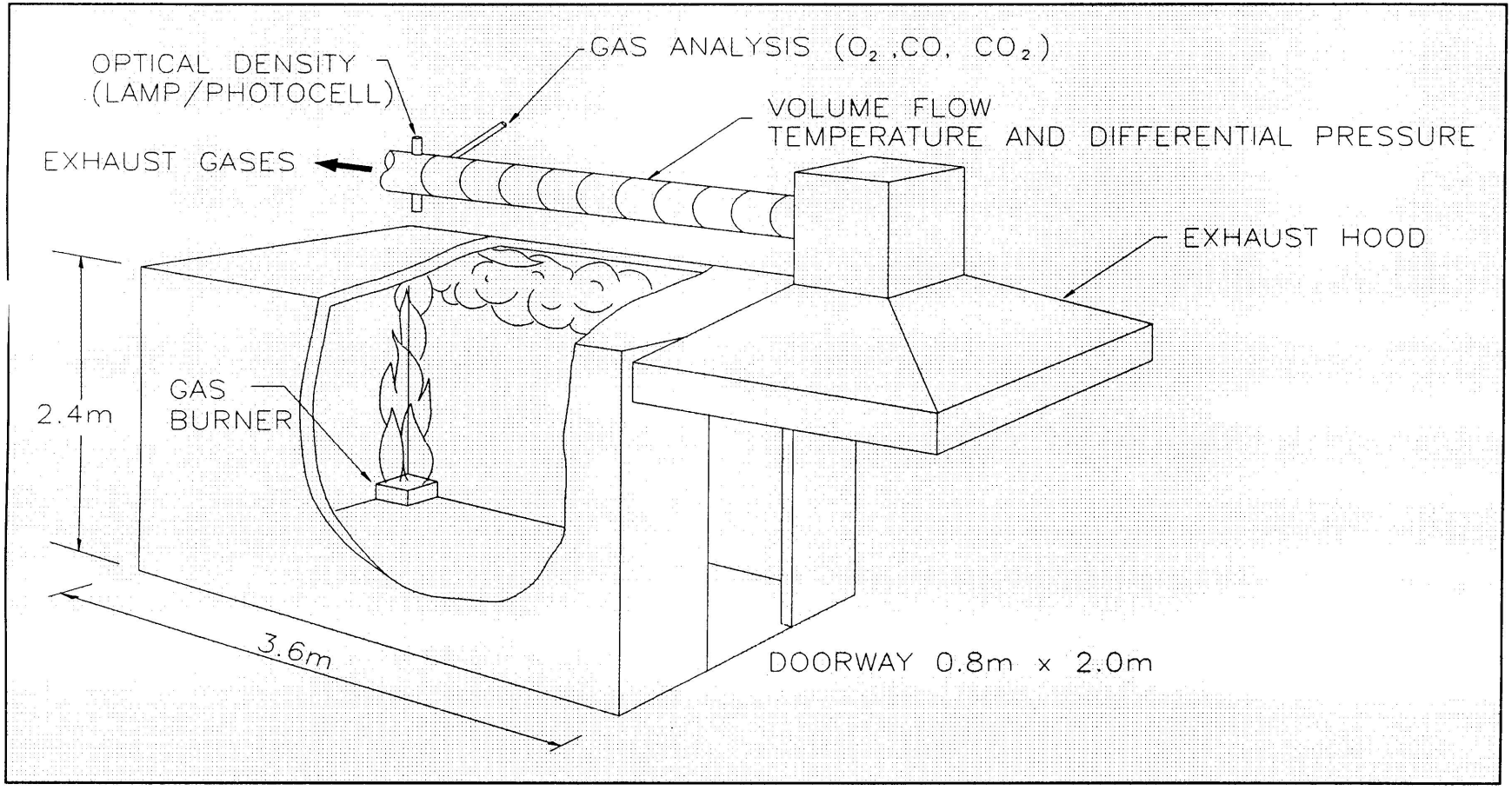
Intermediate-Scale HRR Testing



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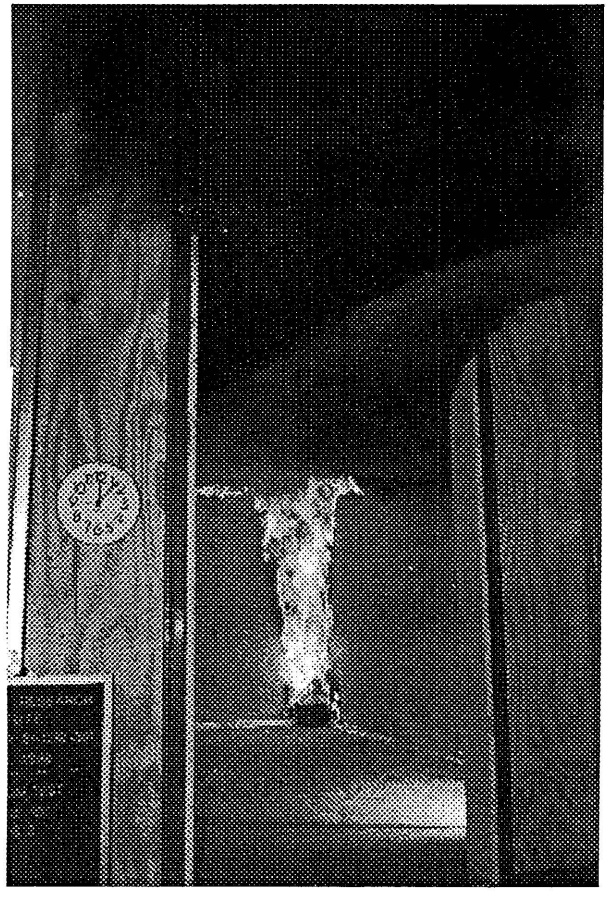
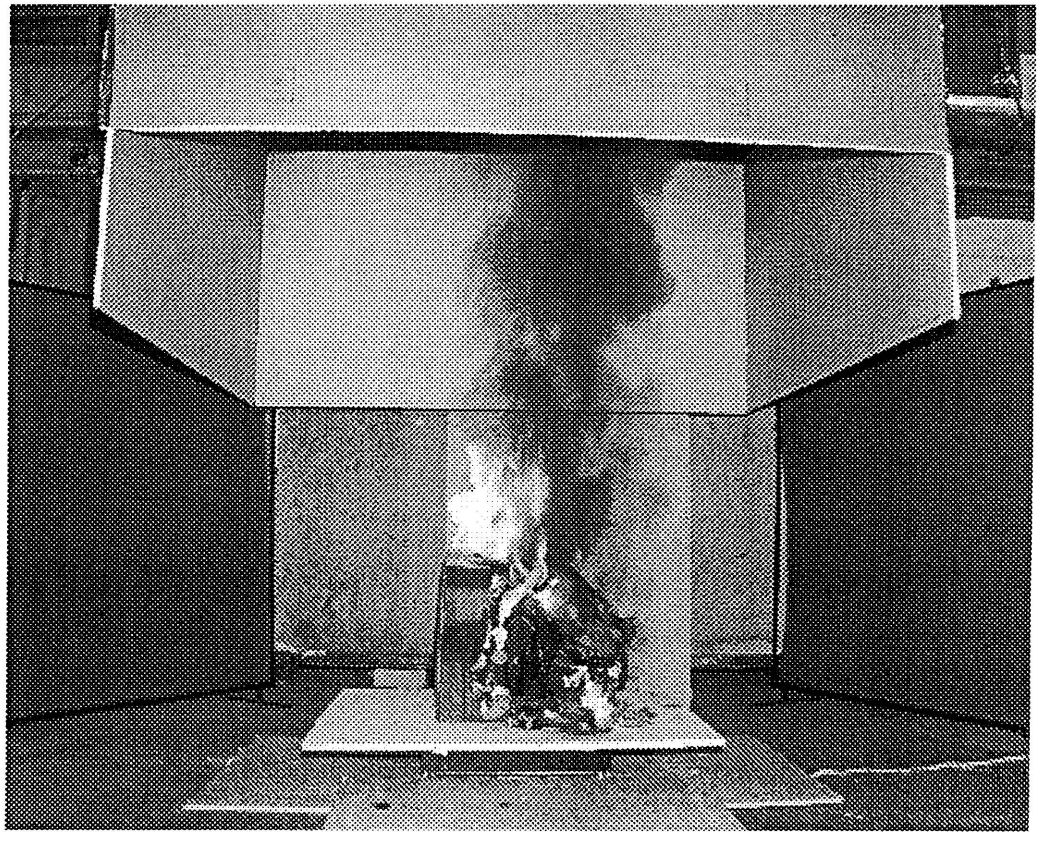
Intermediate-Scale HRR Testing



Room-Corner Test



Furniture Calorimeter

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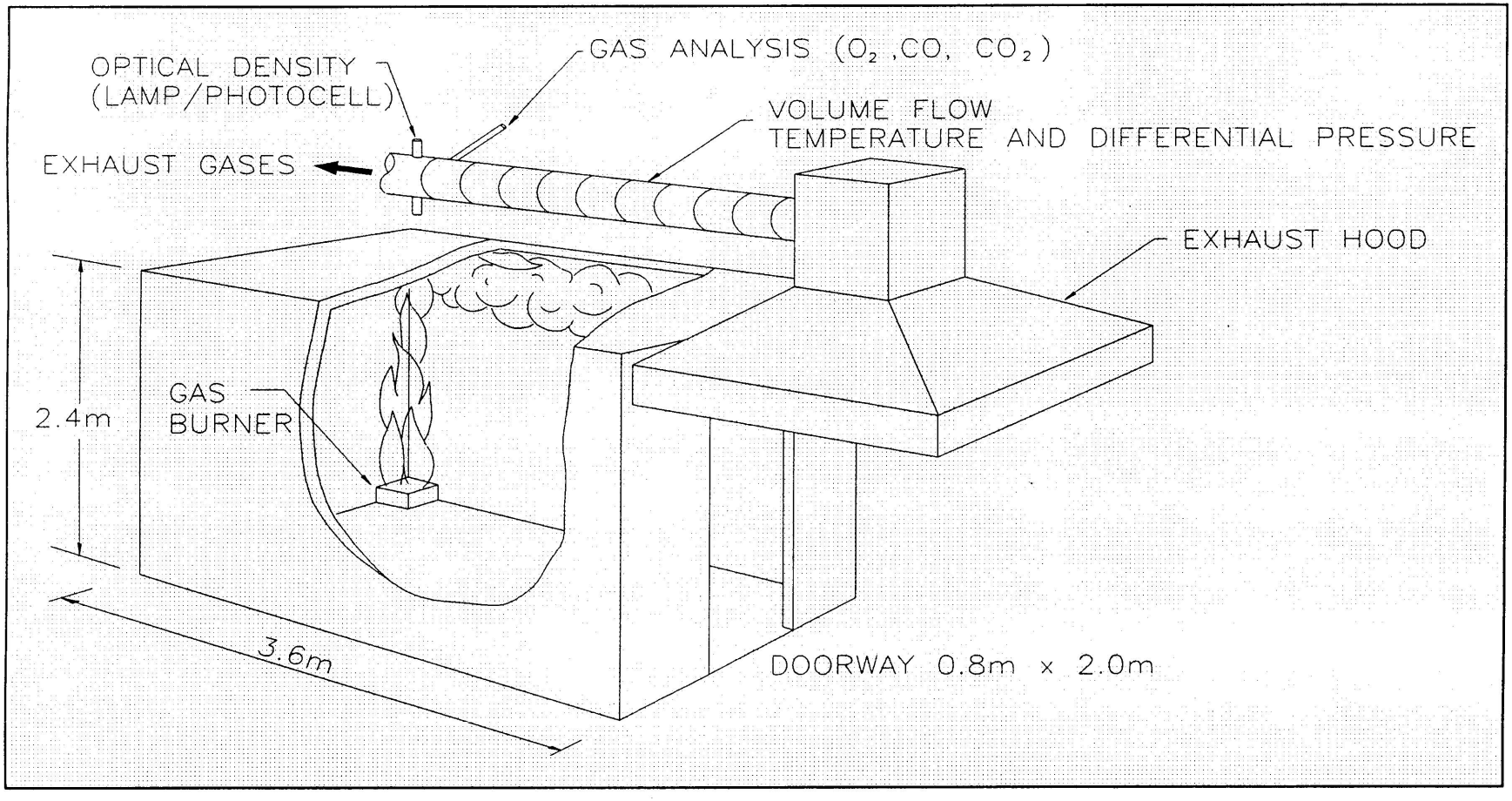
Intermediate-Scale HRR Testing



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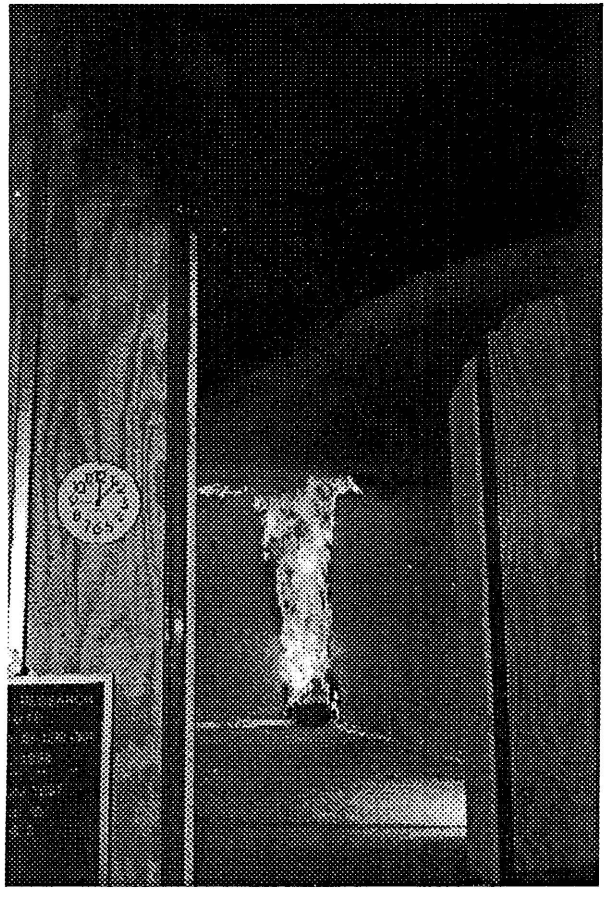
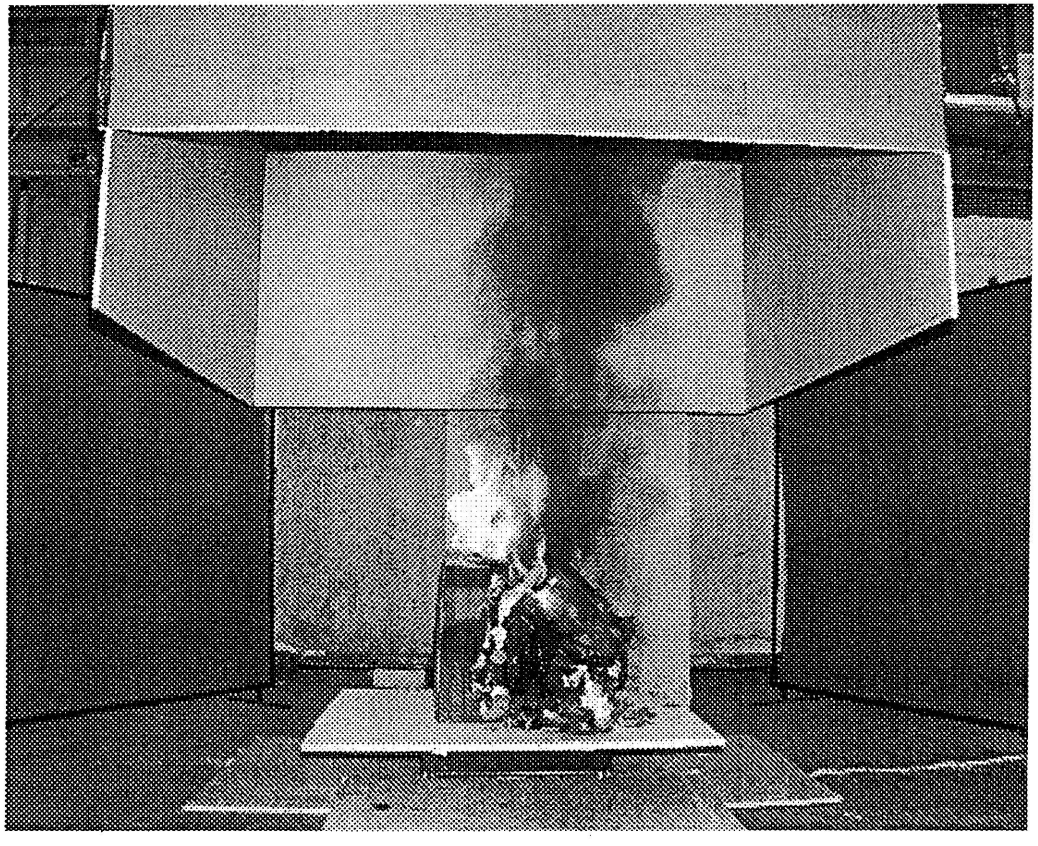
Intermediate-Scale HRR Testing



Room-Corner Test



Furniture Calorimeter

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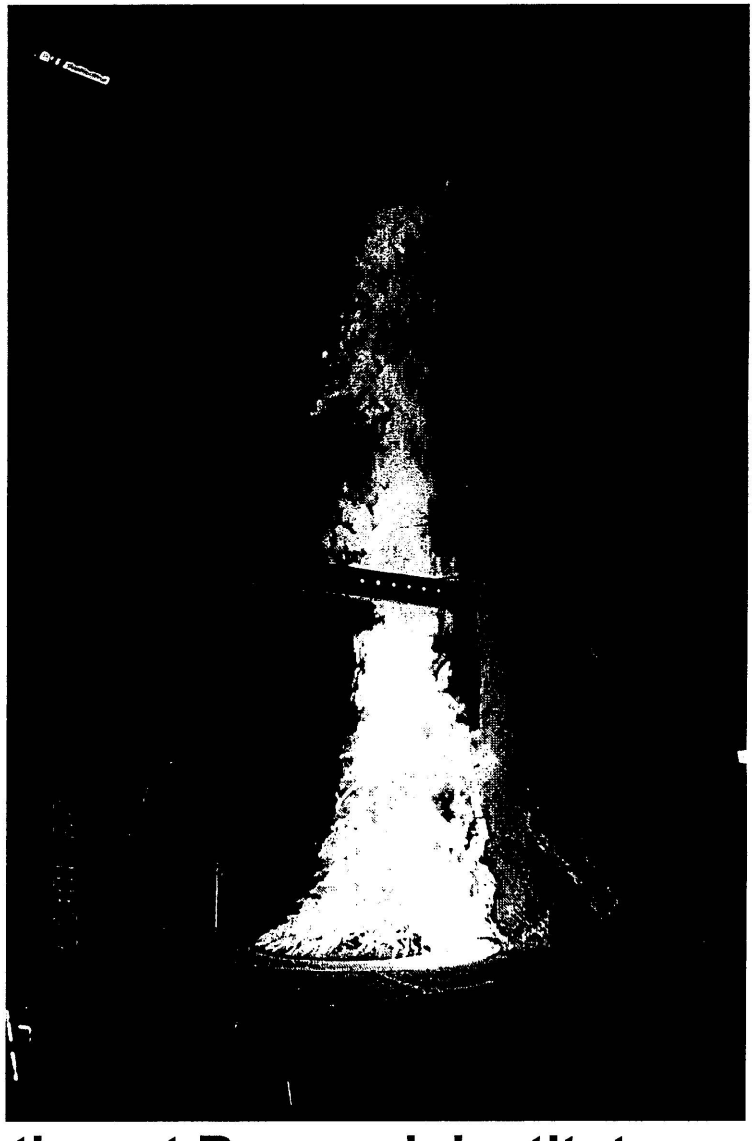
Large-Scale Calorimeter



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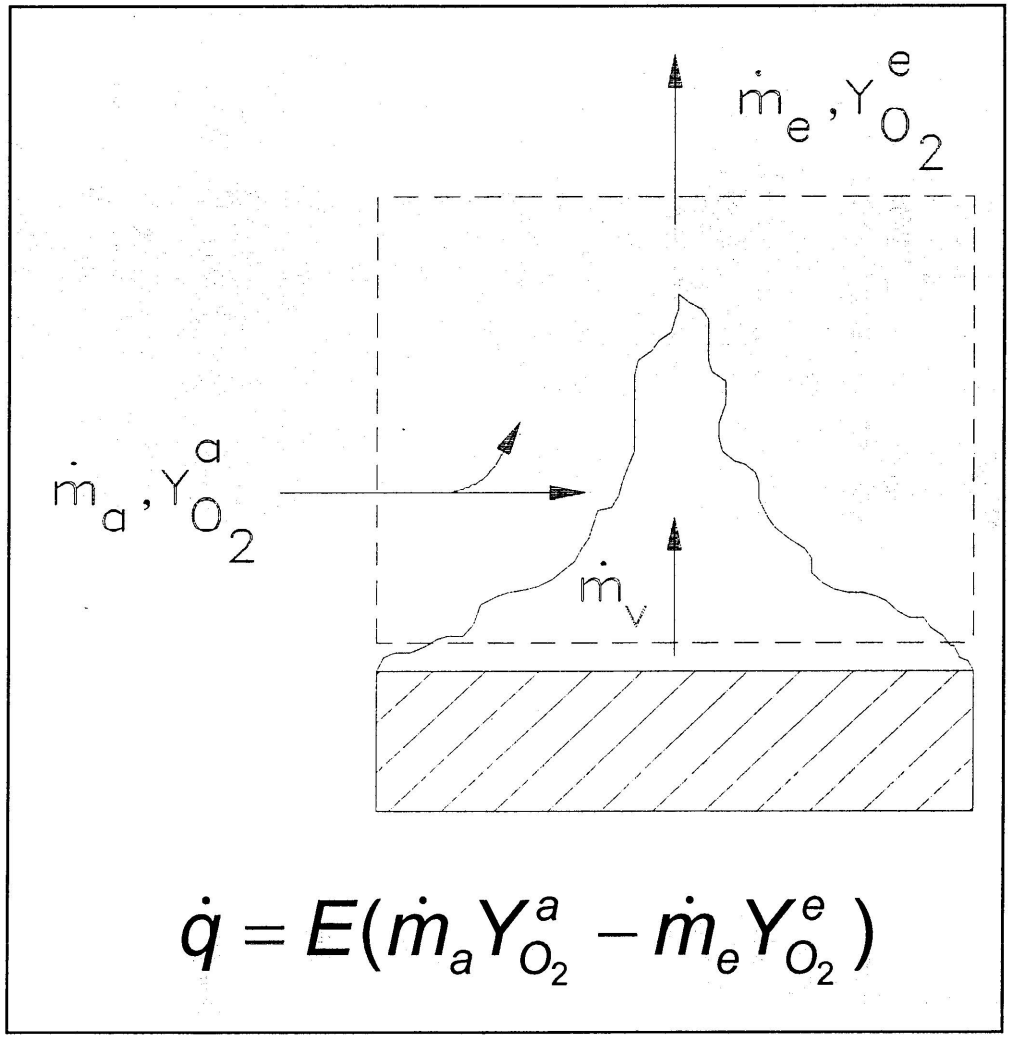
Oxygen Consumption Method



$$\dot{q} = E(\dot{m}_a Y^a_{O_2} - \dot{m}_e Y^e_{O_2})$$

Oxygen Consumption Method

$$\dot{q} = E \frac{\phi}{1+\alpha(\phi-1)} C \sqrt{\frac{\Delta P}{T_e}} \frac{M_{O_2}}{M_a} X^a_{O_2}$$

with

$$\phi = \frac{X^{A^a}_{O_2} - X^{A^e}_{O_2}}{(1 - X^{A^e}_{O_2}) X^{A^a}_{O_2}}$$

- Equations need to be modified if CO_2 is measured
- Equations can be corrected for CO and soot
- More accurate calculations can be made if water vapor is measured

HRR and Fire Modeling

	Model Input	Model Evaluation
Small-scale data	X	
Intermediate-scale data	X	X
Large-scale data		X

Uncertainty Analysis – Terminology

- Accuracy: Agreement between a measured value and the true value
- Error: Difference between the measured value and the true value, consisting of
  - Bias error: Fixed or systematic component
  - Precision error: Random component equal to r + R
- Uncertainty: Interval around the measured value within which the true value lies with C% probability

$$X_{true} = X_{measured} \pm U = X_{measured} \pm \sqrt{U_p^2 + U_b^2}$$

Uncertainty of HRR Measurements

$$\dot{q} = f(E, \alpha, X_{O_2}^{A^e}, X_{O_2}^{A^a}, C, \Delta P, T_e, \ldots)$$

$$U_{\dot{q}} = \sqrt{(\frac{\partial f}{\partial E} U_E)^2 + (\frac{\partial f}{\partial \alpha} U_\alpha)^2 + \ldots}$$

- **Small-scale HRR: U = 5% (Enright/Fleischmann, 1999)**
- **Large-scale HRR: U = 7% (Dahlberg, 1994)**

Uncertainty of HRR Measurements

- Bias can be partially eliminated by calibration
  - ↗ Uncertainty of calibration standard
  - ↗ Test conditions different from calibration conditions
- Precision uncertainty from round robins

	Year	Labs	Levels	Peak HRR		Total HR	
				r (%)	R(%)	r(%)	R(%)
Cone calorimeter	2000	4	16	17	23	8	15
SBI	1997	16	30	38	54	47	71
ICAL	1999	3	8	56	67	72	118
Room	1994	12	5	65	79	25	41

Uncertainty of HRR Measurements

Discrepancies between uncertainty analyses and round robin data:

- **Sample variability**
- **Operator variability**
- **Heat flux variability (small-scale)**
- **Random effects on fire growth (intermediate and large-scale)**
- **Dynamic errors**

Conclusions

- HRR is the primary measure of fire hazard
- HRR is an essential input to fire models
- Databases of HRR data need to be expanded
- Measurement uncertainties need to be reported
- Uncertainties need to be reduced
  - ↗ Proficiency and training programs
  - ↗ Improved accuracy of fundamental measurements
  - ↗ Resolution of dynamic errors

Extractive methods

Per Blomqvist

SP Swedish National Testing and Research Institute

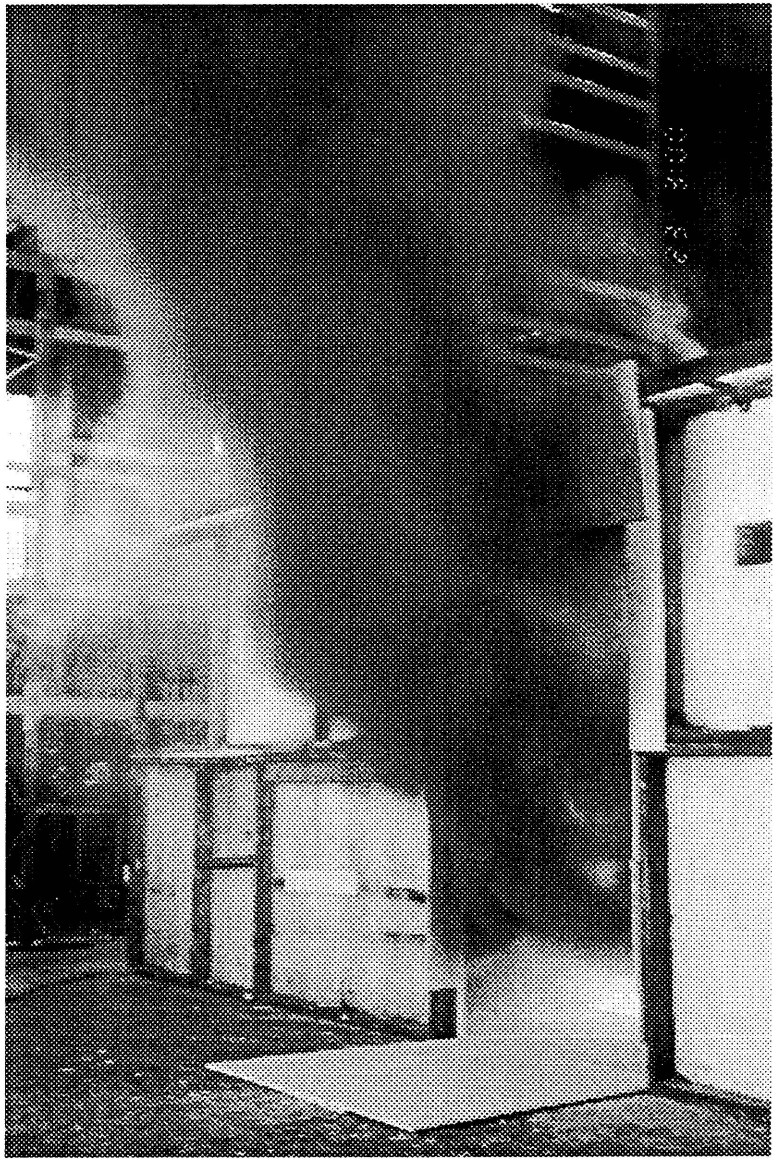
Presentation at NIST 2000-04-05

Why use extractive methods?

- More well-developed compared to optical methods, e.g. Laser methods

Problems in using optical techniques:

- High particle loading
- Limited optical access
- Optical signal absorbed
- Large-scale applications



Sampling

In the flames:

- Probe-induced disturbance
- Quenching needed
- Catalytic effects

In an opening:

- Non-uniform concentrations
- High concentrations

In a duct:

- More well-mixed
- Lower concentrations

Measurement of Fire Gases

Fire Gases:

CO_2, CO, HBr, HCl, HF,

NO, NO_2, HCN, NH_3,

SO_2, COS, C_2H_2,

VOC, PAH, Dioxins

Measurement techniques:

- Sampling for single species
- Dedicated on-line analysers
- FTIR
- GC/MS

Absorption solution

Gas specie	Absorption solution	Analysis method	Limit of detection (ppm (V/V))
Hydrogen chloride (HCl)	1.8 nM Na_2CO_3/ 1.7 mM $NaHCO_3$	Ion chromatography	0.15
Hydrogen cyanide (HCN)	0.5 M NaOH	UV spectroscopy	0.10
Ammonia (NH_3)	5 mM H_2SO_4	UV spectroscopy	0.15

(Sampling 2 *l*/min for 10 min)

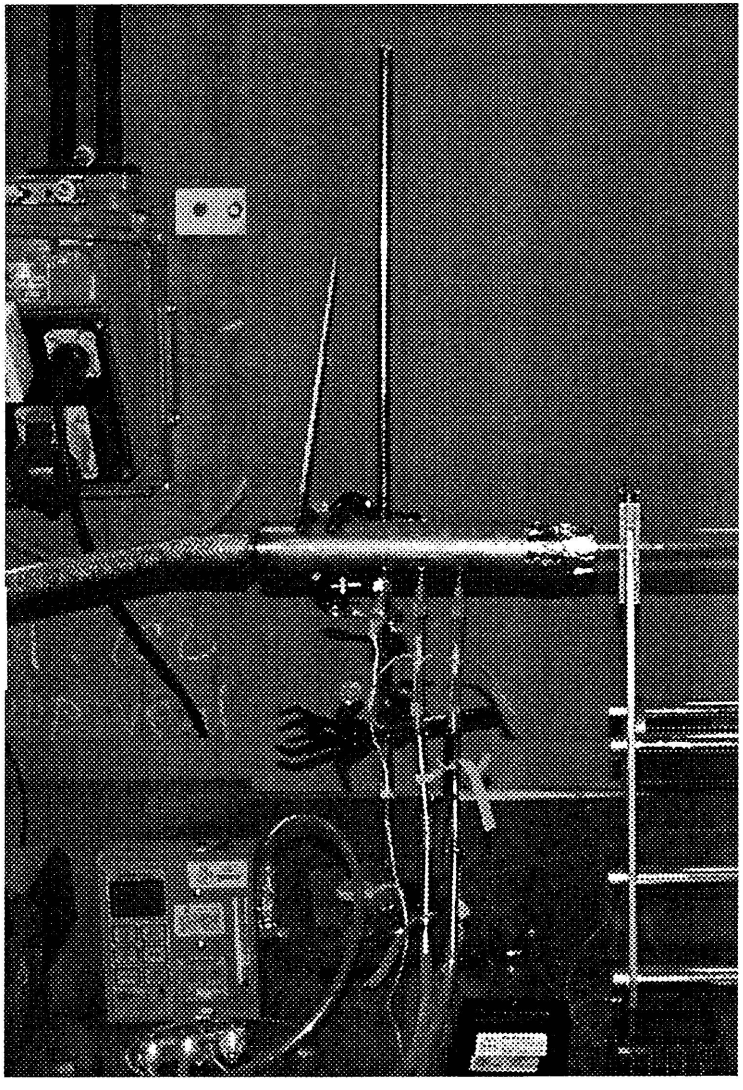
Dedicated on-line analysers

- Reliable
- Often fast (sec.)
- Broad conc. Ranges (ppm to %)
- Often single species …

Applications:

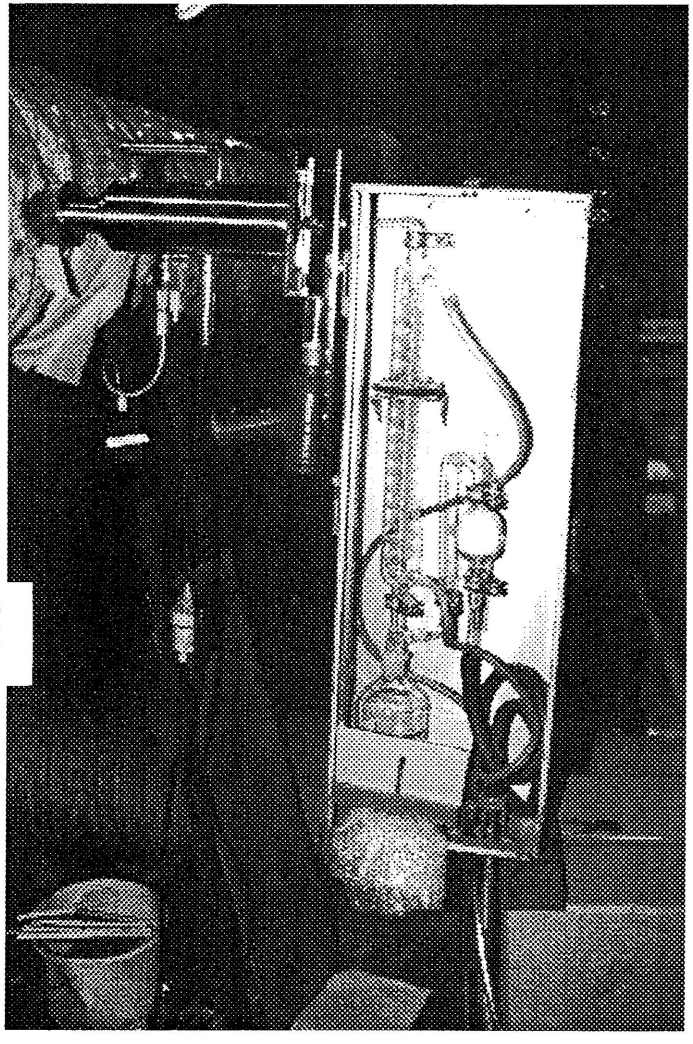
O_2, CO_2/CO, NO_X,

SO_X, THC etc.



Adsorbent sampling I

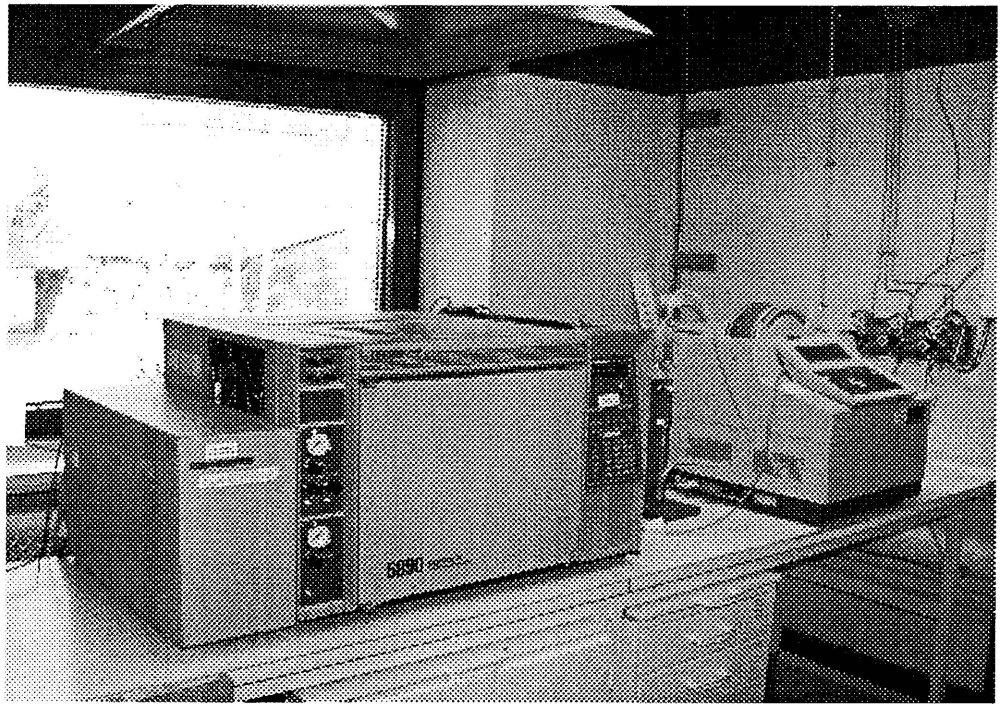
- Accumulative
- Low sampling flow
- Slow (minutes)
- Design for smaller organic species
- Thermal desorption
- ~ 0.1 ppb Benzene, 1 min



Adsorbent sampling II

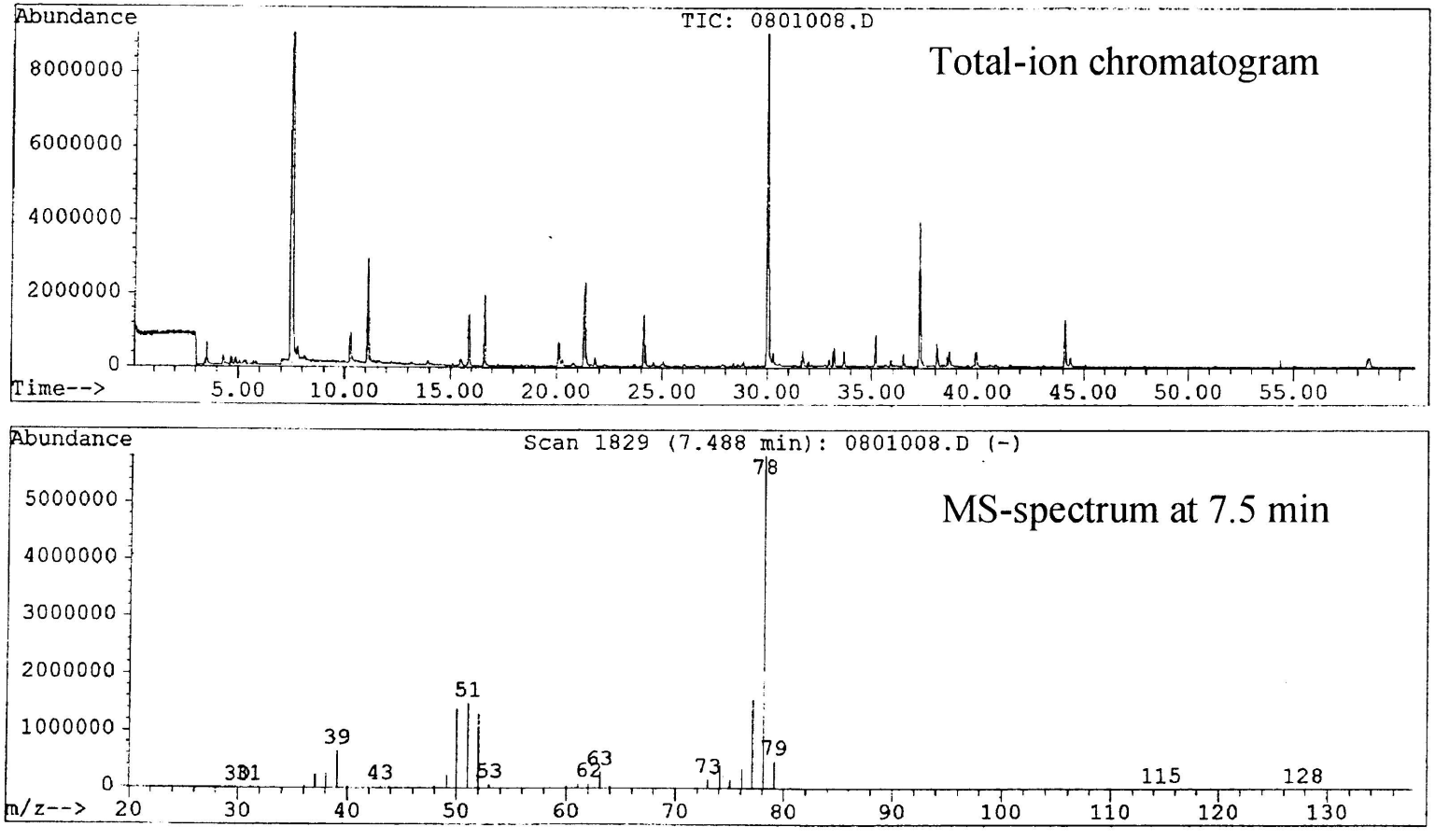
- Accumulative
- High sampling flow
- Slower (minutes …)
- Design for larger organic species
- Solvent desorption
- ~ 0.000001 ppb TCDD, 10 min

GC – MS/FID analysis

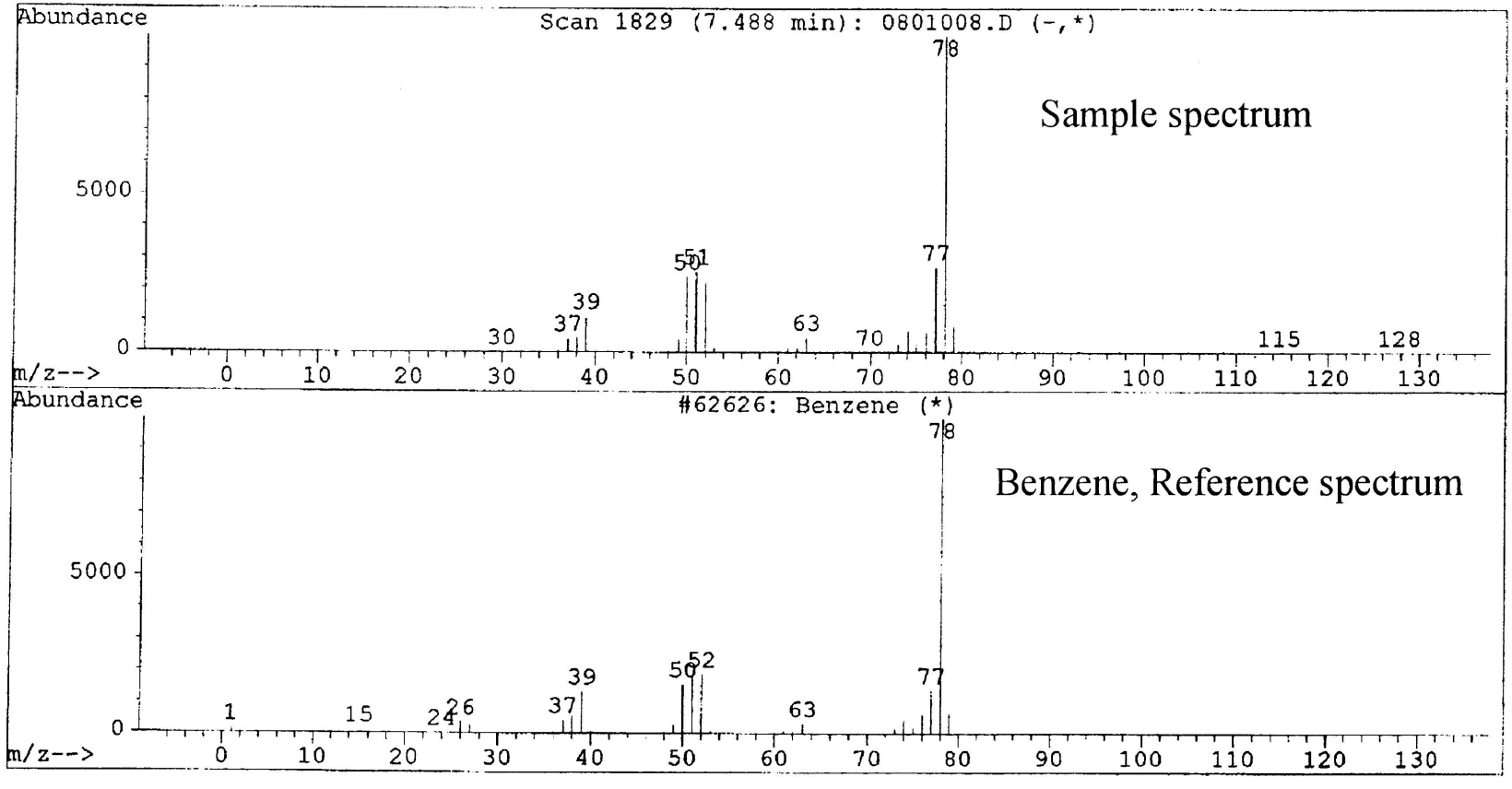


- Automatic thermal desorption
- Accumulation in cryogenic trap
- Separation on GC-column
- Identification MS
- Quantification FID
- Detection: ng

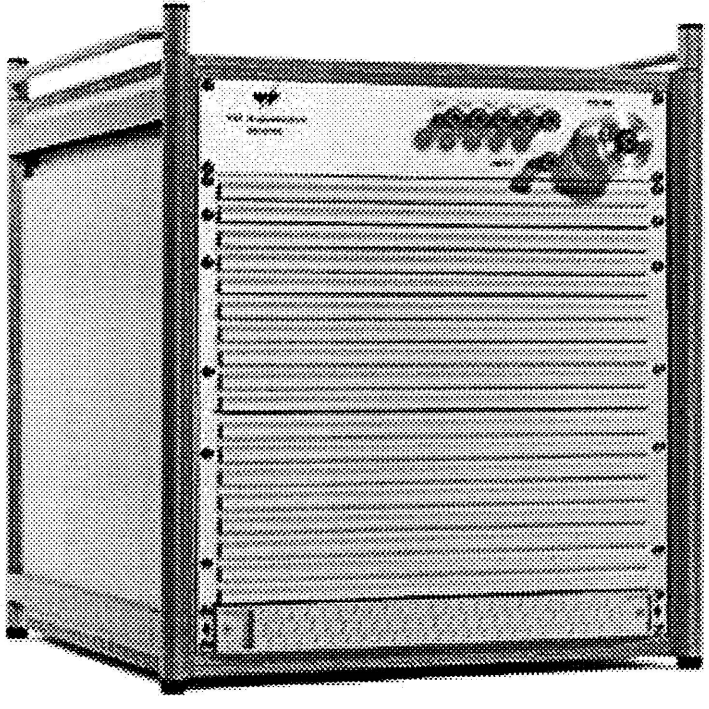
MS analysis of fire test sample

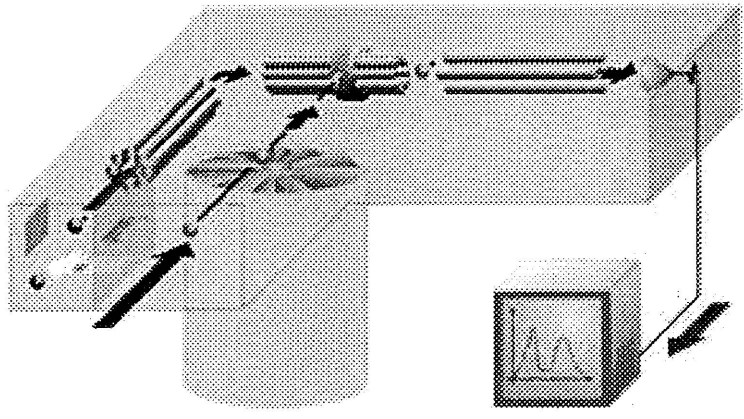


Identification from MS-spectra



On-line MS





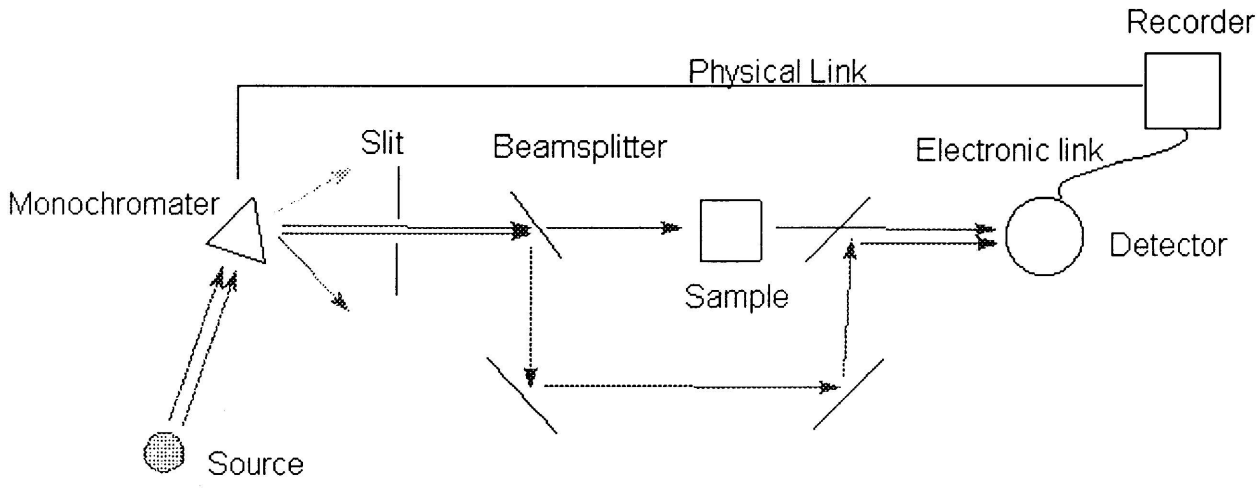
610 × 570 × 700 mm

On-line MS

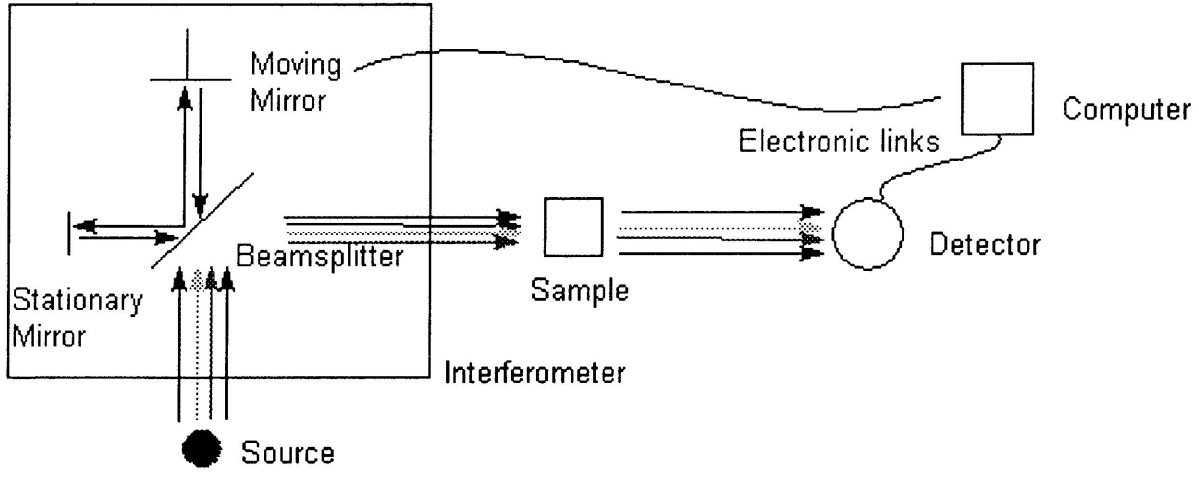
- Commercial instrument
- Automotive applications
- Incinerator and boiler applications
- Small-scale studies of pyrolysis
- On-line meas.
- Fast, 0.05 ppb Benzene, 2 sec.
- Broad range of species, 0 – 500 a.m.u
- Expensive

Fourier Transfer InfraRed (FTIR) spectrometry

- Several gases simultaneously
- Fast measurements
- High optical throughput
- Low limits of detection
- Stable calibration

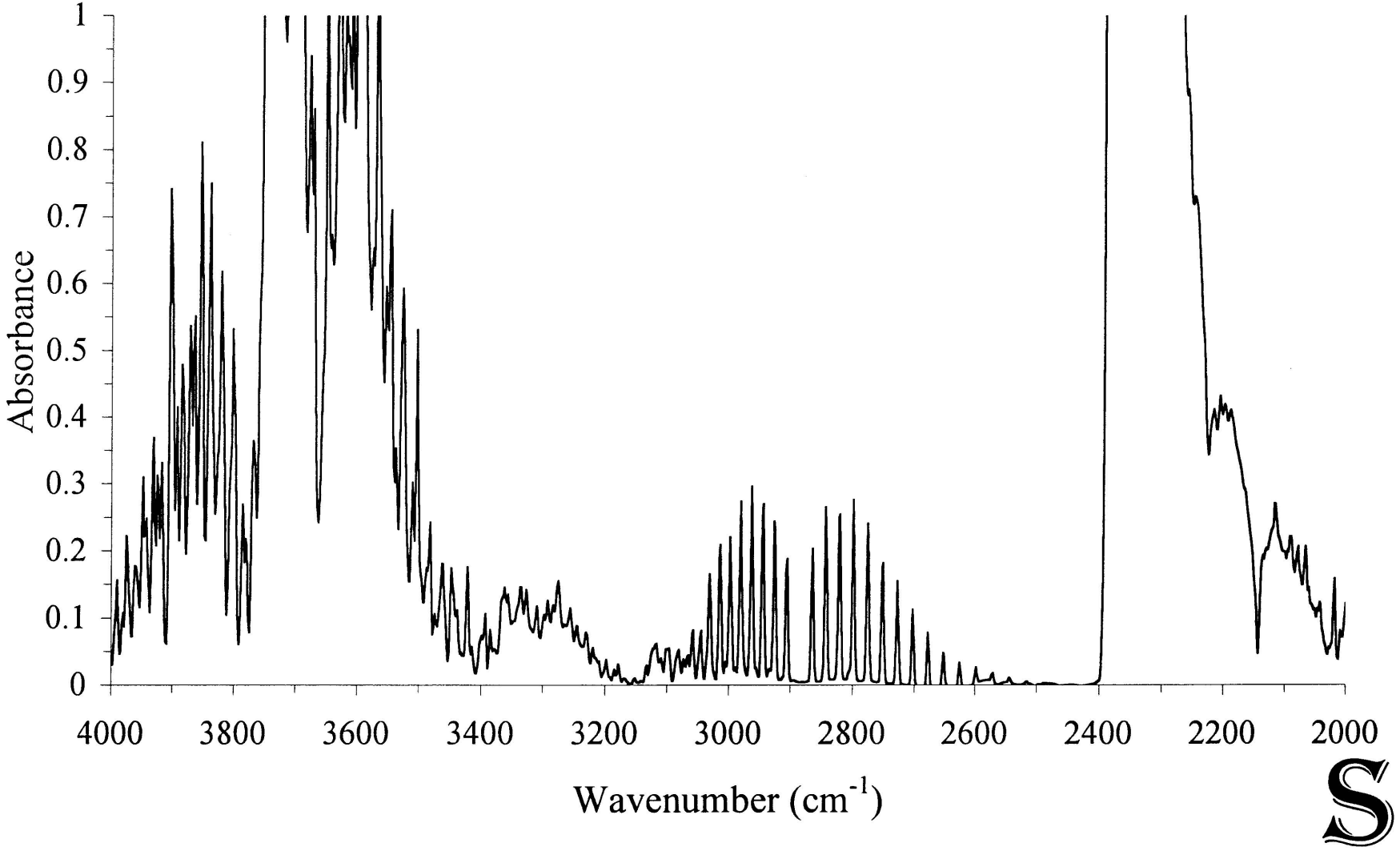


Classical spectrometer



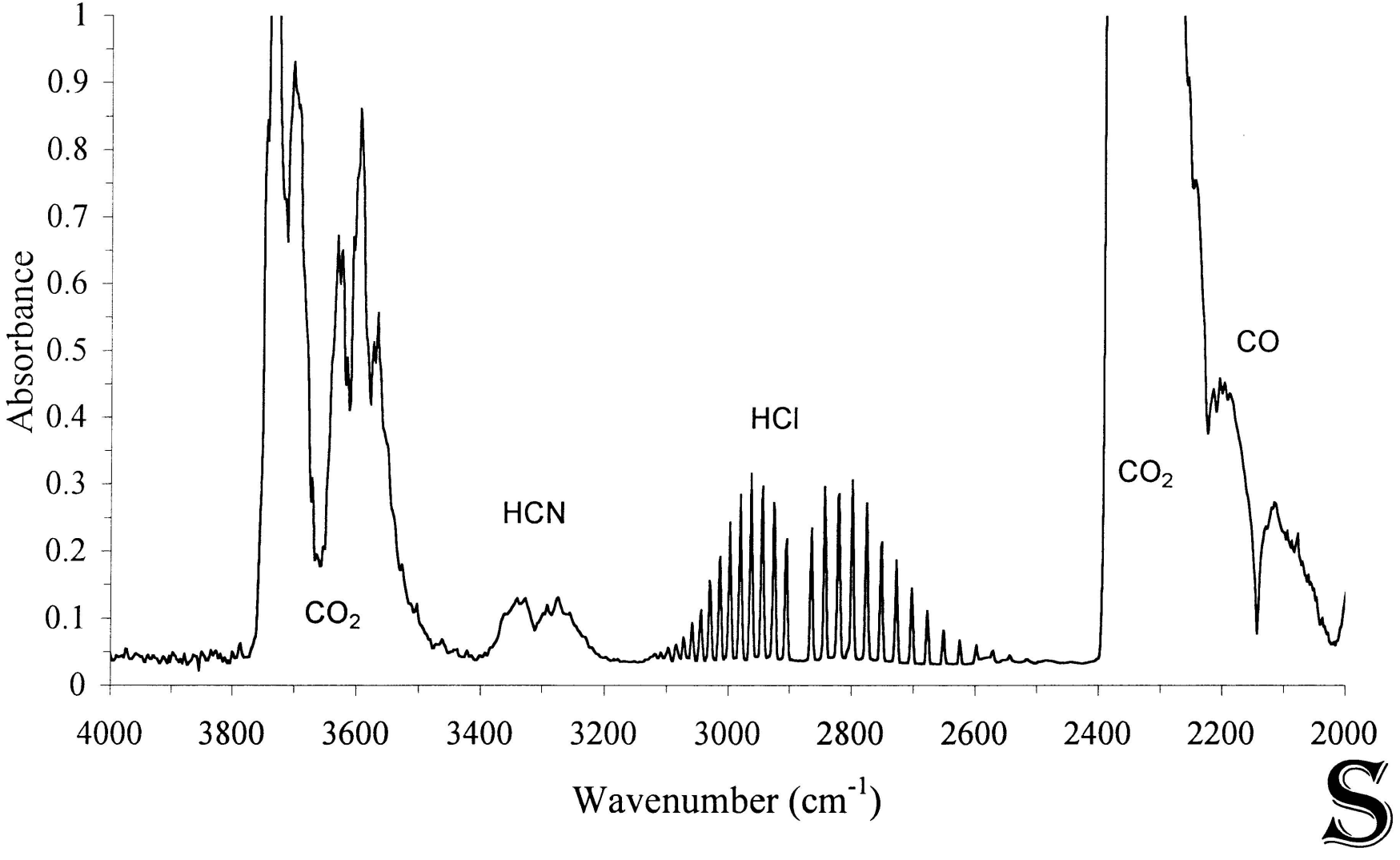
FTIR spectrometer

FTIR Spectrum

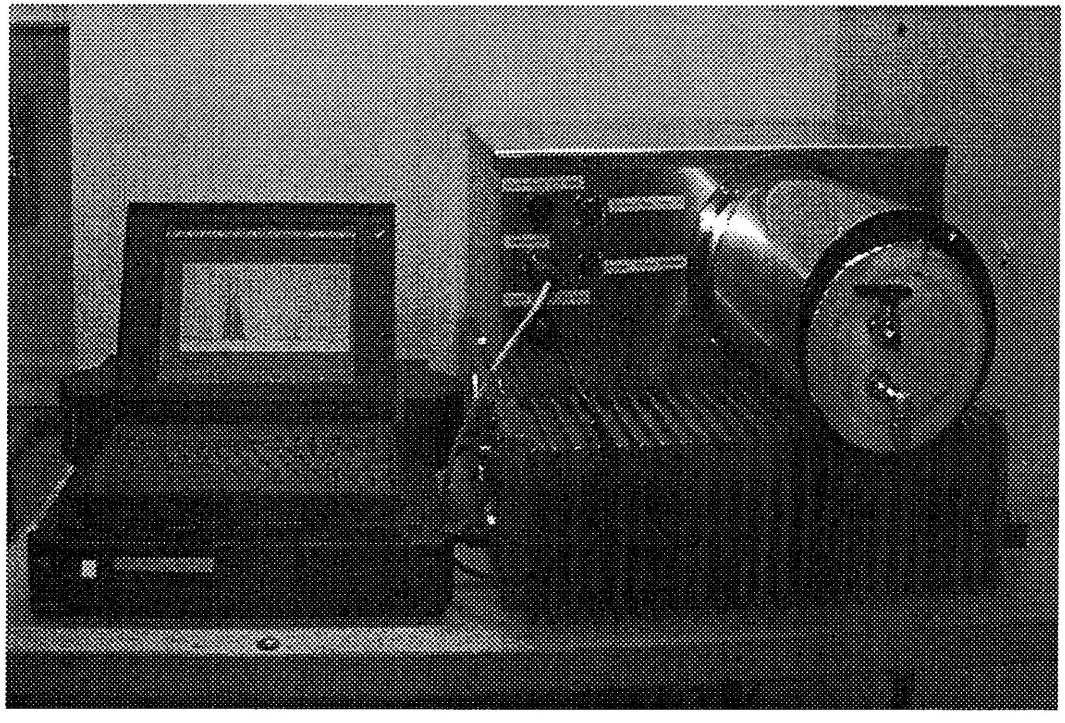


S

FTIR Spectrum with water subtracted

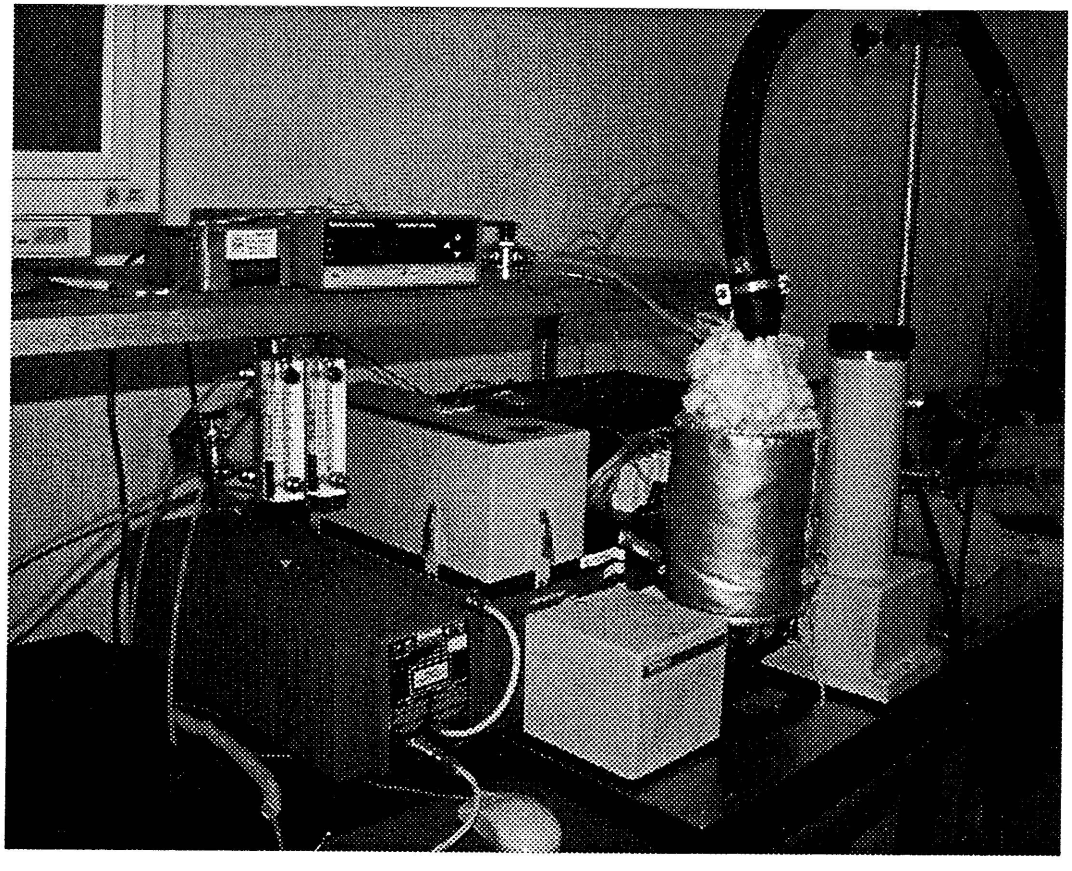


The FTIR apparatus



- IR source
- Interferometer
- Optics
- Gas cell
- Computer

Well-equipped FTIR



- Fast scanning interferometer
- 2 cells, one "pre-calibrated"
- 2 detectors

Temporal resolution and detection limits I

Detection limit: Path-length, Signal-to-noise ratio

Signal-to-noise ratio:

- Number of scans (**temporal resolution**)
- The Spectral resolution
- Optical components
- Quality of detector

Increased temporal resolution ➡ **poorer detection limits**

Temporal resolution and detection limits II

Time ⇩

Number of scan	Collect. time (s)	DTGS	MCT
		MDL (ppm)	MDL (ppm)
1	1-3	8	2
2	2-6	5.6	1.4
4	4-12	4	1
8	8-24	2.8	0.7

S/N ⇩

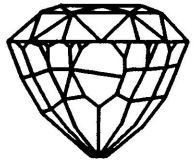
MDL: Minimum Detection Limit, in example for HCl
Spectral resolution: 4 cm^{-1}, Path-length: 4.8 m

S

Example of detection limits (MDL)

Gas	MDL (ppm)
CO	7
NO	8
NO_2	0.5
SO_2	1
HCN	0.5
HCl	5
HBr	10
HF	2

- Path-length: 4.8 m
- No. of scans: 3 (9 sec.)
- Detector: DTGS
- Resolution: 4 cm^{-1}



SAFIR

Smoke gas analysis by Fourier transform infrared spectroscopy

Contract no. SMT4-CT96-2136

Final report of the SAFIR project

Edited by Tuula Hakkarainen, VTT Building Technology

Accuracy of FTIR: Interlaboratory trail

Method / parameters	Repeatability standard deviation s_r/m	Reproducibility standard deviation s_R/m
SBI, 1997		
RHR_{max} , THR	5 - 41 %	7 - 60 %
Smoke prod.	7 - 78 %	19 - 114 %
Cone calorimeter, 1997		
RHR_{max} , THR	3 - 55 %	4 - 87 %
Cone calorimeter, 1991-2		
Smoke prod.	6 - 60 %	16 - 100%
This study		
Max gas conc.	4 - 17 %	15 - 47 %
Gas yield (FTIR)	(11,0 % average)	(27,9 % average)
RHR_{max} , THR	4 - 16 %	10 - 34 %
Smoke prod.	4 - 14 %	9 - 18 %

Summary

- Sampling is critical
- A number of measurement methods exists
- GC/MS, MS: organic species, small to large
- FTIR: inorganic species, smaller organics
- Low detection limits ⇨ longer measurement time

In-Situ Gas Concentration Measurements for Fires

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Building and Fire Research Laboratory
April 6, 2000

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Definition of *In-Situ*

- Not intrusive
- Does not alter environment
- Involves lasers and detectors
- Employs spectroscopy

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Selecting a Method

- Consider application: bench scale experiment, product test, reduced scale enclosure, full scale burns
- What are you measuring? How much is there? What is the temperature?
- What other things are there? gases, early soot, mature soot, droplets
  - these could be interferences
  - also could attenuate or steer light
- Optical Access Possibilities
- $$$$$$ Budget ..... Time Budget
- Available Expertise? technician, engineer, trained MS or PhD laser diagnostician
- Many applications require two or more methods

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Comments on Accuracy

- Major uncertainty sources are systematic errors associated with converting a measured quantity into a concentration
  - temperature effects
  - collisional environment
  - laser power fluctuation, laser line center/shape drift
  - soot extinction, beam steering/defocusing
- Accuracy sometimes expressed as "detection limit"

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Spontaneous Raman Scattering

- Used for Major Species Concentrations
  - H_2, N_2, O_2, CH_4, CO_2, CO
- Inelastic scattering of laser light by molecules
  - Incoherent (scatters in every direction)
  - No specific λ_{laser} is required, although lower λ_{laser} => higher signal
  - Scattering at $\lambda_{emission} > \lambda_{laser}$ (Stokes) and $\lambda_{emission} < \lambda_{laser}$ (Anti-Stokes)
  - Several molecules detectable by monitoring several $\lambda_{emission}$ simultaneously
  - Suffers interference from PAH LIF, Other Raman, Rayleigh
  - Can suffer interference from wall & particulate scattering
  - **Weak Signals**
- Temporal resolution => (typ. < 1 μs) => determined by detector gate or laser
- Spatial resolution => (typ. < 1 mm^3) => determined by collection optics
- Often Combined with Rayleigh Scattering for Temperature & Concentration

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Rayleigh Scattering

- Signal proportional to total ρ -- all molecules contribute
- Used primarily for Temperature
- Can be used for gas concentration in isothermal binary mixtures
- Elastic scattering of laser light by molecules ($\lambda_{emission} = \lambda_{laser}$)
  - Incoherent (scatters in every direction)
  - Requires clean environment
  - Signal much stronger than Raman Scattering
- Temporal resolution => (typ. < 1 μs) => determined by detector gate or laser
- Spatial resolution => (typ. < 1 mm^3) => determined by collection optics
- Can suffer interference from wall & particulate scattering

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Laser Induced Fluorescence (LIF)

- Used for Minor Species Concentrations
  - OH, CH, NO, CO routinely probed
  - Also possible to probe H_2, O_2, H_2O, O, H & other atoms
  - Mixing tracers such as added acetone
- Laser light => photon absorbed by molecule => light emitted
  - A molecule can have several $\lambda_{emission}$ (same & different from λ_{laser})
  - Incoherent (emitted in all directions)
  - Orders of magnitude stronger signals than Raman scattering
  - Sensitive to quenching
- Temporal resolution => (typical < 1 μs) => determined by detector gate or fluorescence lifetime
- Spatial resolution => (typical < 1 mm^3) => determined by collection optics
- Can suffer interference from PAH LIF, Rayleigh
- Can suffer interference from wall & particulate scattering

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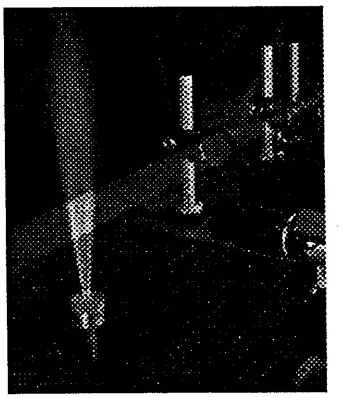
Planar Imaging Measurements

- CH, C_2, CN, NO, H, O, CO, Tracers (acetone)
- Mostly qualitative
- Planar Rayleigh, Planar LIF (PLIF)
- Can be performed simultaneously with planar velocimetry
- Suffer from Raman, Rayleigh, LIF interference sources
- PLIF requires intensified CCD cameras



SNL Website

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Coherent Anti-Stokes Raman Scattering (CARS)

- Used for Major Species N_2, O_2, CO, H_2, H_2O concentrations > 1% vol
- 2 or 3 incident laser beams with special λ_{laser}
  - Produce a coherent (directional) signal beam with an additional λ
  - Can be used in mildly sooting environments
  - Multiple species and/or temperature
  - Signal orders of magnitude stronger than spontaneous Raman
  - Complicated spectra/signal processing
  - Suffers from non-resonant spectral background interference
- Spatial Resolution: Defined by laser overlap geometry (typical ~ 1 mm²)
- Temporal Resolution: (typical < 1 μs) defined by detector gate or laser pulse
- Accuracy: detection limit ~1%

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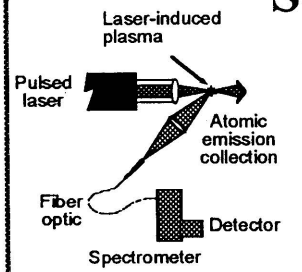
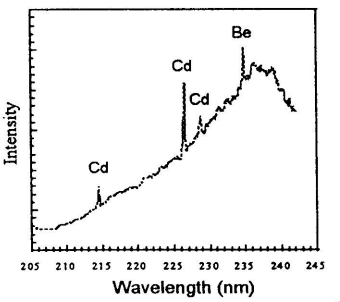
Laser Induced Breakdown Spectroscopy (LIBS)



- **Uses spectral information to measure multiple metals**
- **Good for inorganic species**
- **Temporal resolution ∝ plasma lifetime ≈ 100 μs**
- **Spatial resolution ≈ 2 mm**
- **Detection limits O(ppb)**

- Line position provides species identification
- Line intensity provides species concentration



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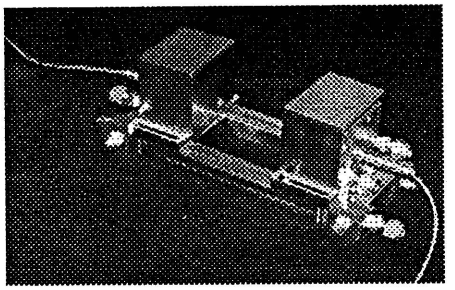
Dr. Steven Buckley, buckley@eng.umd.edu

Tunable Diode Laser Absorption (TDLAS)



- fiber optics
- low-cost miniature lasers
- water-cooled
- purged optics
- quantifiable spatial & temporal resolution
- quantifiable uncertainty
- fast measurements
- use in sooty environments
- detect multiple species simultaneously

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Laser Absorption Spectroscopy

- Laser photon absorbed by molecule
  - traditionally performed using lamps
  - path-averaged measurement
  - now performed with tunable diode lasers
- Near-infrared communication lasers: spectrally narrow
  - H_2O, T, soot, CO, O_2, CO_2, CH_4, C_2H_2, C_2H_4
    also HCN, HCl, NO, NO_2, OH, H_2S, NH_3
- Lasers => narrow spectral coverage
  - ~2.5 nm (10 cm^{-1}) for temperature-tuning
  - ~0.5 nm (2 cm^{-1}) for current-tuning
-

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TDLAS Challenges

- Weak overtone molecular transitions
  - Need to measure τ ~0.99999
- Line shapes change with T & collision partners
- Congested spectra
  - H_2O primary culprit
  - Hot bands at high temperatures
  - Unknown high-temperature spectroscopy
- Interferometric noise (etalons)
- Beam steering/optical alignment

–Spatial Res.: Can be ~10 cm
–Temporal Res.: Can be < 1 ms
–Accuracy:
• τ of 0.99999 or 0.9999 achievable
•space/time/T *trade-off*
•CO => 0.1% per m, 200 ms, 300 K

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Year 2000 TDLAS Work
Fires and Sooty Flames

- NIST
  - CO, C_2H_2 => quantifying signals & determining uncertainty
- Army Research Laboratory (ARL)
  - HF, O_2, hydrocarbons => suppressant effectiveness, fuel-to-air ratio
- Sandia National Laboratories (SNL)
  - H_2O, soot, temperature, C_2H_2, CO_2 => real-scale fire hardware
- Naval Research Laboratory (NRL)
  - O_2 for large-scale suppression studies
- Stanford/Navy Pulse Detonation Engines
  - T, soot fraction, 2-color soot absorption/emission, multiplexed diodes

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Near-IR TDLAS Success Stories

- HF measured during chemical suppression of large Army *fires*--McNesby et al., Appl. Phys. B 67:443, 1998
- 10-kHz control system used to optimize a *50-kW Navy dump combustor*--Furlong et al., AIAA J. 37:732, 1999
- Air mass flux sensor flown on *P&W F-100 aircraft engine*--Allen, Meas. Science & Tech. 9:545 1999
- Hygrometer flown on wing of *NASA P3B research aircraft*--Applied Physics B. 67:275 Sonnenfroh et al., 1998
- O_2, CO, and HCl in stack of a 27-MW *paper mill boiler/incinerator*, HF in *aluminum smelter*, NH_3 in 460-MW *coal boiler flue*, Linnerud, et al., Appl. Phys. B 67:297, 1998
- H_2O & T in NASA microgravity *drop tower flames*--Silver et al., Appl. Opt. 34:2787
- CH_4 sensor in *landfill*--Hovde et al., J. Atm. Chem. 20:141, 1995

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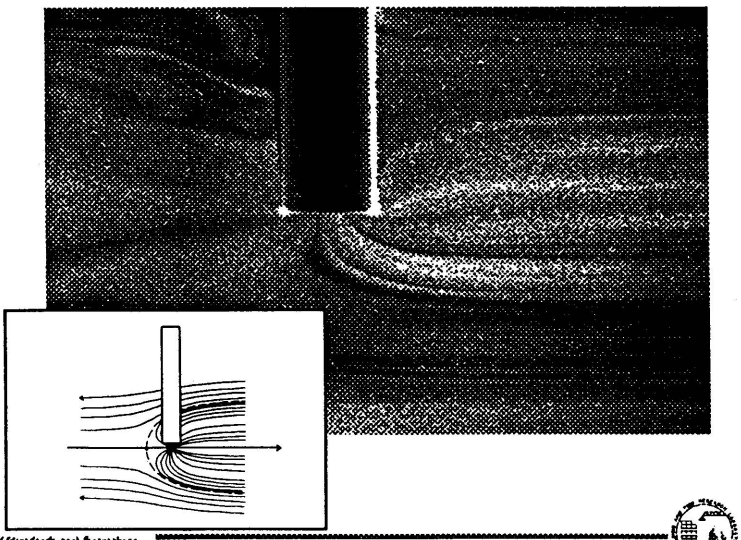
PIV Study of Extractive Probes



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Summary

	Spatial Resolution	Temporal Resolution	Accuracy (?*)	Comments
Raman Scattering	~1 mm	< 1 μs	5 %	Weak Signals Multiple Species
Rayleigh Scattering	~1 mm	< 1 μs	5 %	Clean Environment
LIF	~1 mm	< 1 μs	5 %	Quenching Important
CARS	~2 mm	< 1 μs	5 %	Mild Soot OK Complex Data Reduction
LIBS	~2 mm	~100 μs	5 %	Metals/Toxicity
TDLAS	~10 cm	~1 ms	5 %	Space/Time/Temperature Trade-Off Fire Research Activity

*Accuracy depends on species being measured and its environment, i.e., line strength, temperature dependence of spectroscopy, interfering species, averaging time, beam attenuatio and steering, dynamic range of detector, etc.

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Reading List I

- **Laser Diagnostics for Studies of Turbulent Combustion.** E.P. Hassel and S. Linow. *Meas. Sci. Technol.* 11:R37. 2000.
- **Laser Spectroscopic Techniques for Combustion Diagnostics.** Marcus Alden. *Combust. Sci. Tech.* 149:1. 1999.
- **Laser and Probe Diagnostics in Fundamental Combustion Research.** Katharina Kohse-Hoinghaus. *Israel Journal of Chemistry.* 39:25. 1999.
- **Diode Laser Absorption Sensors for Gas-Dynamic and Combustion Flows.** Mark Allen. *Meas. Sci. Technol.* 9:545. 1998.
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Measurement of Smoke Aerosol

George Mulholland
Building and Fire Research Laboratory
April 6, 2000

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Current Motivation for Smoke Measurements

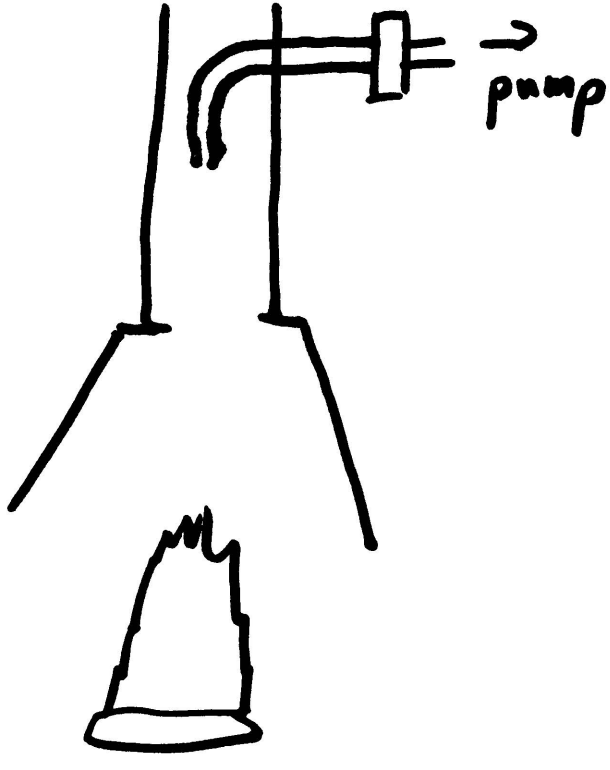
- Reduction in nuisance alarms from smoke detectors
- Improved plastics with less smoke production
- Validation of models for smoke flow/dispersion
- Development of sub-grid flame radiation model

Mass Concentration via Sampling and *in situ* Measurement

- Post-flame
- In-flame
- Distributed

Post-Flame Sampling from a Duct

Lowest Expanded Uncertainty - 4 %
Typical Uncertainty - 10 %



- Isokinetic sampling
- Thermophoretic losses
- Filter efficiency
- Flow control/calibration
- Uniformity of smoke
- Filter weighing

Bouguer's Law

- *relates light intensity ratio I/I_s to the mass concentration smoke M_s and pathlength L.*
- *assumes σ_s is independent of size or structure of the agglomerate.*

$$\frac{I}{I_0} = exp(-\sigma_s M_s L)$$

Recommended Value of σ_s for Smoke Produced by Overventilated Flaming Combustion of Materials in Buildings

8.7 m^2/g

Expanded Total Uncertainty: $\pm$ 1.1 m^2/g

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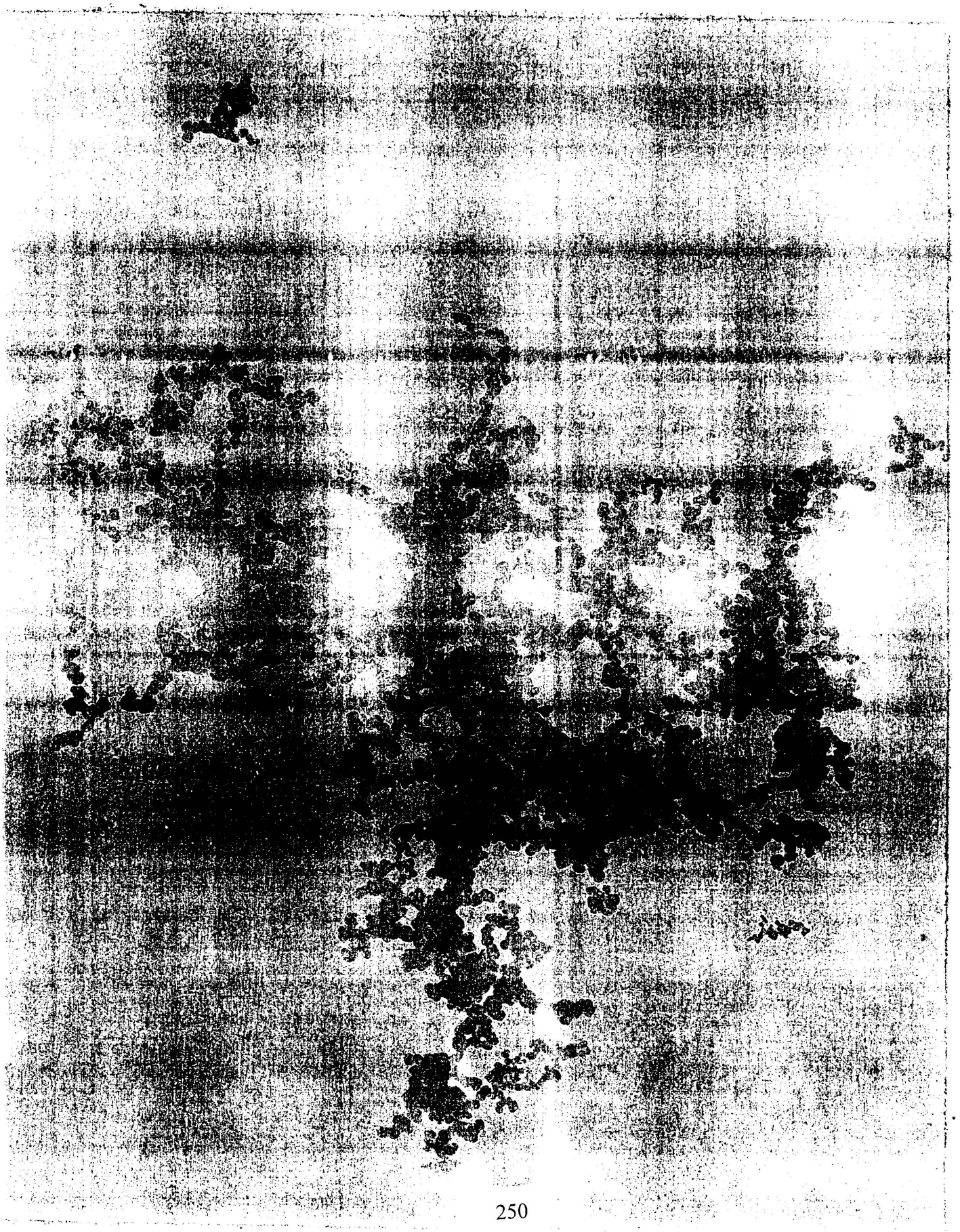
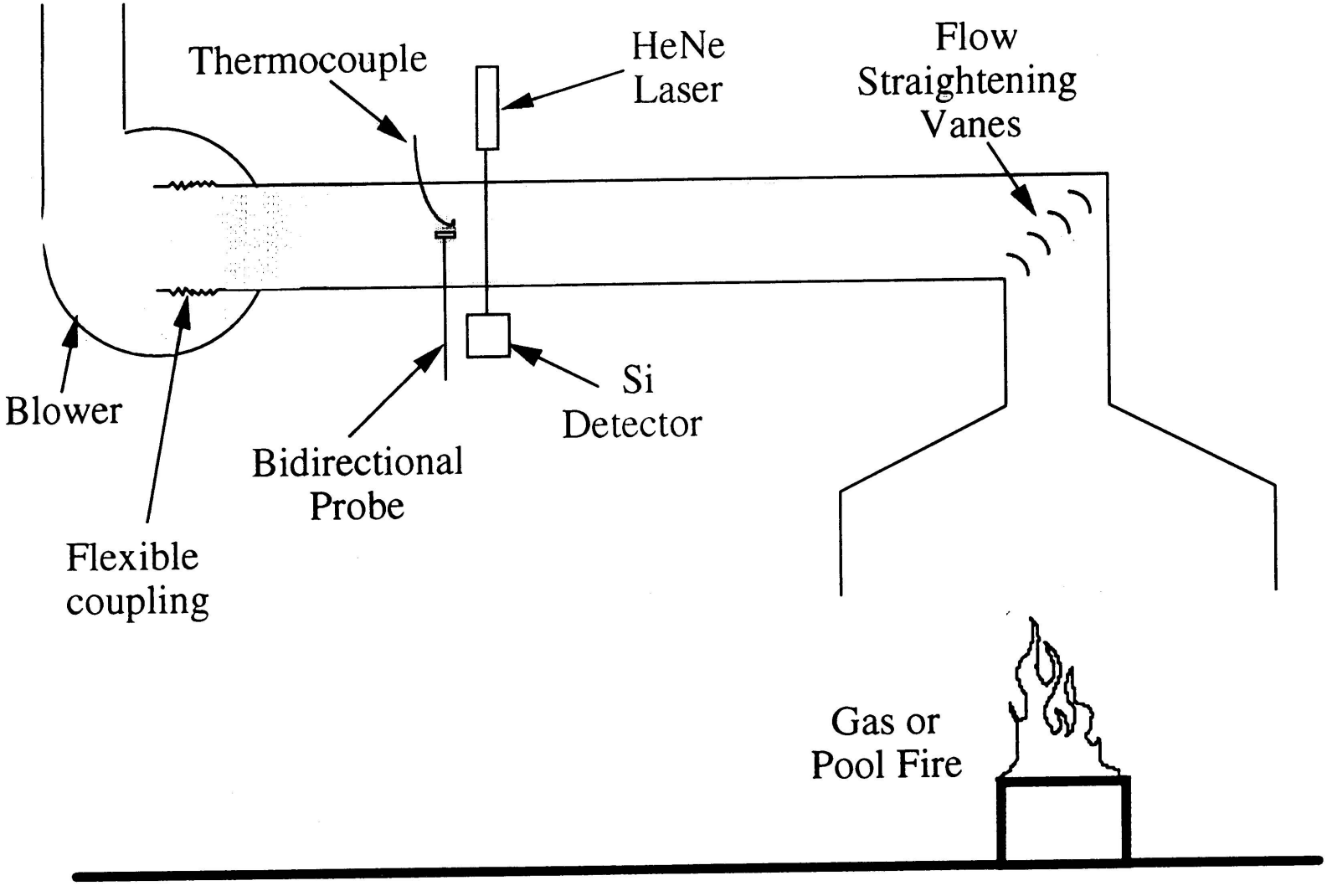


Smoke Meter Overview



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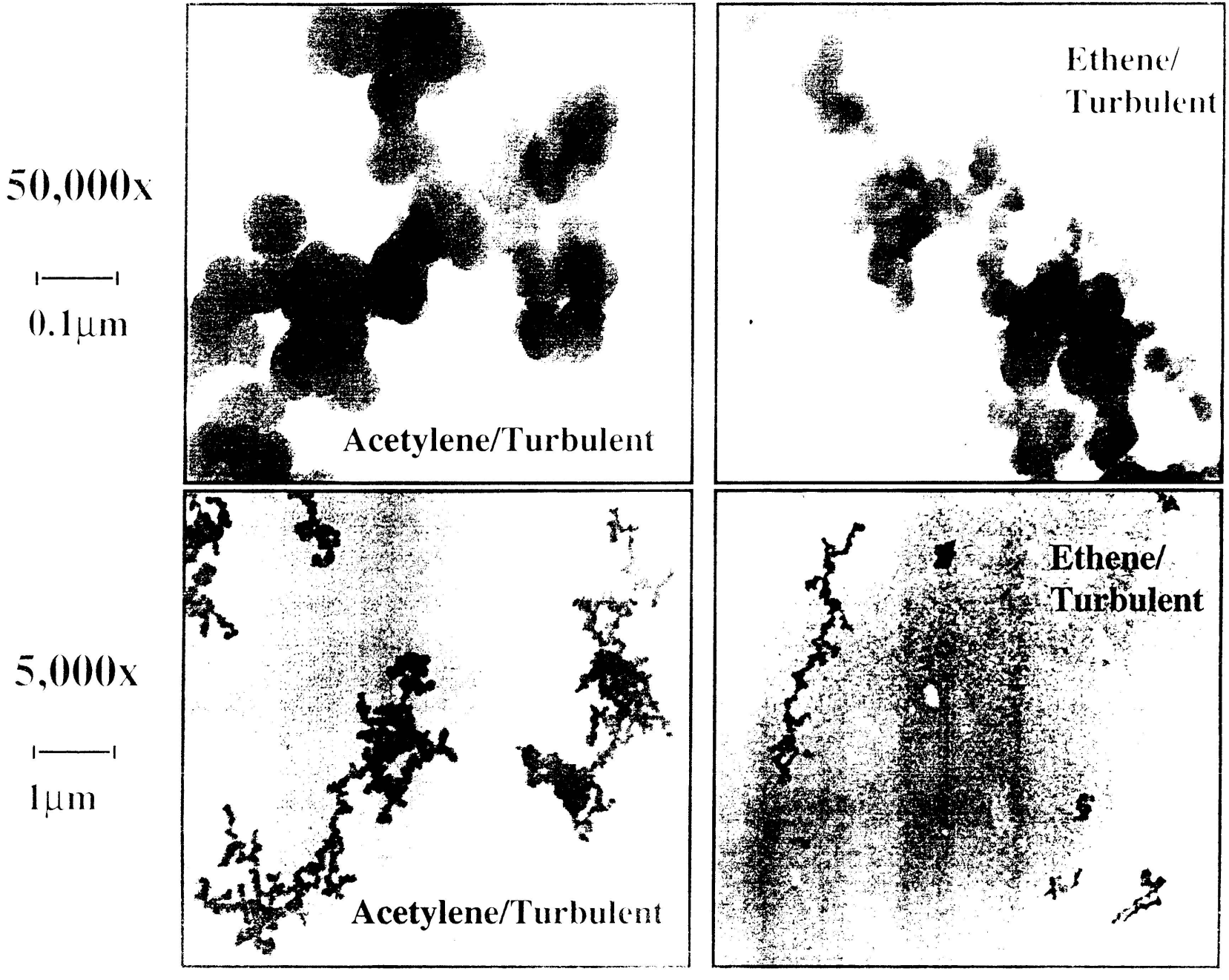
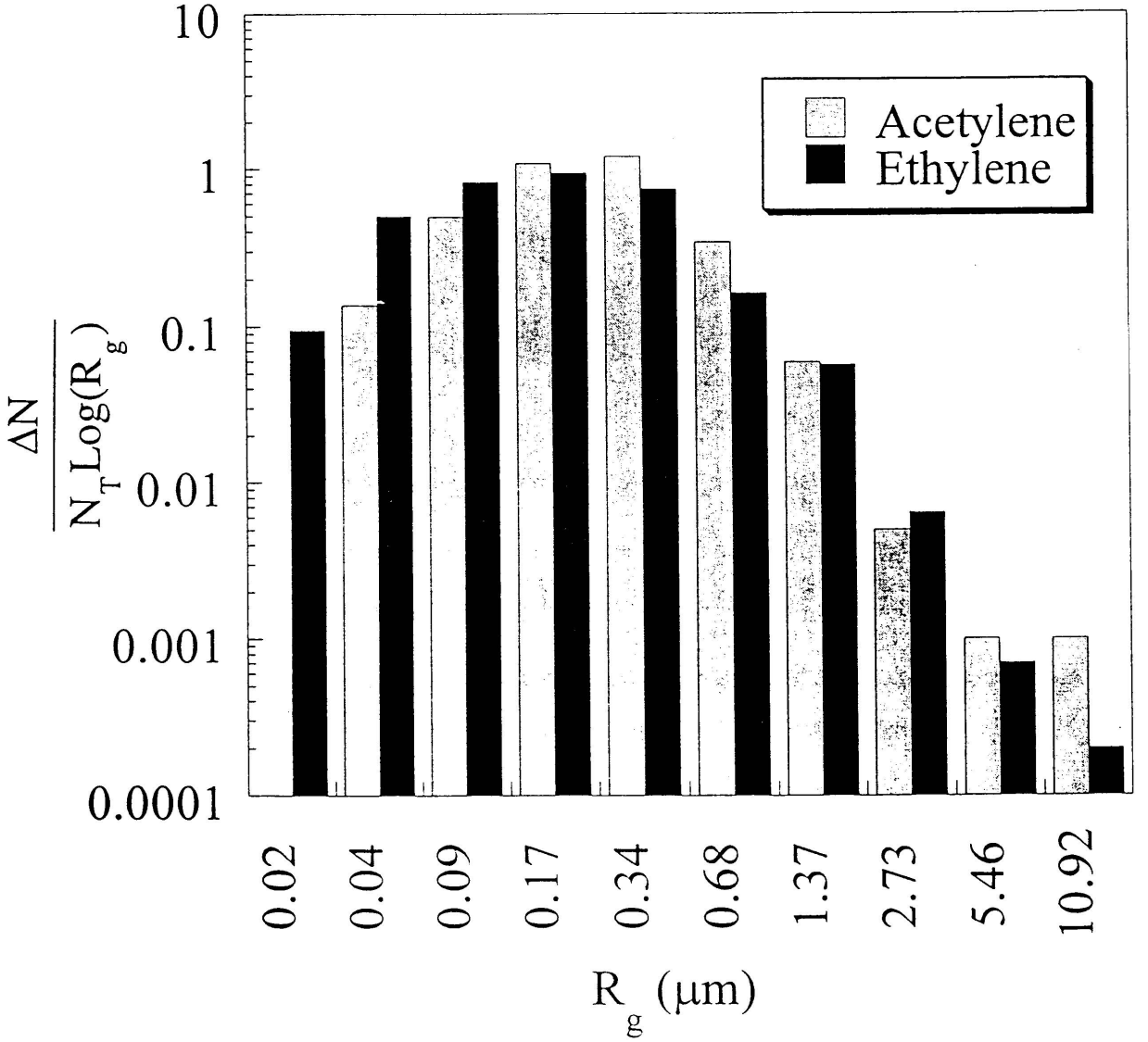
Particle Size Distribution for Soot

Soot Aerosol

- TEM analysis, labor intensive
- Cascade impactor - requires weighing eight samples for each size distribution
- There is no widely used *in situ* method for measuring the agglomerate size


50,000x
0.1μm
Acetylene/Turbulent
Ethene/
Turbulent
5,000x
1μm
Acetylene/Turbulent
Ethene/
Turbulent

Zhy Choi, Mulholland, Critzo



Evans et al, In-Situ Burning of Oil Spills: Mesoscale Experiments (1992)

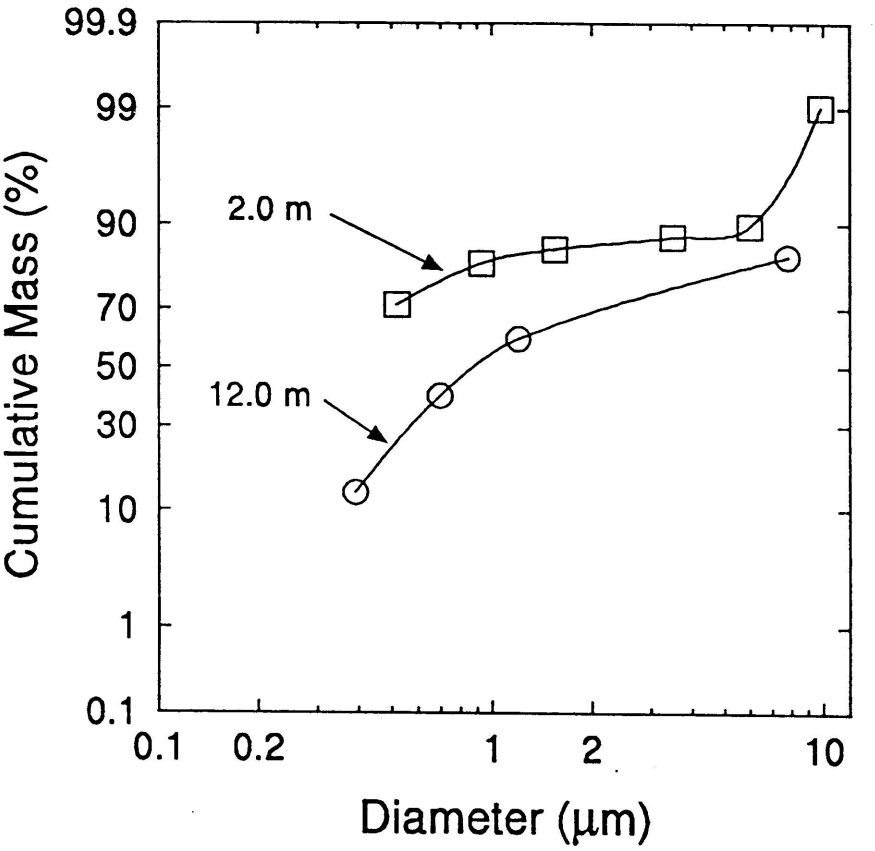
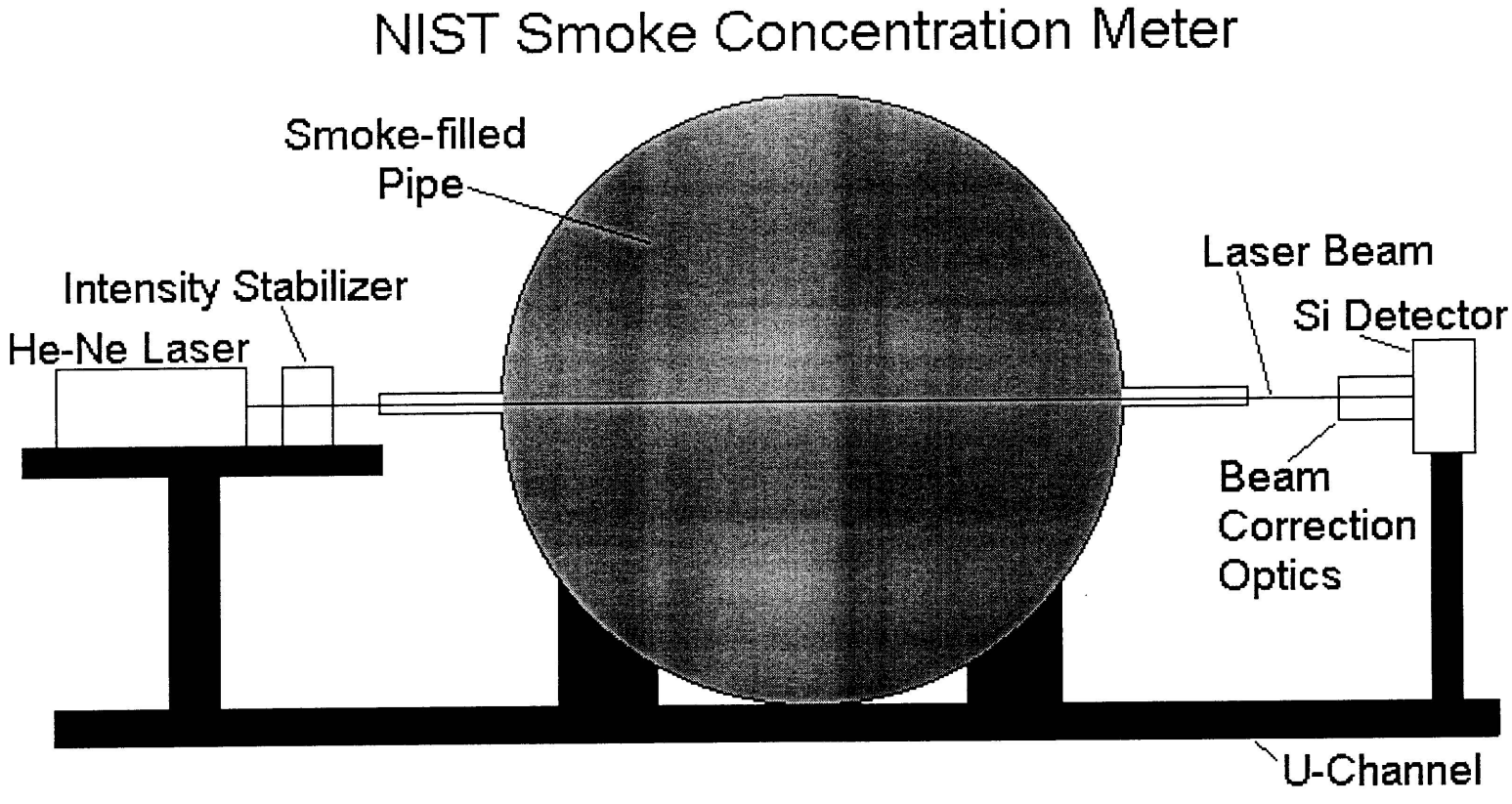


Figure 10. **Size distribution of smoke particulate from a 2.0 m diameter Murban crude oil fire and a 12.0 m diameter Louisiana crude oil fire**


NIST Smoke Concentration Meter
Smoke-filled
Pipe
Intensity Stabilizer
He-Ne Laser
Laser Beam
Si Detector
Beam
Correction
Optics
U-Channel

Major Design Features of New Smoke Concentration Meter

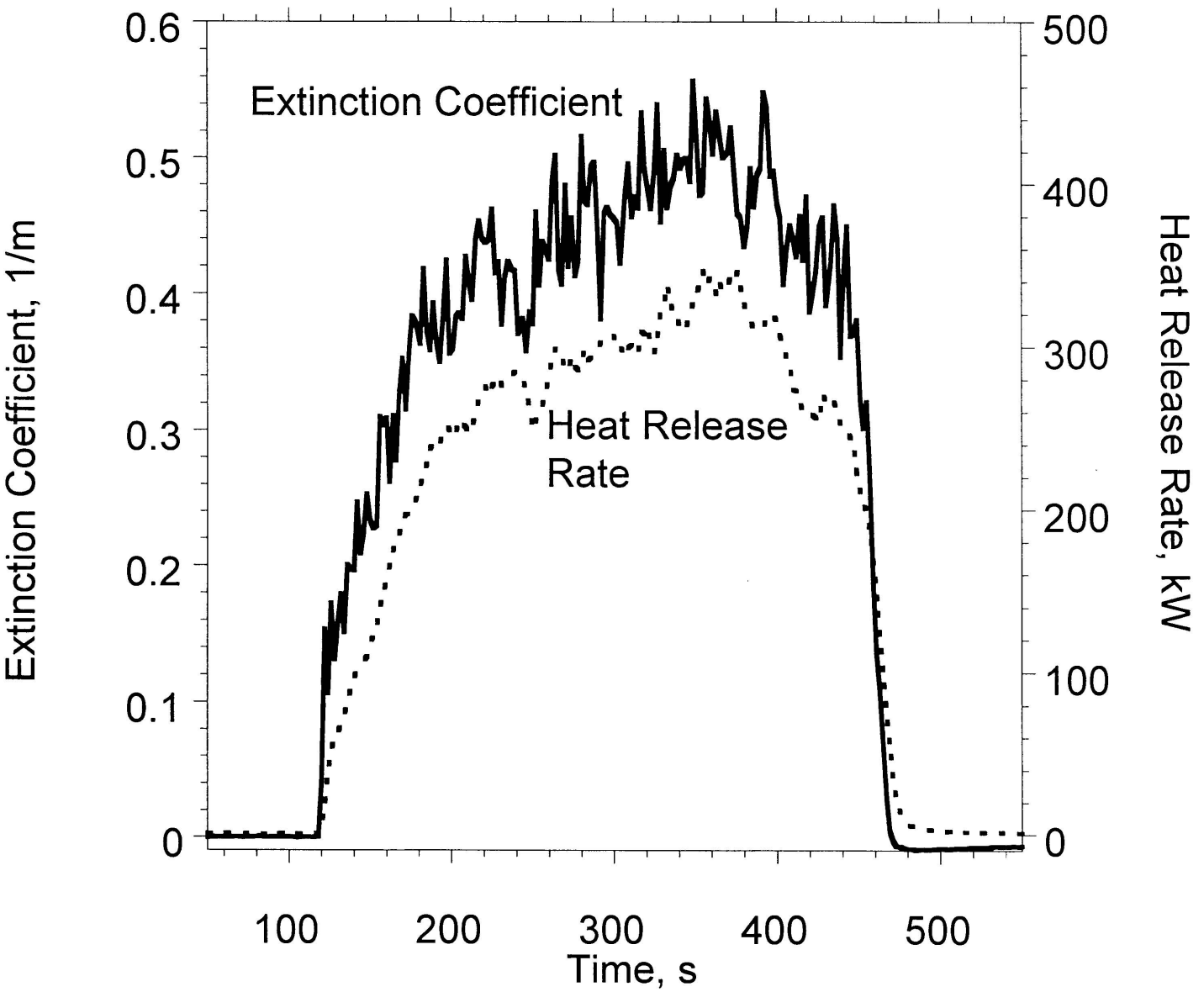
- *Stabilized light source to minimize drift*
- *Purge air to prevent smoke deposition on optics*
- *Focusing lens /diffuser to minimize effect of slight beam deflection*
- *1.2° acceptance angle of detector to minimize the effect of forward scattered light.*
- *Constructed from commercially available components to allow standardization.*

Uncertainty Analysis

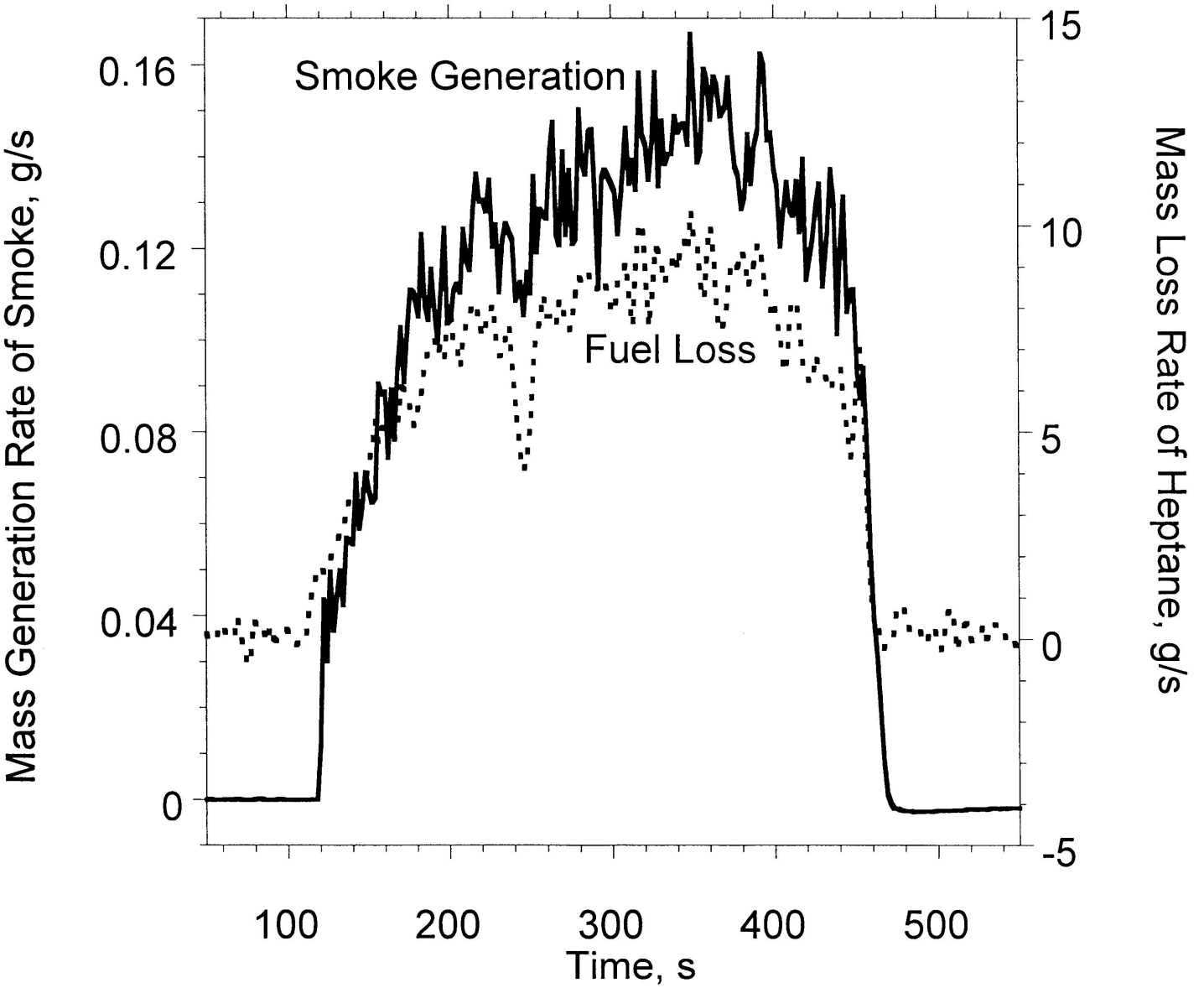
$$Yield = \frac{K\,\dot{V}\,C_1}{\sigma_s \dot{m}_f}$$

Variable	Nominal Value	Rel. Std. Uncert., %
K	0.50 m^{-1}	1.6
σ_s	8.7 m^2/g	5.4
flow coeff.	0.83	(4.8)
$\dot{V}$	2.1 m^3/s	5.9
$\dot{m}_f$	10.0 g/s	2.2
C_1 smoke profile factor	0.97	3.0
Total B uncertainty		9.0
Type A uncertainty		5.3
Combined uncertainty		10.4
Expanded uncertainty (95 % confidence interval)		20.8

Extinction Coefficient and Heat Release Rate for a 50 cm Diameter Heptane Pool Fire



Mass Generation Rate of Smoke and Mass Loss Rate of Heptane for 50 cm Diameter Pool Fire



In-flame Sampling

Thermophoretic sampling (Dobbins, Fletcher, Koylu)

- Size distribution of primaries and agglomerates
- Estimate of soot volume fraction
- Laser microprobe analysis of precursor soot

Sampling (Howard)

- Water cooled stainless steel probe
- Most of smoke aerosol collected on sampling probe (with PTFE insert)before filter
- Gravimetric and chemical analysis

In Situ Light Extinction Measurements (Markstein, Sivathanu, Shaddix)

- cooled probe
- 2 - 10 cm path length
- purge air
- fiber optics
- up to at least 1000 Hz with fair sensitivity
- Total uncertainty ?
- Applied to large pool fires (1 m or larger)

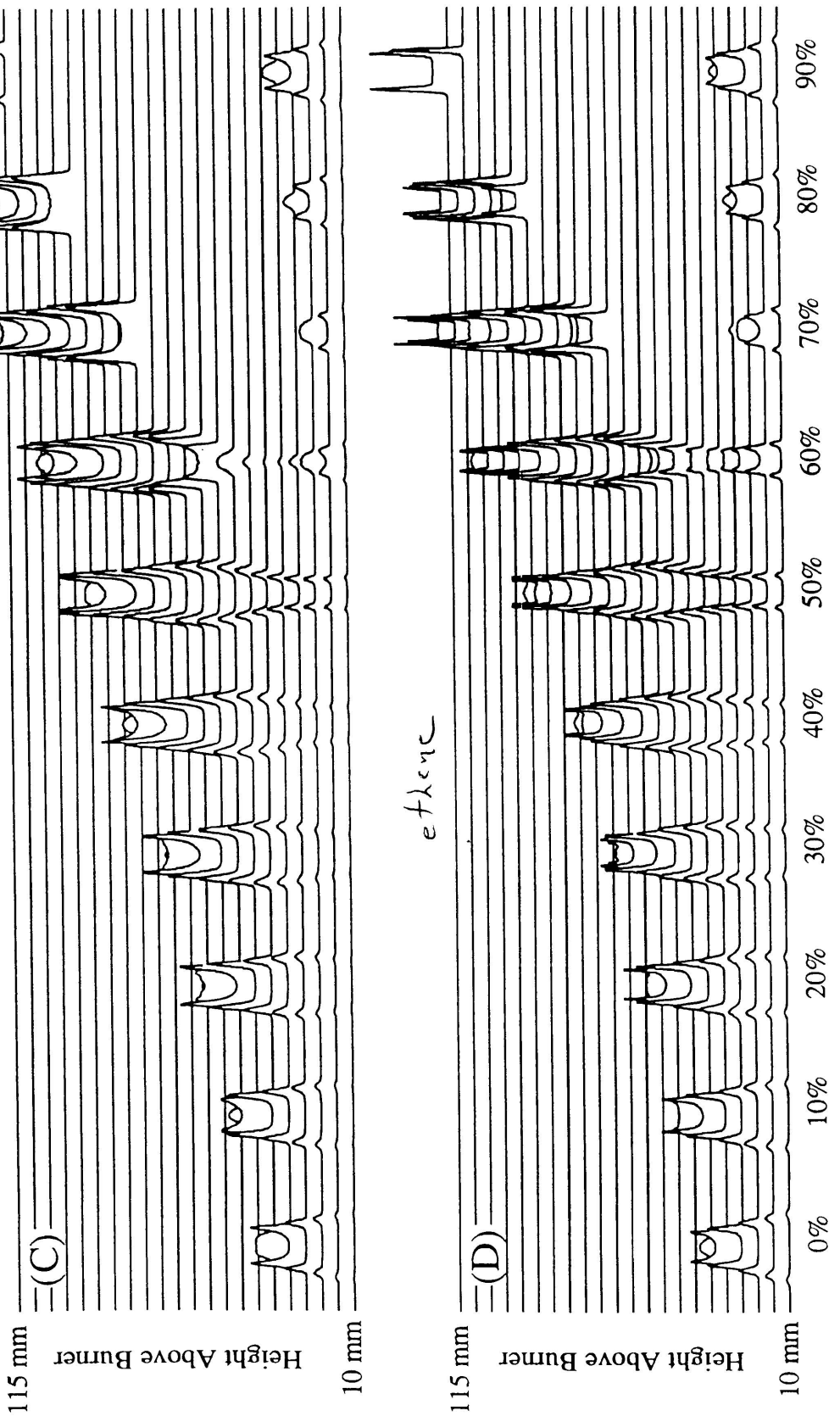
Spatially Resolved Soot Measurements (Smyth, *et al.*, van der Waal, Choi)

Light scattering - 2D distribution of scattering using CCD

Laser Induced Incandescence

- 2D volume fraction distribution with 0.2 mm resolution
- Calibrated versus light extinction and gravimetrically
- less sensitive to early/small soot

Neither method applied to large flames



Shaddix and Smyth

Future Challenges

- Round robin comparison of soot production rate using a known soot generation source
- Local (0.5 mm resolution) soot concentration field in turbulent flames for sub-grid model
- Optical diagnostic for agglomerate size (radius of gyration)

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Title and Subtitle (Cite in full)

Proceedings of the FORUM Workshop on Measurement Needs for Fire Safety

Author(s) (Last Name, First Initial, Second Initial)	Performing Organization:
Ohlemiller, T J (Primary) ; Johnsson, E L ; Gann, R G	NIST/GAITHERSBURG

Laboratory and Division

865 - Fire Science Division

Sponsoring Organization Name and Complete Address (Street, City, State, Zip)

NIST

Type of Publication Proposed

NISTIR

Proposed for Non-NIST Publication (Cite fully)

Publishing Medium:
Paper

Abstract (A 2000-character or less factual summary of most significant information. If document includes a significant bibliography or literature survey, cite it here. Spell out acronyms on first reference.)

At the twelfth meeting of the Forum for International Cooperation in Fire Research, held in Garston, England, members agreed to convene a workshop focused on improving their capabilities in scientifically-based fire measurements as a basis for further progress in the field of fire research. With this Workshop, members agreed to seek an area of collaboration where each could devote internal funds toward specific mutual goals in the area of fire measurements. The Workshop was convened to review needs and establish common interests, thereby to converge on one or more specific inter-laboratory projects. Experts from various laboratories were asked to summarize their views on the capabilities and needs of specific areas which included fire models (compartment and burning object models), product tests and in quantifying the internal parameters of fires (heat flux, temperature, flow velocities and species concentrations). In the following pages we have attempted to summarize the sense of the presentations in the various sessions of the Workshop and also to convey the range of ideas which arose in the discussions following the presentations. Ultimately, a vote was held among the participants as to the areas of primary interest for collaboration. Heat flux measurements emerged as the main candidate.

Supplementary Notes

Key Words (Maximum of 9; 28 characters and spaces each; Alphabetic order; Capitalize only proper names)

1. fire research	2. fire measurements
3. fire models	4. model validation
5. product tests	6. international cooperation
7. measurement improvement	8. scientific collaboration
9. fire science	

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