NBSIR 83-2800

Summaries of Center for Fire Research Grants and In-House Programs - 1983

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Center for Fire Research
Washington, DC 20234

December 1983

Final Report

U.S. DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS

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Sonya M. Cherry, Editor

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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

FOREWORD

The Seventh Annual Conference on Fire Research honors Professor Howard Emmons who retires from Harvard University this year. Professor Emmons has provided leadership and inspiration to many in this field as attested by the breadth and depth of the topics in the conference--modeling of fire growth, flame phenomena and spread, diffusion flames and radiation, fire plumes, extinction and suppression--and the contributions of those he has taught. Howard Emmons has demonstrated the viability of scientifically based fire protection engineering practice.

Of course, much remains to be done. The conference program and papers (to be published separately) provide a good indication of where we are in a number of critical areas of fire science. This document contains summaries of Center for Fire Research in-house and grants work. This ongoing work is intended to sustain the momentum in fire science research that has built up over the last decade and to continue the development of rigorous fire protection engineering practices.

This year has been an important one of testing for the Center for Fire Research in the budget process. The results have been most gratifying, and that challenge appears to be behind us. We hope now to focus fully on the technical issues before us and welcome the opportunity to work with all of you on addressing them.

Jack E. Snell, Director
Center for Fire Research

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August 23-25, 1983

Abstract

This report was prepared for distribution at the 7th Annual Conference on Fire Research, August 23-25, 1983. It contains extended abstracts of grants and contracts for fire research sponsored by the Center for Fire Research, National Bureau of Standards, as well as descriptions of the internal programs of the Center for Fire Research.

Key words: Combustion; decision analysis; fire models; flame spread; human behavior; ignition; polymers; smoke; soot; toxicity; wood.

AD HOC WORKING GROUP OF MATHEMATICAL FIRE MODELING
CENTER FOR FIRE RESEARCH
FY 83

Professional Personnel

Robert S. Levine, Chairman of Steering Committee
John A. Rockett, Chairman of Computer Committee
James G. Quintiere, Chairman of Models Subcommittee

Note: The Modeling Committee is chaired by Professor Howard Emmons of Harvard University, the Subprogram Committee by John de Ris of Factory Mutual, and the User's Needs Committee by Irwin Benjamin of Benjamin-Clarke.

A number of CFR personnel are members of the technical committees.

Program Objectives

The objectives of this committee are to facilitate the development and use of mathematical models of fire and to coordinate and facilitate research needed to improve the models. The steering committee includes members from other government agencies who have influence on their agencies' research and development in this field. The coordination, of course, is voluntary.

Project Areas

Each applicable area is included in another program abstract. The major portion of the CFR effort is in the Fire Modeling Program.

Associated Grants

Several grants as listed elsewhere.

EXPLORATORY FIRE RESEARCH
FIRE MEASUREMENT AND RESEARCH DIVISION
CENTER FOR FIRE RESEARCH
FY 83

Professional Personnel

Kermit C. Smyth, Research Chemist and Head
James E. Brown, Research Chemist
Toshimi Hirata, Guest Worker
Takashi Kashiwagi, Materials Research Engineer
W. Gary Mallard, Research Chemist
J. Houston Miller, Faculty Research Associate
Thomas J. Ohlemiller, General Engineer
William M. Pitts, Research Chemist
Kathleen E. Werner, Chemist

Program Objectives

(1) Improve the understanding of the chemical and physical processes which underlie macroscopic fire phenomena. The research embraces broad areas covering both solid and gas phase processes, with particular attention to polymer degradation, the effects of radiation, and the hot gas chemistry and physics leading to incomplete combustion.

(2) Devise new techniques and methods for studying these phenomena.

(3) Furnish fundamental scientific information to support the other activities within the Center for Fire Research.

Scope

This work is scientific not empirical. It embraces broad areas underpinning CFR programs with focussed study in the areas of materials degradation, hot gas physics and chemistry, and radiation. Efforts are directed towards improved understanding of the chemical and physical processes which underlie macroscopic fire phenomena and include development of new techniques and methods for studying these processes.

Projects

1. Polymer Gasification and Ignition

Transient gasification characteristics of polymeric materials under nonflaming conditions are being investigated at fire level radiant heat fluxes. Results show that the gas phase oxygen level has a marked effect on the rate of gasification and also decreases the averaged molecular weights and affects their distribution in the polymer undergoing depolymerization. Molecular weight distributions of PMMA residues have been measured by gel permeation chromatography. Two types of residues were studied; one from a thermally thick sample irradiated under non-flaming conditions with thermal radiation from an electrically heated graphite plate. The other was a small, thermally thin sample ($\sim$ 10 mg) heated isothermally. The former samples were exposed to different radiant fluxes, to different atmospheres containing various concentrations of oxgyen, and for different exposure times. Eight to ten thin layers ($\sim$ 125 μm thick) were sliced from the surface, and their molecular weight distributions were measured. Results indicate that the effects of gas phase oxygen on the molecular weight distribution appear as deep as 0.6 mm. The broad molecular weight distribution (large polydispersivity of 5-10) indicates that a mixture of oxidized and non-oxidized PMMA exists in the molten layer near the surface.

The objective of the isothermal experiment with small PMMA samples is to obtain values of degradation kinetic constants and to understand the degradation mechanisms. The observed molecular weight distributions indicate that the values of the polydispersivity are close to 2 in both nitrogen and air. This means that the molecular weight distribution of degradating PMMA follows the most probable distribution. In air the number averaged molecular weight of PMMA decreased sharply, falling below 10% of the original averaged molecular weight values at about 10% weight loss. Thus, the effect of gas phase oxygen on the reduction of the molecular weight is significant even at small weight loss. These preliminary data indicate that the initiation mechanism of thermal oxidation of PMMA appears to be random scission.

Kashiwagi, T., "Effects of Sample Orientation on Radiative Ignition", Combustion and Flame <u>44</u>, 223 (1982).

Kashiwagi, T. and Kashiwagi, T., "A Study of the Radiative Ignition Mechanism of a Solid Fuel Using Holographic Interferometry", presented at the AIAA 20th Aerospace Sciences Meeting, Jan., 1982.

Kashiwagi, T. and Ohlemiller, T.J., "A Study of Oxygen Effects on Nonflaming Transient Gasification of PMMA and PE During Thermal Irradiation", 19th International Symposium on Combustion (to be published).

2. Smoldering Combustion of Cellulosics

The propensity for smoldering exhibited by cellulosic materials continues to be a subject of major concern. The smolder characteristics of cellulosic insulation (made from wood pulp) represent the present focus for this work. Smolder propagation through a thick horizontal layer of such insulation has been investigated. Temperature, oxygen, and remaining solid fuel distributions have been measured as a means of determining the factors controlling propagation. The overall structure appears to be determined by the diffusion of oxygen. Boric acid slows the propagation and alters the smolder wave structure, but does not cause extinction in these thick layers.

There are two overall stages of oxidation (oxidative pyrolysis and char oxidation) that couple together to support smolder propagation in a thick layer.

The smolder initiation process, however, depends solely on the oxidative pyrolysis. The qualitative impact of additives on this reaction stage can be measured by means of differential scanning calorimetry, and the results can be used to make predictions about how the additives will affect the smolder ignition temperature. The oxidation behavior of the wood fibers and their components (cellulose, lignin, etc.) is being compared to see which of these contributes the most to the low temperature exothermicity responsible for smolder initiation.

The transition from smoldering to flaming combustion as a result of increased air flow is being investigated experimentally. The congfiguration of most practical interest is a horizontal layer of fuel over which a varying air flow passes. The critical air flow for transition is being investigated parametrically. Future plans include mechanistic studies of the transition process.

Mulholland, G. and Ohlemiller, T.J., "Aerosol Characterization of a Smoldering Source", Aerosol Science and Technology 1, 59 (1982).

Ohlemiller, T.J. and Lucca, D.A., "An Experimental Comparison of Foward and Reverse Smolder Propagation in Permeable Fuel Beds", Combustion and Flame (to be published).

Ohlemiller, T.J., "Modelling of Smoldering Combustion Propagation", Progress in Energy and Combustion Science (to be submitted).

3. Products of Wood Combustion

The objective of this research is to understand the degradation processes of wood under fire conditions and the formation and evolution of the combustion products. Major support for this work comes from the Department of Energy under its residential alternate fuels program. Our prior studies began to elucidate the chemical processes occurring in the fuel itself under controlled pyrolysis. High resolution nuclear magnetic resonance spectra clearly show the evolution from a cellulosic/lignin structure to a highly aromatic structure. Gaseous samples from various locations in the stack of a wood stove show no chemical change once they leave the firebox. Current work is focused on the conversion of wood to fuel gases at various heat fluxes and with varying ambient oxygen levels. The products from transiently gasifying, thermally thick samples of wood and wood components are captured and analyzed. The global pyrolytic degradation and oxidation kinetics of representative gasification products will be examined.

4. Soot Formation Chemistry and Physics

Flame radiation from incandescent soot dominates flame spread and heat transfer in large fires. Escaping particulates hinder vision and impair breathing, as well as being a sensitive signature for fire detection. Despite this importance, there is little understanding at the molecular level of the soot formation process; i.e., how small molecules grow rapidly to become soot particles. We are now in the fourth year of a long-term study of the fundamental chemistry and physics of soot formation, carried out jointly with the NBS Thermal Processes Division in the Center for Chemical Engineering.

Our studies have included a wide range of optical and mass spectrometric experimental work, as well as theoretical models of the condensation of large molecules. On the experimental side, new data for proposed models of soot formation have been obtained by investigations of (1) the ion-molecule chemistry of $C_3H_3^+$, thought to be a key precursor and (2) fluorescence from polycyclic aromatic molecules, which are likely to be important building blocks in soot formation. In addition, by using the optogalvanic effect in flames the laser-induced ionization of very small soot particles has been observed. More recently, multiphoton ionization experiments on several hydrocarbons have established this technique as extremely sensitive for flame diagnostics. Multiphoton ionization may prove to be very useful in detecting the formation and decay of specific intermediate size organic molecules in a non-intrusive manner. We will also be characterizing the radical pool in various flames to determine the relevance of premixed flame data to diffusion flames. On the theoretical side, our work on condensation processes seeks to establish the molecular size below which chemical reaction kinetics dominate and above which the physical condensation process is controlling. Methods of calculating the dispersive and overlap parts of the intermolecular potential for polycyclic aromatic hydrocarbons of D_{6h} symmetry have been developed. The resulting total potentials are used to predict stable dimer configurations and the corresponding binding energies.

Smyth, K.C., Lias, S.G, and Ausloos, P., "The Ion-Molecule Chemistry of $C_3H_3^+$ and the Implications for Soot Formation", Combustion Science and Technology 28, 147 (1982).

Miller, J.H., Mallard, W.G., and Smyth, K.C., "The Observation of Laser-Induced Visible Fluorescence in Sooting Diffusion Flames", Combustion and Flame 44, 61 (1982).

Mallard, W.G., Miller, J.H., and Smyth, K.C., "Resonantly Enhanced Two-Photon Photoionization of NO in an Atmospheric Flame", Journal of Chemical Physics 76, 3483 (1982).

Smyth, K.C. and Mallard, W.G., "Two-Photon Ionization Processes of PO in a C_2H_2/Air Flame", Journal of Chemical Physics 77, 1779 (1982).

Miller, J.H., Mallard, W.G., and Smyth, K.C., "Intermolecular Potential Calculations for Polycyclic Aromatic Hydrocarbons", Journal of Chemical Physics (submitted).

5. Turbulent Chemically-Reacting Flow

In a large fire plume, the combustion region is turbulent and is characterized by highly variable (both spatial and temporal) distributions of temperature and species concentration. In such cases the flame properties are dominated by the substantial temperature and species concentration fluctuations. Due to the scarcity of measurements on such systems and the complexity of the phenomena, the understanding of turbulent fire plumes is poor. We have initiated an investigation of turbulent chemically-reacting flow for the purpose of enchancing the understanding of the nonlinear coupling which occurs between chemical reaction and turbulent flow mixing. Currently, as a first step in a planned series of experiments, the effect of density differences on the mixing behavior of a turbulent jet with its surroundings is being investigated. A novel technique using combined Rayleigh light scattering and hot-wire anemometry has been developed for performing simultaneous time-resolved concentration and velocity measurements in the flow field. Detailed measurements are being made for axisymmetric turbulent jets of C_3H_8, CH_4, CO_2, and He mixing with coflows of air or CO_2. Furture work will incorporate chemical reaction into the experimental system. The experimental work is to be coupled with a theoretical modeling effort.

Pitts, W.M. and Kashiwagi, T., "The Application of Laser-Induced Rayleigh Light Scattering to the Study of Turbulent Mixing", NBS-IR 83-2641 and Journal of Fluid Mehcanics (submitted).

Pitts, W.M., McCaffrey, B.J., and Kashiwagi, T., "A New Diagnostic Technique for Simultaneous, Time-Resolved Measurements of Concentration and Velocity in Simple Turbulent Flow Systems", Fourth Symposium on Turbulent Shear Flows, Karisruhe, Germany, Sept. 1983.

Associated Grants and Contracts

1. Sharon K. Brauman - SRI International, "Polymer Degradation During Combustion."

2. Michael J. Drews and Christine W. Jarvis - Clemson University, "Ternary Reactions Among Polymer Substrate-Organohalogen-Antimony Oxides in the Condensed Phase Under Pyrolytic, Oxidative and Flaming Conditions."

3. Irvin Glassman, Ian M. Kennedy, and Frederick L. Dryer, Princeton Univeristy - "Flow Field Effects on the Sooting Structure of Diffusion Flames."

4. Patrick Pagni - Lawrence Berkeley Laboratory, "Fire Modeling."

5. Fred Shafizadeh - University of Montana, "Chemistry of Smoldering Combustion and Its Control."

6. Chang-Lin Tien - Lawrence Berkeley Laboratory, "Flame Radiation."

Facility Fire Safety Performance
Center for Fire Research

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Professional Personnel

Harold E. Nelson, Head
Bernard M. Levin, Research Psychologist
Leonard Y. Cooper, Research Fire Protection Engineer
A. Jeffrey Shibe, Research Fire Protection Engineer
W. Douglas Walton, Research Fire Protection Engineer
David Stroup, Fire Protection Engineer
Philip Chen, Research Engineer
Eric Rosenbaum, Coop Student-Fire Protection Engineer
Steven Thorne, Coop Student-Fire Protection Engineer

Program Objectives

The objectives of the Facility Fire Safety thrust encompass the development of a system of relevant engineering methods for use in predicting the performance of facilities and people in response to the potential fire threats.

This thrust focuses on development of a wide range of fire protection systems, models, and other tools targeted for the practicing fire protection engineering, design, or regulatory professional. It utilizes the state of the art in scientific knowledge, physical property data, empirical results from tests, fire experience, and sound engineering practice judgment. It involves development of a framework of macro models and other systems for setting performance requirements and/or evaluating active and passive systems for facility fire protection and use. It draws heavily on closely related activities in the area of fire growth processes, suppression and extinguishment, smoke and toxic gases, building response, and human response.

Project Areas

1. Engineering Methodologies for Predicting Facility Fire Safety Performance

The purpose of this project area is the development of a consistant system of scientifically based engineering methods for predicting the performance of facilities and people in response to a potential fire.

Significant progress items include:

a. The development and initial exercise of a total deterministic system linking engineering models and calculations into a facility performance system. (See attached figure)

b. The completion and publication of a user friendly computer program for calculating available safe egress time. The current program handles fire growth in a single space and sets a model approach for handling multi-space problems. The processes is on-line and has demonstrated transferability between computers and useability by practicing engineers.

c. The development and completion of initial report of an escape and rescue model having capabilities of appraising the time involved in undertaking emergency actions for evacuation, rescue, or other purposes. (This work has been undertaken jointly by the American Institute of Architect Research Corporation and the CFR staff)

d. The publication of the first laboratory acquired data on the time increments involved in important acts necessary for successful evacuation.

e. Improved concepts for use in the available egress time modeling on the convected heat transfer to ceilings above enclosure fires and the significance of wall effects during growth stages of enclosure fires.

f. Development of an optimization mode to the escape and rescue model.

g. Improvement of the subsystems within the engineering models with emphasis on the response of fire protection devices and involvement of combustible ceilings or other linings.

h. Increased activity in transferring of engineering methodology to the applied fire protection engineering field.

With the help of important financial assistance from the Dept. of Health and Human Services, (HHS), an enhancement of this project has been initiated. The concepts of the engineering methodologies are being used to address a series of "Life Safety Code" types of problems of concern to HHS. Work will involve the definition and solution of the code problems in engineering terms, the execution of large scale tests to validate the solutions, and derivation of validated or otherwise accredited field applicable engineering solutions to the basic problems. The problem areas concern fire development and transport of hazardous conditions throughout a smoke zone of origin, the impact of such on the surrounding barriers (smoke doors, dampers, etc.) of the smoke zone, and the response of heat and smoke detectors and automatic sprinklers within the space.

The directions in engineering methodology project include:

(a) Completion of a first facility fire safety performance model using the HHS sponsored data as a base and presenting the best transferable current state of the art.

(b) The development and proofing of multi-room methods of analyses of hazard in building spaces.

(c) Development of essential human factors subsystems for the engineering methods approach.

2. Rational Fire for the National Park Service

Emphasis on this past year has been on the completion of a fire safety evaluation system covering overnight accommodations in the national park system. The Park Service now has the evaluation system and is in the process of applying it in the field. In the process, extensive training of park service personnel and the development of a guidance manual, for use by architects and maintenence personnel not intimately familiar with fire protection terminology, has been developed. Advances have also been made on the development of a priority calculation method to assist the National Park Service in gaining the greatest return for expenditures in my safety improvements.

More recently the Park Service has requested extension of the project to address problems in museums, historical buildings, and similar types of public facilities that are not involved in overnight accommodations. An effort is now underway to develop an evaluation system that will be based on engineering methodologies rather than a professional judgment. This phase of the project is just underway and examination of typical buildings is being made.

3. Coal Mine Fire Safety Evaluation

This project is concentrating on the development of an alternative means for evaluating fire safety in coal mines. The project is in its second phase involving the development of a suitable fire safety evaluation concept that can be reviewed and tested through establish consensus methods. It was intended to be beyond phase 2 and into the proofing phase by this date. The problem has, however, been more difficult than anticipated and additional means of seeking concensus among the advisory group and bringing the critical question into appropriate focus for such appraisal are being pursued at this time. The field test and consensus proofing phases cannot be started until the initial consensus has been achieved.

4. Rational System for Health Care Facilities

A significant portion of the current activities in this area relative to "Life Safety Code" questions is covered under the first project of this report on engineering methodologies. This subject covers the work that has been underway over the last several years on the development of evaluation systems for board and care facilities.

Board and Care Homes house persons or groups that have less capability of avoiding fire threat than the general population but are not in need of the level of care provided by institutional occupancies such as hospitals and nursing homes. While these homes have many names such as group homes for the developmentally disabled, residential care facilities, and community residential facilities, they all are designed to provide needed assistance in a less restrictive, more stimulating, more pleasant and, hopefully, less expensive environment than that which would be provided by an institution. The Homes provide a sheltered residence for people with a wide range of disabilities ranging from mental retardation, or physical injuries to frailty due to age. The services provided include lodging, food, and the social support of group or family style living. Additional services sometimes include rehabilitative training, assistance in handling personal finances, purchasing of clothing, transportation to medical services, etc. The residential structure includes buildings typical of single family residences, large and small hotels, and apartment buildings.

This project has been progressively underway for several years and is nearing completion. The major task of the project has been the development of a Fire Safety Evaluation System for Board and Care Homes (FSES/B&C). The FSES/B&C provides a flexible instrument of for evaluating the fire safety of the homes. It is based on a proposed new Chapter of Life Safety Code covering thi occupancy as a new class of occupancy. Both the proposed chapter and FSES/B&C are under active review and consideration by the National Fire Protection Association for inclusion in the next edition of the Life Safety Code.

The evaluation system provides a grading system to determine the emergency evacuation difficulty potential in groups of persons that include residents with varying degrees of difficulty supported by staff that can do some degree compensate for those shortcomings during an emergency. The proposed chapter to the Life Safety Code and accompancying evaluation system also includes fire safety evaluation systems for determining the level of facility safeguards provided in small residential type structures, larger hotel type structures, and apartment buildings used to house one or more board and care facilities. The level of facility safeguard is coordinated with the degree of evacuation difficulty involved.

The FSES/B&C was published with a description of its development and testing in NBSIR 83-2659 "A Fire Safety Evaluation System for Board and Care Homes." Current effort involves working with the appropriate committees of NFPA in their review and potential modification of the FSES/B&C, and working with various Federal and state agencies in their review of the System for potential adoption.

A second important task has been the development of a manual to assist the owners and operator s of Board and Care Homes to upgrade the fire safety of their homes through better planning and improved training of the residents.

The manual prepared at the University of Maryland has been published as NBS-GCR-82-408, "A Matter of Time--A Comprehensive Guide to Fire Emergency Planning for Board and Care Homes" by N.E. Groner.

Associated Grants

1. University of Maryland, John Bryan, The Determination of Behavior Response Patterns in Fire Situations - Project People II. (Completed 1983)

2. North Carolina State Universtiy, Richard Pearson, Occupant Egress from Simulated Fires. (Completed 1983)

3. University of Maryland, Norman Groner, The Development and Field Testing of a Fire Safety Manual for Board and Care Homes Operators. (Completed 1982)

4. University of Washington, John Keating and Elizabeth Loftus, Post Fire Interviews: Development and Field Validation.

5. AIA Research Corporation, Earle Kennett, Fire Safety Evaluation System for Board and Care Homes (Escape and Rescue Model).

6. University of Washington, Norman Groner and John Keating, A Fire Emergency Planning and Training Manual for National Park Residential Buildings.

7. University of Florida, R.L. Francis and T.M. Kisco, Network Models of Building Evacuation: Development of Software System.

Publications (and other products)

1. Calculating Available Safe Egress Time (ASET) - A Computer Program and User's Guide, Cooper, L.Y. and Stroup, D.W., presented at the 1982 CFR Annual Research Conference; NBSIR 82-2578.

2. A Concept for Estimating Available Safe Egress Time in Fires, Cooper, L.Y., Fire Safety Journal, 5(2), pp. 135-144, 1983.

3. A Mathematical Model for Estimating Available Safe Egress Time in Fires, Cooper, L.Y., Fire Materials, 6, (3/4), p. 135-144, 1982.

4. The Development of Hazardous Conditions in Enclosures with Growing Fires, Fires, Cooper, L.Y., presented at 1982 Fall Meeting of the Eastern Sect. of Combustion Institute with abbreviated version of paper appearing in Proceedings of the Meeting; NBSIR 82-2622; to appear in Combustion

Science and Technology.

5. Convective Heat Transfer to Ceilings Above Enclosure Fires, Cooper, L.Y., presented at the 19th International Symposium on Combustion, August, 1982; and appears in Proceedings of the Symposium.

6. On the Significance of A Wall Effect in Enclosures with Growing Fires, Cooper, L.Y., presented at 12/18/82 Ad Hoc Math Modeling Committee Meeting, and at 1982 Fall Conference of the Eastern Section of the Combustion Inst., to be presented at 1983 ASME/AICHE National Heat Transfer Conference and at 1983 Annual CFR Research Conference; to appear as NBSIR; to be submitted for publication.

7. Life Safety Through Designed Safe Egress - A Framework for Research, Development and Implementation, Cooper, L.Y., and Nelson, H.E., CFR Memorandum for File, Jan., 1982; presented at the UJNR Fire Research Panel Meeting, May, 1982; and appearing in Proceedings of the Meeting.

8. Heat Transfer From a Buoyant Plume to an Unconfined Ceiling, Cooper, L.Y., Journal of Heat Transfer, Vol. 104, No. 3, 1982.

9. An Experimental Study of Upper Hot Layer Stratification in Full-Scale, Multiroom, Fire Scenarios, Cooper, L.Y. Harkelroad, M., Quintiere, J., Rinkinen, W., Journal of Heat Transfer, Vol, 104, No. 4, 1982.

10. A Mathematical Simulation of Enclosure Fire Phenomena and Its Application to Life Safety, Cooper, L.Y., presented at a Rutger's University Mechanical and Aerospace Engineering Colloquium, May, 1982.

11. The Concept of Life Safety Through Designed Safe Egress, Cooper, L.Y., presented at the 1982 NFPA Conference (Architects, Engineers and Building Code Official Section).

12. A Buoyant Source in the Lower of Two Homogeneous, Stably Stratified Layers - A Problem of Fire in an Enclosure, Cooper, L.Y., to be presented at the Symp. of Modeling of Enclosure Flow Systems during 1983 Annual ASME Conference and to appear in Symp. Proceedings, to appear as NBSIR.

13. The Need and Availability of Test Methods for Measuring the Smoke Leakage Characteristics of Door Assemblies, Cooper, L.Y., presented as a report on 12/6/82 ASTM E5.12 Committee on Protection of Openings; to appear as NBSIR; (abstract) subcommittee for presentation of 1984 ASTM Symp. on Application of Fire Science to Fire Engineering; manuscript under NBS review.

14. Smoke Movement in Rooms of Fire Origin and Adjacent Spaces, Cooper, L.Y., to be presented at 1983 SFPE Symp. on Smoke - Its Chemistry, Physics and Control Through Engineering; manuscript under NBS review, to be submitted for publication.

15. Occupancy Types-- Relative Hazards, Cooper, L.Y., to be presented at the Manhatten College Fire Engineering Institute's 1983 (First) Annual Fire Engineering Conference.

16. A Fire Safety Evaluation System for Board and Care Homes, Nelson, H.E.; Levin, B.M.; Shibe, A.J.; Groner, N.E.; Paulsen, R.L.; Alvord,D.M.; and Thorne, S.D.; NBSIR 83-2659.

17. A Matter of Time--A Comprehensive Guide to Fire Emergency Planning for Board and Care Homes, Groner, N.E.; NBS-GCR-82-408.

18. Egress Behavior Response Time of Handicapped and Elderly Subjects to Simulate Residential Fires Situations, Pearson and Joost, North Carolina State University, NBS-GCR-83-429.

19. Implication for Codes and Behavior Models from the Analysis of Behavior Response Patterns in Fire Situations as Selected from the Project People and Project People's Study to Programs, Bryan, John; University of Maryland, NBS-GCR-83-425.

20. A System for Fire Safety Evaluation for Multifamily Housing, Nelson, H.E. and Shibe, A.J.; NBSIR 82-2562.

21. User Guide for the Application of Table 1-Safety Parameter Values for the Fire Safety Evaluation System for National Park Service Facilities, Bush, K.; Bradley, H.; Hicks, H., NBS-GCR-83-427.

FIRE GROWTH PROCESSES
CENTER FOR FIRE RESEARCH
FY-83

Professional Personnel

James Quintiere, Head
Howard Baum, Research Physicist
Dan Corley, Physicist
Margaret Harkleroad, Physicist
Ken Steckler, Physicist
Hisahiro Takeda, Guest Worker
Yuji Hasemi, Guest Worker
Yogesh Jaluria, Summer Faculty (82)
Arvind Atreya, Summer Faculty (83)
Anil Kulkarni, Summer Faculty (83)

Program Objectives

Through research we aim to develop predictive methods to describe the comprehensive dynamics and elemental processes of fire growth within and about compartment structures.

Scope

The work addresses fire growth within a single compartment, spread to the adjoining space, and spread through a multi-compartment structure. It examines the overall dynamics of the fire scenario and its elemental processes such as ignition, flame spread, pyrolysis rate, extinction, and the fire related transport processes. It utilizes mathematical techniques, experimental studies and correlations, and similitude methods to develop accurate predictions for realistic configurations and materials. As appropriate, it formulates and demonstrates its predictive methods for specific applications.

Project

1. Fire Generated Enclosure Phenomena

This is a joint project with the Center for Applied Mathematics. Primarily it has sought to develop detailed predictions of phenomena generated by fire in an enclosure. Specifically it has addressed the flow field and smoke coagulation. This year it has achieved a notable accomplishment; namely, transient three-dimensional results for fire generated flows with particle tracking in a closed room (Figure 1). Although computer resources still limit the easy execution and extension of such computations, their potential applications, particularly illustrated through dynamic computer graphic display, have been demonstrated. Related activities included the development of a smoke detector response simulation, and improved numerical methods for fire applications.

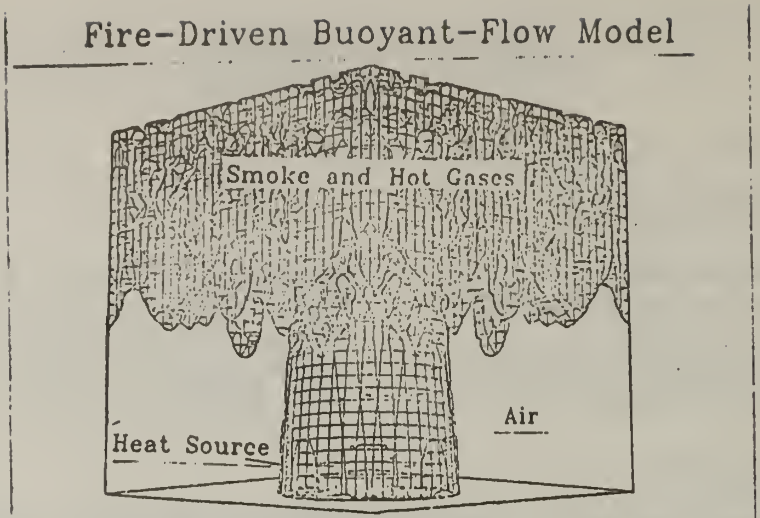

Figure 1. 3-D isotherms

Reports

1. Baum, H.R. and Rehm, R.G., "Numerical Computation of Large Scale Fire Induced Flows", in Lecture Notes in Physics, Vol. 170, Springer Vertig, Berlin, Heidelberg, N. Y., p. 124 (1982).

2. Baum, H.R., Rehm, R.G., and Mulholland, G.W., "Computation of Fire Induced Flow and Smoke Coagulation", Nineteenth Symp. (International) on Combustion, The Combustion Institute, Pittsburgh, p. 921 (1982).

3. Baum, H.R., Rehm, R.G., Barnett, P.D., and Corley, D.M., "Finite Difference Calculations of Buoyant Convection in an Enclosure, I. The Basic Algorithm", SIAM J. Sci. Stat. Comput., 4, p. 117 (1983).

4. Baum, H.R., Rehm, R.G., and Mulholland, G.W., "Prediction of Heat and Smoke Movement in Enclosure Fires", Proceedings, Eighth International Conference on Problems of Automatic Detectors, H. Luck, Ed., Univ. of Duisburg, p. 259, Oct 1982.

5. Rehm, R.G., Baum, H.R., Barnett, P.D., Sweet, R.A., O'Leary, D.P., and Corley, D.M., "Three Dimensional Computations of Fire Induced Flow, - A Preliminary Report" 1982 Technical Meeting, The Eastern Section of The Combustion Institute, Dec. 14-16, Atlantic City, N.J.

6. Beier, R.A., deRis, J., and Baum, H.R., "Accuracy of Finite Difference Methods in Recirculating Flows", Factory Mutual Res. Corp. Report FMRC J.I. OEOJ4.BU, Sept. 1982.

7. Baum, H.R. and Rockett, J., "An Investigation of the Forced Ventilation in Containership Holds", NBSIR, May 1983.

2. Flame Spread on Materials

Attention has been focused on the development of methods to predict downward or lateral spread rate, and upward spread rate on vertical materials. The opposed flow case has been studied for many materials, and a straight-forward procedure yields results for spread and ignition. From these data phenomenological constants are deduced which enable predictions of material spread rate and ignition times in terms of irradiance. Over thirty materials have been characterized. A typical result is shown in Figure 2.

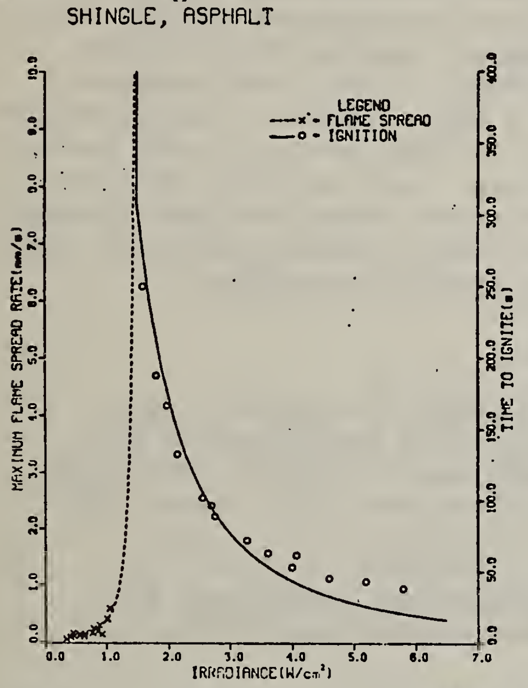

Figure 2. Ignition and Spread Rate

Upward spread is being investigated by measuring forward flame heat flux and flame length beyond the pyrolysis zone. It is felt that this heat transfer process is significant in upward spread. To determine these data an apparatus has been constructed which allows a 30 x 30 cm sample to burn under externally radiated conditions. The heat transfer from its extended flame is measured to a water heated plate by radiometers and total heat flux sensors.

Reports

1. Quintiere, J., Harkleroad, M., and Walton, D., "Measurements of Material Flame Spread Properties", Comb. Sci. Technol., 32, 67 (1983).

2. Harkleroad, M., Quintiere, J., and Walton, D., "Radiative Ignition and Opposed Flow Flame Spread Measurements on Materials", FAA Report (in press).

3. Fernandez-Pello, A.C., and Quintiere, J., "A Simplified Model of Radiating - Turbulent - Upward Flame Spread Over the Surface of a Charring Combustible", 1982 Meeting, Eastern Section of Combustion Institute, Atlantic City, Dec. 1982.

4. Baum, H.R. and Corley, D.M., "The Emmons Problem with External Radiation, An Analytical Approach", Ibid.

3. Dynamics of Compartment Wall Fires

This project embraces three approaches to understanding the fire growth on lining materials in compartments. In this problem the material and its self-generated environment in the room interact. In one approach a computer model attempts to simulate the fire growth on a wall of a room. The flame spread and pyrolysis rates are treated as functions of incident radiative heat flux and local oxygen concentration. Many aspects of the simulation model need to be refined and extended for the model to be complete. To develop confidence in such models, a laboratory scale compartment experiment has been designed to study the combustion of wall slabs. The time dependent burning rate of a PMMA fixed area wall slabs shows a steady increase in mass loss rate over a significantly long period. Finally, as a third approach, the literature on full-scale room lining material fires has been reviewed. The results of the review suggest that low density (e.g. foam) materials with low energy rates of combustion can yield extensive spread over room linings. This may be due to their relatively more rapid opposed flow spread rates than spread rates of more common (higher density) materials.

Reports

1. Steckler, K.D., "Calculations of Wall Fire Spread in an Enclosure", CSNI Specialist Meeting on Interaction of Fire and Explosion with Ventilation Systems in Nuclear Facilities, Los Alamos National Lab, Los Alamos, April 1983. (Also NBSIR in press).

2. Quintiere, J., "Some Factors Influencing Fire Spread Over Room Linings and in the ASTM E-84 Tunnel Test", (in review).

4. Fire Induced Flows

Over the last several years this project has focused on the measurement of mass flow rates through door or window openings. These flows have been generated by controlled steady-state fires within a room. The experiments have been done at full-scale with fires of 30 to 150 kW. In the last year line-fires against a wall have been studied. To date the results have shown that vent flow coefficients are insensitive to the vent geometry, fire size and fire configuration. However, theoretical results show that the flow coefficient, predicted from potential flow analysis, agrees with the experimental results for the conditions tested (0.62-0.72), but should increase to 1 as the opening size approaches the wall area. With a knowledge of the flow coefficient it is possible to estimate the vent flow rate from temperature measurements alone, and this has been demonstrated in Figure 3 and exploited as a measurement technique. Using this method over 100 wall fire flows were studied. Those data and associated estimates of mixing within the room due to wall boundary layers and entrainment effects are being analyzed.

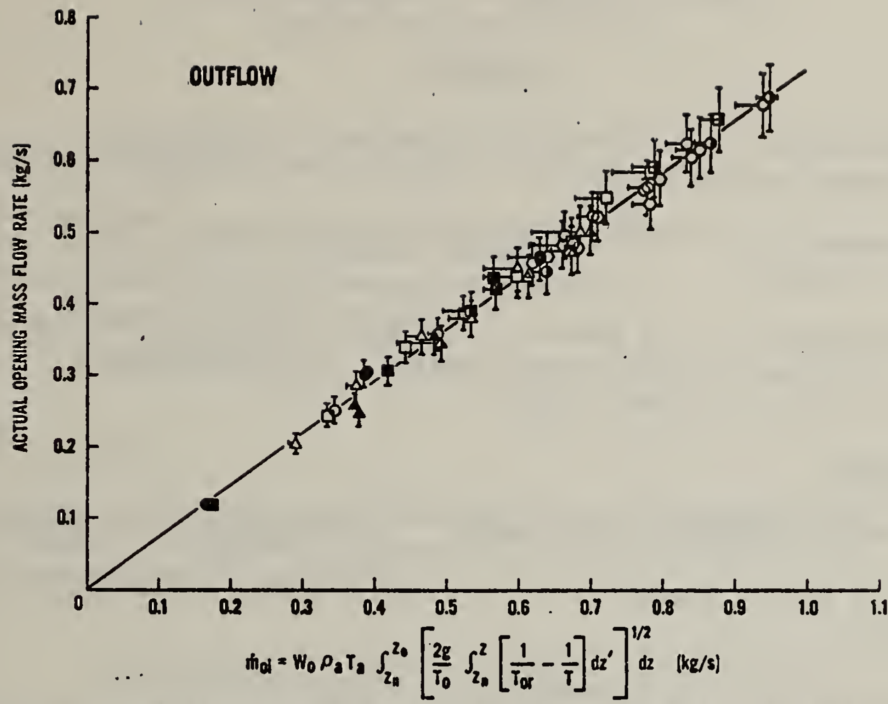

Figure 3. Mass flow rate derived from temperature data

Reports

1. Steckler, K., Quintiere, J., and Rinkinen, W., "Flow Induced by Fire in a Compartment", Nineteenth International Symposium on Combustion, The Combustion Institute, 1982, p. 913, also see NBSIR 82-2520, Sept. 1982.

2. Jaluria, Y., "Buoyancy-Induced Wall Flow Due to Fire in a Room", NBSIR (in review) plus presentation at the 1982 Tech. Mtg., Eastern Sec. Comb. Inst., Atlantic City, N.J., Dec. 1982

3. Steckler, K., Baum, H., and Quintiere, J., "Fire Induced Flows Through Room Openings - Flow Coefficients", in review.

5. Fire Growth in Enclosures

This project deals with the general area of fire growth in compartments. Primarily it is based on the zone modeling concept which treats a room fire in terms of discrete physical zones. The scope of activities has ranged, from investigating an empirically derived formula to predict temperature rise in a room fire, to developing a start at modeling fire growth in multi-compartments. Literature results on fully-developed compartment fires of wood cribs has revealed the prospect of highly fuel rich fires (equivalence ratios in excess of 20). These effects must be understood to enable prediction of flame lengths for doors or windows. Currently we are studying the role of lining materials in aircraft fires, and the early growth of fire due to blast effects.

Reports

1. Quintiere, J., "A Simple Correlation for Predicting Temperature in a Room Fire", NBSIR, March 1983.

2. Tanaka, T., "A Model of Multiroom Fire Spread", NBSIR (in press).

3. Quintiere, J. and Tanaka, T., "Some Analyses of the FAA Post Crash Aircraft Fire Scenario", Fire Technology, Vol. 19, p. 77, May 1983.

Grant Research

1a. Harvard University, H. W. Emmons - "Compartment Fire Modeling".

1b. Factory Mutual Research, R. Friedman - "Flame Radiation and Pool Fires".

2. Pennsylvania State University, G. Faeth - "Wall Fires".

3. California Institute of Technology, E. Zukoski - "Vent Mixing and Gas-phase Flammability in Compartments".

4. Case-Western Reserve, J. Tien - "Flame Spread Limits".

5. Harvard University, G. Carrier and TRW, F. Fendell - "Wind-Aided Flame Spread".

FIRE PERFORMANCE AND VALIDATION
FIRE MEASUREMENT AND RESEARCH DIVISION
CENTER FOR FIRE RESEARCH
FY 83

Professional Personnel

Sanford Davis, Head
J. Randall Lawson, General Physical Scientist
Billy T. Lee, Research Fire Prevention Engineer
Richard D. Peacock, Chemical Engineer
J. Samuel Steel, Physicist

Program Objectives

The objectives are to design and conduct tests to evaluate the fire performance of systems, components, and structures and to validate mathematical fire models.

Scope

This thrust includes two important efforts. First, the conduct of unique, highly instrumented experiments to establish fire behavior on a realistic scale. Second, the conduct of validation programs in collaboration with other groups. This thrust provides particular expertise in facility fire test experimental design, instrumentation, and data processing and analysis.

Projects

1. Standard Room Fire Test

The objective of this project is to further develop the standard room fire test for use by ASTM, with studies of fire spread and growth involving wall and ceiling finish materials when exposed to different ignition scenarios. A secondary objective is to set up a quarter-scale model of the test in order to (1) learn firsthand the problems which might be encountered and to find workable solutions or necessary modifications to the proposed test method, (2) provide a data base for the development and refinement of mathematical models which might be used to predict the performance of materials in the standard room fire test, and (3) evaluate the quarter-scale model room fire test as an interim screening tool for use by industry.

Room fire tests of several materials having a wide range of fire properties have been conducted under three different ignition exposures. In these tests, the test material fully lined three walls and the ceiling.

For some materials, the room fire development rate was found to be a strong function of the ignition exposures considered. Fire tests with the same materials lining only the walls or just the ceiling will be performed next. Quarter-scale tests of these same materials will be carried out also.

Lee, B.T., Quarter-Scale Modeling of Room Fire Tests of Interior Finish, Nat. Bur. Stds. NBSIR 81-2453, March 1982.

2. Validation of Fire Models

With increased activity in the development of analytical models for the description of fire growth processes and other fire-related phenomena, there is a need to develop a systematic approach to determine what constitutes validation of these models. The validation of any model aims at demonstrating that the model bears a close resemblance to the system being modeled.

Basically, model validation involves two kinds of concerns: technical and operational. Technical validation deals with identifying all the assumptions, variables, and relationships used in relating the model to the real world, problems of the accuracy of the input data, the correctness of mathematical and numerical calculations, and agreement between the model and the observed outcomes. Operational validation appraises the importance of the errors and divergences found under technical validation. It is concerned with whether or not the model can produce bad answers for proper ranges of parameter values and includes sensitivity analysis.

The entire process of model validation is dynamic. As theoretical insights, computational and instrumentation capabilities improve, it is desirable to re-examine existing models to determine if they remain valid in the light of these improved understandings.

Accordingly, this Fire Model Validation project, initiated in FY 83, will be an ongoing process. In order to set up the mechanisms for determining to what extent validation has been achieved, there is a need for mathematics capability not yet applied to this situation. A joint program with the Center for Applied Math has been developed and the project has begun with the choice of an appropriate operational model for which suitable validation experiments can be devised. The protocols are being developed for a series of full scale fire experiments, including the statistical design of the conditions for the trials and the frequency and types of data to be collected. The methodology ultimately will be developed for determining when the predictions of the mathematical model and the data from the full scale fire experiments agree closely enough to constitute validation.

3. Fire Safety Aspects of Wood as a Fuel

The objective of this project is to study the hazards associated with the installation, operation, and maintenance of wood-burning appliances used for space heating in single-family dwellings and similar small-scale applications. The overall research program included (1) a survey of fire incidents involving wood-burning appliances, (2) a review of codes and standards dealing with solid-fuel appliances, and (3) experimental studies to develop information in the areas of clearance to combustibles, chimney creosoting and chimney fires, fireplace inserts, and products of combustion.

Items (1) and (2) have been completed and show wood heating as a major cause of fire in the United States. In 1981, one in every five or six fires in residential property were caused by such appliances. A report, "Intensity and Duration of Chimney Fires in Several Chimneys" will be published shortly, detailing our studies in chimney creosoting and creosote burnouts. The report presents data showing temperature levels during chimney fires higher than current testing standards specify. Current studies are directed towards evaluating proper techniques for connecting appliances to masonry chimneys through combustible walls.

A report entitled "Wall Protection Systems for Wood Heating Appliances" was published in 1982 describing the results of tests to investigate alternative methods to reduce clearances between heat producing appliances and combustible materials.

A newly revised code for installation of solid fuel appliances incorporating the results of these research efforts should be published in early 1984.

Loftus, J.J., Evaluation of Wall Protection Systems for Wood Heating Appliances, Nat. Bur. Stds. NBSIR 82-2506, May 1982.

4. Solar Collector Fire Assessment

The objective of this program is to evaluate a method for determining the propensities of materials (used in the fabrication of solar heat collectors) to self heat after exposure to elevated temperatures for extended periods of time. A total of eight different urethane foams plus exterior grade plywood, untreated and retardant treated, are being subjected to adiabatic furnace tests; activation energies are determined for each of the materials. Temperatures found to start the self-heating process will be compared with data in the literature and available field experience on the effects of long-term heating on material fire properties. Calculations of critical size for a material can be made if specific heat and thermal conductivity values are known. Test results will be tabulated so as to be useful to designers of solar collectors.

5. Fire Performance Testing of Walk-on Platforms of the VA Hospital Building System

The objective of this project is to evaluate the fire resistive properties of building materials and construction systems proposed for use in VA medical facilities. The VA Building System concept incorporates an interstitial space with a walk-on ceiling platform between each functional floor of a hospital building. These systems are designed to provide a fire endurance of two hours between patient floors. A three-level steel frame representing a portion of a mid-rise building serves as the test structure. The walk-on platforms are built into the second-level of this structure and they are exposed from below to a fire which follows the ASTM E 119 time-temperature curve. Temperature measurements are made throughout the structure by 136 thermocouples.

In addition to the tests, a computer model is being used to simulate the fire performance of the building systems. Data from the tests are being compared to the calculated values in an attempt to further validate the computer model.

6. Fire Safety of Amtrak Passenger Car Interior Furnishings

The objective of this project is to develop and test cost beneficial concepts for reducing fire hazards in passenger rail vehicles. Full-size mock-ups of vehicle interiors have been tested with different combinations of materials currently under consideration for use as seating, wall covering, floor covering, window masks, and window glazing.

Laboratory-scale testing of the individual materials compliments the full-scale test program. A comparison of the laboratory-scale tests and the full-size mock-up tests shows that while the laboratory-scale tests are able to predict the effects of material changes in the same geometric configuration, they cannot predict effects due to changes in geometry in the full-size mock-up tests. A report entitled "Fire Tests of Amtrak Passenger Rail Vehicle Interiors" will be published shortly.

7. Fire Test Standards

The objective of this project is to support CFR's participation in the maintenance of existing and proposed voluntary consensus standard test methods. To accomplish this objective, CFR works closely with the various consensus standard groups and responds to the need for research for the solution of technical problems related to fire test methods. Work has continued on the evaluation of pilot burners for the ASTM E 162 surface flammability test. Results of the study are being submitted to the ASTM Committee and other laboratories are conducting compartive investigations. The development of the ease of ignition by flame exposure test for vertically oriented interior finish materials has continued.

The improvements identified during the preliminary round robin carried out on the test method have been incorporated into the test procedure. An interlaboratory test program is currently underway to evaluate the revised test procedure. In addition, other ASTM and NFPA standard tests are being reviewed to identify potential areas where improvements may be realized.

CFR has cooperated with the National Voluntary Laboratory Accreditation Program (NVLAP) on the evaluation of test results from various fire test proficiency test programs in an attempt to identify possible causes of variation noted from some data. The flooring radiant panel test for carpet and for attic floor insulation and the smoldering combustion test for insulation have been the main subjects for discussion.

Lawson, J.R. and Parker, W.J., Development of an Ease of Ignition Test Using a Flame Exposure, Nat. Bur. Stds. NBSIR 82-2503, June 1982.

8. Consensus Guideline for Arson Accelerant Analysis

An ad hoc working group of competent forensic laboratory personnel has been working with NBS personnel on the development of a consensus standard for forensic laboratories to use in the recovery and analysis of accelerants in samples from suspected arson fires. Two interlaboratory programs have been carried out in the recent past. Based on the complete analysis of the second (more extensive) program, a revised draft standard will be prepared for submittal to NFPA.

9. Large-Scale Fire Research Facilities

The large-scale testing facilities at the Gaithersburg site are available for use by CFR programs as needed. Building 205 is a 60-ft by 120-ft test building with controlled environmental conditions; a large smoke collection hood serves the individual experimental facilities and is connected to a large stack with afterburner. Building 205 also houses special calorimeters for measuring rate of heat release, pilot furnaces, and reduced-scale model enclosures. Of particular interest has been the development of a calorimeter for measuring the rate of heat release from full-size items of furniture; this provides a means for determining input data for analytical models. Laboratories are available for toxicology studies in conjunction with large-scale fire experiments. A new room/corridor facility has been constructed recently for studying smoke and toxic gas transport phenomena. In addition, we are in the process of up-grading the data acquisition system to provide increased scanning speeds, improved reliability, and real-time graphics display during the course of the test. The NBS Annex is a former DOD facility adjacent to the NBS site, which is available for special tests.

Associated Grants

University of Notre Dame, Murty Kanury - "Scaling Correlations of Flashover Experiments."

FIRE RESEARCH INFORMATION SERVICES
OFFICE OF FIRE RESEARCH RESOURCES
CENTER FOR FIRE RESEARCH
FY 83

Project Leader

Nora H. Jason

Program Objective

The Fire Research Information Services (FRIS) is an on-going project within the Center for Fire Research (CFR), National Bureau of Standards. It was started in 1971 and incorporated several personal collections at the National Bureau of Standards, as well as the Federal Fire Council collection. Over the years it has grown and now contains approximately 30,000 reports, documents and books. (On an average, 1500 items are added to the collection each year.) It reflects the programmatic needs of the Center for Fire Research, as well as developing a national and international fire research collection for use by NBS staff, researchers, fire departments, fire science students and the fire community at large.

An extensive document distribution program is carried on, both on a regular basis and on a demand basis. The publication and distribution of grantee reports (in the NBS Government Contract Report series) to selected subject interest groups is part of this program. All NBS report series are listed in the automated bibliographic data base and available through the Government Printing Office of the National Technical Information Services.

The journal collection contains approximately 100 titles. The focus is on the research activities of the CFR, as well as fire-related research needs. The titles are quite unique to FRIS.

For interested people who cannot come to the FRIS, an extensive inter-library loan program is carried out with participating libraries throughout the United States. FRIS is located at the National Bureau of Standards, Building 224, Room A-252. The telephone number is (301) 921-3249.

FIRE RISK ANALYSIS
FIRE SAFETY TECHNOLOGY DIVISION
CENTER FOR FIRE RESEARCH
FY 83

Professional Personnel

Alan Gomberg, Head
S. Wayne Stiefel, Operations Research Analyst
John R. Hall, Jr., Operations Research Analyst
Kwan-nan Yeh, Operations Research Analyst (IPA)

Program Objectives

The primary objective of the Fire Risk Analysis Group is the development of quantitative means to measure and manage fire risk to people, property, or systems from various specified factors for use by specified decision makers. A secondary objective is to provide access to, and analysis of, fire loss data for CFR.

Scope

Since fire and fire loss/cost are random events the desired measures involve probability statements and stochastic processes and their linkage to deterministic models. Estimates of risk are to be specified in terms such as likelihood of occurrence and outcome measures and involve present (i.e. actual or known) or future (i.e. presumed) situations, designs, materials, procedures, behavior, regulatory requirements, decisions, etc. The tools developed in this thrust are intended for use by code or regulatory officials, policy-makers, corporate managers or others.

Projects

1. Risk Assessment

This project area focuses on the development of risk assessment tools and methodologies to enable users to perform risk management functions. Emphasis is on developing risk estimation methods that can interact in a comprehensive approach to fire risk assessment. Current efforts in this area include the development of a risk assessment based management system to assist in the allocation of fire safety project funds in national park facilities, design and testing of an overall framework for risk assessment, modeling of ignition risk in buildings, and development and testing of a risk assessment methodology for nuclear facilities.

2. Decision Analysis

Decision on the choice between strategic alternatives for reducing fire losses should be based on a systematic consideration of all benefits, risks and costs. We have developed analytical techniques for assessing the risks and benefits associated with different fire safety alternatives, and the economic costs of these alternatives. Decision analysis provides the analytical framework for combining these loss and cost assessments and determining how sensitive the resultant cost effectiveness is to the variables. The initial decision analysis study of alternatives for the reduction of upholstered furniture fire losses served to establish the utility of this approach for fire hazard applications. A major decision analysis study is now nearing completion on the residential fire problem, to compare alternatives such as smoke detection, sprinklers, and "fast response" sprinklers on a cost/benefit basis.

Decision analysis techniques are being used to develop a risk based evaluation system for commercial aircraft fire safety alternatives, with the initial effort focusing on the effect of seat blocking in survivable crash fires. Decision analysis is also being applied in other fire safety areas including health care facilities and arson.

Clark, L. P., A Life-Cycle Cost Analysis Methodology for Fire Protection in New Health Care Facilities, Nat. Bur. Stds., Rept. NBSIR 82-2558 (1982).

Gomberg, A., Buchbinder, B., and Offensend, F. J., Evaluating Alternative Strategies for Reducing Residential Fire Loss - The Fire Loss Model, Nat. Bur. Stds., Rept. NBSIR 82-2551 (1982).

Stiefel, S. W., Use of Decision Analysis in Arson Program Planning, Nat. Bur. Stds., Rept. NBSIR 82-2596 (1982).

3. Special Studies

Using the National Fire Incident Reporting System and other data, we perform special studies to characterize specific fire hazards. Current special study topics include the following:

- Identification of factors associated with high fire death rates in rural areas and certain geographical areas.

- Analysis of electrical fire investigation data to establish key electrical fire causal chains and possible intervention strategies.

- Assessment of potential cost effectiveness of residential sprinkler systems and development of methods to improve sprinkler cost effectiveness.

- Identification of the nature and magnitude of fireplace and space heater fire problems in mobile homes.

Gomberg, A., and Clark, L. P., Rural and Non-Rural Civilian Residential Fire Fatalities in Twelve States, Nat. Bur. Stds., Rept. NBSIR 82-2519 (1982).

Gomberg, A., and Hall, J. R., Space Heater - Rural Death Link, Fire Service Today, Vol. 49, No. 9, 18-21, September 1982.

Gomberg, A. and Hall, J. R., Analysis of Electrical Fire Investigations in Ten Cities, Nat. Bur. Stds., Rept. NBSIR 83-2677 (1983).

Associated Contracts

1. SRI International, Fred L. Offensend - "Continuation of Decision Analysis Studies in Fire Hazard Analysis".

2. Center for Applied Mathematics, National Bureau of Standards - "Economic Analysis of Residential Automatic Sprinkler Systems".

3. Center for Applied Mathematics, National Bureau of Standards - "Expected Utility Theory for Selecting Fire Mitigation Strategies".

FIRE SUPPRESSION AND EXTINGUISHMENT
FIRE SAFETY TECHNOLOGY DIVISION
CENTER FOR FIRE RESEARCH
FY 83

Professional Personnel

Edward K. Budnick, Head
David D. Evans, Mechanical Engineer
Warren D. Hayes, Fire Prevention Engineer
Bernard J. McCaffrey, Mechanical Engineer
James A. Milke, Fire Protection Engineer (Part time)
Richard H. Zile, Engineering Technician

Program Objectives

The principal objective of this research group is to establish a basis for the technologies of extinguishment and suppression of fire processes through development of an understanding of how flames and smoldering are quenched, development of means to evaluate the effectiveness of materials or systems designed for this purpose, and development of performance data and test methods.

Scope

This effort involves studies of the basic phenomenology of extinction, studies of model systems, and mechanical testing of realistic configurations. The thrust involves fundamental studies, mathematical and computer models, and substantial experimental and laboratory effort. Principal emphasis is upon solid fuels, although gases and liquids will be included. The work treats both smoldering and flaming combustion and includes liquid, gaseous and solid powder suppressants. Suppression and extinguishment mechanisms are considered at all phases of the fire development process. Integrated results should be sufficient to serve as technical basis for advancing the state of engineering practice in the development, design, selection, and performance evaluation of a wide variety of types of fixed or portable extinguishment/suppression systems.

Projects

1. Prediction of Thermal Activation Conditions in Enclosures

Theoretical and experimental efforts are being combined in order to develop a means of predicting temperature and velocity conditions near the ceiling and upper walls in compartments. Accurate predictions of these conditions are necessary to provide the basis for engineering models designed to identify optimum siting locations for thermally activated suppression systems. Initial work involved full-scale and laboratory scaled experiments to provide a basis for calculations and scaling methods for simple, axisymmetric geometries. Initial results of this work indicate that accumulated hot gas layers significantly effect temperatures in the ceiling jet flow in small compartments. Therefore, in order to predict flow temperatures with sufficient accuracy to be meaningful in developing predictive methods for activation of thermal devices, a means of accounting for the plume flow in a two layer system was developed. In 1983 work involved modification of existing methods to develop both an exact mathematical solution and an approximate method for correction of plume temperatures due to the influence of the heated upper layer. Good agreement was obtained between calculations and controlled experimental measurements for ceiling impingement temperatures, and temperature and velocity conditions along the ceiling. Work will continue in 1984 to extend the model to more complex geometries, and to attempt to predict conditions at the wall-ceiling juncture, a common location for sprinkler installation.

Evans, D. and Madrzykowski, D., Characterizing the Thermal Response of Fusible-Link Sprinklers, NBSIR 81-2329, August 1981.

Evans, D., Plume Flow in a Two-Layer Environment, paper presented at ASME-AIChE National Heat Transfer Conference, Seattle, Washington, July 1983.

Evans, D., Sprinklers Come Home at Last, Fire Service Today, Vol. 49, No. 10, October 1982.

2. Fire Plume Characterization

The prediction of the burning rate of materials in a pool configuration remains one of the outstanding problems of fire research. To this end, measurements of gas velocity, temperature and chemical species concentrations are being made in the near field of buoyant diffusion flames. Together with measurements of both total and radiative heat flux back to the burning surface, as well as to distant targets, analytical representations of the phenomena are being developed.

It is realized that the plume is not well-mixed, and that it is highly likely that the flame-determining physics and chemistry are dominated by the local fuel-air ratio. Thus we are in the process of determining the fluctuation magnitudes and frequency distribution of the temperature and reactant concentrations in turbulent plumes.

McCaffrey, B., Momentum Implications for Buoyant Diffusion Flames, Combustion and Flame, 1983.

3. Measurement of Suppression Agent Plume Penetration

Important elements in determining the effects of suppressants on burning fuels are the amounts and rates of the agent which reach the burning surfaces of the fuel. The buoyancy forces of the heated plume above fires of various sizes are being examined experimentally to determine the effects on the agent penetration to the burning surface. As an initial effort, an apparatus has been constructed to provide such measurements for water sprays. Initial experiments with monodisperse sprays of known droplet sizes have been completed. Work will be continued in 1984 in order to develop a correlation for effects of fire size on water spray penetration to burning fuels, leading to an empirically based method for optimization of water sprays for extinguishment.

4. Measurement of Agent Effect on Solid Fuels

A study was initiated in 1983 to examine the thermal effects of known quantities of suppressants on burning solids. The primary focus in 1983 has been the design of an experimental apparatus that would provide baseline measurements for well characterized water sprays and simple fuel arrays. This effort will be continued in 1984 in order to establish baseline information necessary to pursue the development of a first cut model for suppression effects on solid fuel combustion.

5. Suppression Systems for Offshore Platform Blowout Fires

The primary objective of this multi-year project is to demonstrate the feasibility and provide engineering guidelines regarding the extinguishment of hydrocarbon fires resulting from gas and oil well blowouts by water spray. Blowout fires with heat release rates on the order of 1000 MW may be expected.

All laboratory work in 1983 has been directed at developing an understanding of the cooling and extinction of turbulent methane diffusion flames with water sprays. Laboratory work has been at heat release rates on from 1 to 10 MW. Based on these experiments, scaling parameters will be established and an effort will be made to predict the result at approximately 200 MW, or one-fifth the actual scale anticipated. Validation of the prediction of 200 MW will then be performed.

Evans, D., McCaffrey, B., Control of Blowout Fires with Water Sprays, Proceeding of Outer Continental Shelf Oil and Gas Operations, Technical Report, 1983.

Evans, D. O'Neill, J., Feasibility Study of Extinguishing Gas Well Blowout Fire with Water Sprays, NBSIR, (in review).

McCaffrey, B., Jet Diffusion Flame Suppression Using Water Sprays, NBSIR, 1983.

Associated Grants

1. Case Western Reserve University, Joseph M. Prahl - "Experimental and Analytical Study of Fire Sprinkler Scaling Laws".

2. Factory Mutual Research Corporation, Ronald Alpert - "Calculated Interaction of Water Droplet Sprays with Fire Plumes in Compartments".

FIRE TOXICOLOGY
FIRE MEASUREMENT AND RESEARCH DIVISION
CENTER FOR FIRE RESEARCH
FY 83

Professional Personnel

Barbara C. Levin, Head
Maya Paabo, Research Chemist
Cheryl Bailey, Research Chemist
Joshua Gurman, Research Associate, American Iron and Steel Institute
Steven E. Harris, Guest Worker, University of Pittsburgh

Program Objective

To identify potentially harmful combustion products and measure their effect on living organisms.

Scope

This thrust determines composition of potentially toxic combustion products under different fire exposures, establishes the physiological effects of such products, and provides measurement methods.

Projects

1. Toxicity Test Method Development

The current version of the NBS toxicity test method, which was developed to assess the acute inhalation toxicity of combustion products, has certain limitations with regard to the combustion system. A new combustion system has been designed and is a modification of the cone calorimeter developed by V. Babrauskas to measure rate of heat release. This new radiant energy system will permit the evaluation of materials in both a vertical and horizontal orientation. The evaluation of composite materials will allow the surface normally exposed in a real fire to be exposed to the heat source first. In addition, the continuous mass loss of the material during the thermal decomposition and the oxygen (O_2) levels both at the site of combustion and in the exposure chamber will be measured. Control of the O_2 levels at both sites will now be possible.

Levin, B.C., Fowell, A.J., Birky, M.M., Paabo, M., Stolte, A. and Malek, D., "Further Development of a Test Method for the Assessment of the Acute Inhalation Toxicity of Combustion Products," Nat. Bur. Stds., NBSIR 82-2532, June 1982.

Snell, J.E., Levin, B.C. and Fowell, A.J., "Workshop on Combustion Product Toxicity, Summary of Presentations, September 10, 1982," Nat. Bur. Stds., NBSIR 82-2634, November 1982.

Levin, B.C., "Toxic Gases and Fire Deaths," Nature 300:18 (1982).

Levin, B.C., Paabo, M., Birky, M.M., "An Interlaboratory Evaluation of the 1980 Version of the National Bureau of Standards Test Method for Assessing the Acute Inhalation Toxicity of Combustion Products," Nat. Bur. Stds., NBSIR 83-2678, April 1983.

Levin, B.C., "The National Bureau of Standards Toxicity Test Method," Proceedings of the Flame Retardant Chemical Association, March 22-24, 1983, Baltimore, Maryland. In press.

2. Toxicity of Flexible Polyurethane Foam With and Without Flame Retardants and a Polyester Fiberous Filling Material

This study is being performed for the Consumer Product Safety Commission who provided the Fire Toxicology Group with five samples of upholstered furniture filling materials. Two different formulations of flexible polyurethane foam were treated with different flame retardants and both treated and untreated samples were tested according to the NBS toxicity test method. In addition, a polyester fiber is also being evaluated. The addition of the flame retardants did not significantly change the autoignition temperatures of the polyurethane foam samples. Most of the animal deaths occurred during the 14 day post-exposure observation period, although a few were noted during the 30 minute exposure. This study is nearing completion and the final report will be ready in September.

3. Conditions Conducive to Hydrogen Cyanide Generation from Flexible Polyurethane Foam (GM-21)

Large-scale room burns of both flexible polyurethane foam slabs (GM-21) and polyurethane chairs showed that increased concentrations of hydrogen cyanide (HCN) were generated when the samples burst into flames after an earlier smoldering period. These levels of HCN were not observed in small-scale tests performed 25°C above (flaming) or 25°C below (non-flaming) the autoignition temperature of this flexible polyurethane foam (GM-21).

An attempt was made to simulate the large-scale conditions in the laboratory as follows. First, the material was exposed to a temperature 25°C below its autoignition temperature for 15 minutes, then the residue was heated at an elevated temperature. Flaming was not observed; however, the HCN levels increased tenfold. Further experiments indicated that only exposing the material to the higher temperatures did not produce the HCN, but rather a two step process was involved. First, the material was charred under the non-flaming conditions and then the char had to be heated. The HCN levels were related to the amount of char formed. A flame retarded polyurethane foam (GM-24) produced twice as much char and twice as much HCN. Elemental analysis indicated the concentration of nitrogen increased about 3 fold in the char when compared to the virgin foam whether the foam was flame retarded or not. Work is progressing on determination of the chemical or physical mechanism which is responsible for this increased cyanide production.

Alarie, Y., Stock, M.F., Matijak-Schaper, M. and Birky, M.M., "Toxicity of Smoke During Chair Smoldering Tests and Small Scale Tests Using the Same Materials," Fund. and Appl. Toxicology, in press.

Braun, E., Krasny, J.F., Peacock, R.D., Paabo, M., Smith, G.F., and Stolte, A., "Cigarette Ignition of Upholstered Chairs," J. Consumer Product Flammability, 9:167 (1982).

4. Pure Gas Studies

The purpose of these studies is to accummulate baseline data to determine if toxicity can be equated with discrete gas concentrations produced in typical fires. To date, results from pure carbon monoxide studies performed in the exposure chamber (described in the NBS toxicity test method report, NBSIR 82-2532) indicated that an average concentration of 5000 ppm over 30 minutes was necessary to kill half of the test animals (rats). The carboxyhemoglobin (COHb) levels necessary for death to occur were 87-89%. Preliminary results indicated that adding sublethal amounts of CO_2 to previously determined non-lethal concentrations of CO resulted in 4/6 of the animals dying. These animals had COHb levels of 84% which correlated well with previous results on CO and COHb. These studies provided information on both formation of COHb during exposure and reduction following removal of the animals from the test atmosphere. Recovery from these high levels of COHb appeared to be very rapid. (%COHb dropped from 84% to 40% in less than 15 minutes.) An examination of CO and COHb levels generated at the LC_{50} concentrations for 30 minutes calculated for the materials studied during the interlaboratory evaluation indicated that the COHb levels for some materials were lower than expected. These materials all contained nitrogen and produced hydrogen cyanide upon thermal decomposition. The additive effects of these two toxicants (CO and HCN) appear to account for most of the deaths observed in these experiments.

Associated Grants

1. University of Pittsburgh, Yves Alarie, "Toxicity of Plastic Combustion Products."

2. Colorado School of Mines, Kent Voorhees, "Characterization of Aerosols from Fires."

3. Southwest Research Institute, Gordon Hartzell, "Analysis of Hazards to Life Safety in Fires."

MATERIALS FIRE PROPERTIES
FIRE MEASUREMENT AND RESEARCH DIVISION
CENTER FOR FIRE RESEARCH
FY 83

Professional Personnel

Vytenis Babrauskas, Fire Protection Engineer, Acting Head
Emil Braun, Physicist
Zhanxian Han, Guest worker
John Krasny, Textile Technologist
Joseph Loftus, Research Chemist
William Parker, Physicist

Program Objectives

The objectives are to develop and validate measurement methods and to generate data necessary to characterize the fire performance of materials and products in engineering applications or for use in the modeling of fires.

Scope

This thrust involves significant effort in materials science, measurement technology development, and experimental work covering the behavior and response of materials to the range of energy sources encountered in incipient and fully developed fires. Materials include single substances and combinations. Test methods relate to actual materials and realistic configurations and conditions and cover a variety of scales from bench to full-scale.

The outputs from this thrust represent crucial inputs to the fire processes and other modeling activities of the fire protection engineering thrusts of the Center. Therefore, very close coordination with these thrusts is required in establishing clear definition of key technical parameters, their means of measurement, the kinds of data collected, and relative priorities among the test method development and data generation elements of this thrust.

Projects

1. Development of the Cone Calorimeter

During the past year the construction was finished on the cone calorimeter, which is a new bench-scale rate of heat release calorimeter using the oxygen consumption principle. A report giving construction details and calibration results was issued. Since the instrument is intended primarily for measurements on commercial products, including composites, a test standard based on this instrument was proposed to Committee E-5 of the ASTM, where a task group was formed to investigate its standardization. This instrument has enabled us to gather, at much less cost, the type of information for which the NBS-II calorimeter has previously been required;

furthermore, the rate of heat release curves show substantially less noise, in comparison. On-going work includes the development of instrumentation for suitable real-time measurements of additional important gas species and particulate measurements.

Babrauskas, V., Development of the Cone Calorimeter -- A Bench-Scale Heat Release Apparatus Based on Oxygen Consumption (NBSIR 82-2611). Nat. Bur. Stand. (1982).

2. Upholstered Furniture Burning Rates

An extensive series of furniture calorimeter burns had been completed in the prior year; a report and a journal article documenting these findings were recently published.

During the past year work was finished on mockup flame spread testing and the data were analyzed. This arrangement involved full-sized chair assemblies using steel frames but realistic cushions. The primary objective was to obtain a quantitative data base on flame spread rates. A major finding was that the flame spread rates could be well correlated to trip-thread burn-through times and to the times required to reach a 100 kW burning rate, both substantially easier to measure variables.

Work continued on the bench-scale (cone calorimeter) measurements of heat release and on the correlation of these to full-scale values. This was done for both the real furniture test series and for the mockup test series. Conditions of 25 kW/m^2 irradiance and 180 s averaging time were found to give the best predictability. The approximate heat release rate estimating rule first proposed as part of the analysis of the furniture calorimeter tests has now been extended to include appropriate bench-scale data from the cone calorimeter.

Babrauskas, V., Lawson, J. R., Walton, W. D., and Twilley, W. H., Upholstered Furniture Heat Release Rates Measured with a Furniture Calorimeter (NBSIR 82-2604). Nat. Bur. Stand. (1982).

Babrauskas, V., Upholstered Furniture Heat Release Rates: Measurements and Estimation, J. of Fire Sciences. 1, 932 (Jan/Feb 1983).

3. Flame Spread

Flame spread rates are an important hazard aspect for furniture and other combustibles. Upholstered furniture presents some unique measurement problems since typically multiple, but not bonded, layers of materials are present. This has generally precluded their testing in general-purpose flame spread apparatuses. An apparatus designed especially to avoid some of these problems was recently calibrated and placed into operation. It includes a fabric hold-down mechanism and involves linear spread, against the wind, on a horizontal (face up) specimen being heated by uniform external irradiation. A narrow-angle radiance meter and a two-color pyrometer have been provided to enable measurements of average flame radiation properties. The results will be analyzed according to the theory of radiatively-driven flame spread, with special emphasis on measurements of the flame flux.

4. Heat Release Rate of Char Forming Materials

A model is being developed for the heat release rate of char forming materials as a function of their chemical, thermochemical, and thermophysical properties along with their exposure and boundary conditions. It is a theoretical and experimental program devoted initially to wood-based materials. It is intended to predict the results of the various heat release rate calorimeters being considered for national and international tests and thus explain their differences in their reported data in terms of operational, instrumental, and specimen size and orientation variations. More importantly such a model is needed to couple the flame spread and fire growth models which have been successful for simple materials such as PMMA to more complex cellulosic materials for which a constant effective heat of vaporization does not apply. The model has to treat the external radiation and flame heat transfer to the surface as well as the internal heat transfer and pyrolysis. The work draws from the large amount of work already in the literature on flame spread, flame radiation, pyrolysis and charring rates. As a starting point, the thermophysical properties as a function of temperature and degree of char are being obtained to check out some of the existing mass loss rate models. However, it is not sufficient to merely predict the mass loss rate since the chemical composition of the volatile pyrolysis products changes during exposure. It is essential to individually account for the mass release rates of H, C, and O in order to predict the heat release rate. This requires the postulation of a pyrolysis mechanism. The effect of fissuring due to char consolidation on the heat transfer must also be taken into account.

5. Solar Glazing Flame Spread Performance

Solar collector glazing materials are often combustible. Their roof mounting makes them particularly vulnerable to fire spread, thus it is important that they not be easily ignitable from flying brands and that flame spread, if started, be slow. To determine this, a number of typical solar glazing plastics have been tested in both small-scale tests for flame spread and in full-scale exposures. Analysis is now being done to lead to a recommendation to the Department of Energy on appropriate bench-scale tests.

<u>Associated Grants</u>

1. Brown University, Merwin Sibulkin - Study of Effects of Material Properties on Flaming Combustion of Charring Fuels.

2. Factory Mutual, A. Tewarson - Determination of Fuel Parameters for Fire Modeling.

3. University of Michigan, George Springer - The Behavior of Furniture Frames During Fire.

SMOKE AND TOXIC GASES
FIRE SAFETY TECHNOLOGY DIVISION
CENTER FOR FIRE RESEARCH
FY-83

Professional Personnel

Richard W. Bukowski, Head
Walter Jones, General Physical Scientist
John Klote, Mechanical Engineer
George Mulholland, Research Chemist

Program Objectives

To provide an understanding of the rate of production, properties, and spread of smoke and toxic gases from fires and the technical basis for control of these products to enable reduction of their harmful impacts, particularly on people in fire situations.

Scope

This thrust covers control of smoke and toxic gases in and around facilities involved in fire. It includes the studies of the properties of combustion products and entrained materials and the effects on a facility and its occupants. It includes the development of models of smoke generation and transport in facilities, development of quantitative means to assess the impact of smoke and toxic gases under assumed fire and occupant conditions in specified facilities; and models for the development and performance evaluation of alternative strategies or technologies for smoke control, for detection and communication systems design, and for predicting available egress times for occupants.

Projects

1. Toxic Hazard Assessment

The toxicity of combustion products is possibly the most debated topic of fire research today. Toxicity test methods are being developed by a number of groups. But toxicity is only one aspect of the hazard to people from a fire and is not always the dominant factor. This project was established to develop a method by which a quantitative evaluation of occupant hazard can be obtained including the relative contribution of toxicity, ignitability, rate of heat release, building design, fire protection features, and others. The project will take advantage of the advances in computer fire modeling and graphics display over the past decade as the core of this method. The resulting model can be used to assess the hazards presented by specific materials and assemblies, the relative value of materials with modified properties, and the counterbalancing effects of protection systems in hazard reduction.

2. Smoke Transport Modeling

This is one of the primary subtasks of the toxic hazard assessment project and involves the development of efficient and accurate models to predict the spread of smoke and gases in a building. While this model, as most others currently available, is a zone model, it differs from many in two major ways. First, considerable effort has been put into the numerical implementation and solution to the equations to improve speed and minimize the convergance problems common to the other models.

Second, this model retains the transient pressure term which most other models disregard. Such a formulation gives the model increased flexibility by allowing for unvented enclosures and pressure related effects such as flame puffing. Verification of these models is an ongoing process. Validation of these models is particularly important if the toxic hazard assessment protocol is to be included in a credible way.

Jones, W., "A Review of Compartment Fire Models", NBSIR 83-2684 (1983).

Jones, W. and Quintiere, J., "Prediction of Corridor Smoke Filling by Zone Models, to be published in Combustion Science and Technology.

3. Computer Graphics

The purpose of this project is to develop the hardware and software capabilities necessary to input the geometry and arrangement of a large structure into a computer and to display the massive amount of data produced by the models in a manner which is relatively easily understood and assimilated. We are working with the state-of-the-art high resolution color graphics equipment and developing animation techniques to show smoke spread in real time with 3 dimensional isometric views of these structures.

Jones, W., "Use of Graphics in Modeling Building Fires", Invited paper to be given at the Perkin-Elmer Users Group Meeting, October 1983.

4. Smoke Dynamics in an Enclosure

For several years, CFR has been developing a field model of plume dynamics in an enclosure. This model is now performing 3 dimensional calculations of the spatial distribution of products including particle tracking and coagulation. The purpose of the smoke dynamics project is to conduct experimental verification of these field model predictions by developing a half-scale, air-tight test enclosure, well characterized aerosol/plume source, and fast response gas and particle instrumentation capable of localized, in situ concentration/size measurements.

Baum, Rehm, and Mulholland, "Prediction of Heat and Smoke Movement in Enclosure Fires", Proceedings of the Eighth International Symposium on Problems of Automatic Fire Detection. Duisburg, W. Germany, Oct. 1982.

Mulholland, G., "How Well Are We Measuring Smoke?", Fire & Mat., 6, 65.

5. Smoke Production

This project is an attempt to include soot particle formation and growth in a first order model for smoke production from materials. This first order model will provide insight into the most important measurement parameters to characterize the smoke yield of materials and to estimate aerosol properties which affect smoke detector response, loss of visibility, and radiation from the smokey, upper layer in the compartment of origin.

Dobbins and Mulholland, "The Evolution of Size Distribution During Particle Formation and Accompanied by Coagulation in Flames", submitted to J. Combustion Science and Technology.

6. Smoke Control Design Manual

Over the past 3 years, CFR, with support from ASHRAE and Veteran's Administration, has written a design manual for building smoke control systems which covers the fundamentals of smoke control and the specific application of zone smoke control and pressurized stairways. This manual has been published as an ASHRAE special publication and an NBS handbook and is the first comprehensive design guide for such systems.

Klote, J. H. and Fothergill, J. W., "Design of Smoke Control Systems for Buildings", Nat. Bur. Stds. (U.S.) NBS Handbook 141 and ASHRAE publication DSCS, July 1983.

Klote, J. H., "Smoke Movement through a Suspended Ceiling System", Nat. Bur. Stds. (U.S.) NBSIR 81-2444, February 1982.

Klote, J. H., "A Computer Program for Analysis of Smoke Control Systems, Nat. Bur. Stds. (U.S.) NBSIR 82-2512, June 1983.

Klote, J. H., "Smoke Control by Stairwell Pressurization, Engineering Applications of Fire Technology Workshop, Society of Fire Protection Engineers, Boston, MA, to be published.

Klote, J. H., "Smoke Control for Elevators", Nat. Bur. Stds. (U.S.) NBSIR 83-2715, 1983.

7. Dynamic Air Movement Through a Small Opening

This project involves study of pulsating flows through small openings such as leakage around closed doors or through construction cracks around door frames driven by low fluctuating pressure differences. These fluctuations can be caused by the fire and, most often, by wind effects on the building. These effects may be important to leakage through smoke barriers, particularly at some distance from the fire where buoyancy effects are small.

CENTER FOR FIRE RESEARCH
NATIONAL BUREAU OF STANDARDS
FY 83

Institution: The American Institute of Architects Foundation

Grant No.: NB81NADA0237

Grant Title: Fire Safety Evaluation System for Board and Care Homes

Principal Investigator: Earle Kennett
The American Institute of Architects Foundation
1735 New York Avenue, NW
Washington, D.C.

Other Professional Personnel: Daniel Alvord

NBS Scientific Officer: Bernard Levin

Technical Abstract

The Fire Safety Evaluation System for Board and Care Homes is a flexible fire protection standard for such facilities. It consists of two parts. One part evaluates the fire safety of the building itself, while the second part estimates the severity of the evacuation problem presented by the staff-resident population currently in the facility. The fire safety of the building, as determined by the first part, must be high enough to provide sufficient time in the event of a fire to compensate for the evacuation difficulty of the residents, as estimated by the second part. Otherwise, the facility "flunks" the system. A simulation model called the Escape and Rescue Model has aided in the development and validation of the evaluation system.

The Escape and Rescue Model is a deterministic discrete-event simulation program written in Simscript II.5 for the NBS Univac 1180/2 computer. It is designed to simulate the emergency movement and building occupant actions involved in escape and/or rescue of people from a board and care home housing a small live-in staff, along with a group of residents possessing varying degrees of physical or mental disabilities. It may be used to simulate the emergency evacuation problems of more general types of buildings, but not as accurately. The reliability of the results is mainly dependent on the appropriateness of the resident disabilities and preparation times inputted into the model.

The first step in simulating a facility with the model is to convert the floor plan into a simpler form. The model represents the building by means of a network consisting of discrete nodes and straight-line connectors between them, and people are only permitted to move from node to node along the connectors. After the network has been prepared, the staff and the residents must be given initial node locations, the nature of the residents' disabilities must be specified as well as their initial preparation-for-egress times, and a rescue priority must be

assigned to each resident initially requiring staff aid. When run with the aforementioned information, the model prints the input data in a readable format and then computes and prints the time that each resident reaches safety, each resident's egress route, the total time to clear the building, and a record of various significant events that occur in the course of the simulation.

Once a simulation run of a facility has been performed, all input items are easily adjustable, giving great flexibility to the model. Changing the input values can provide the user with some idea of the sensitivity of the evacuation times to alterations in the building and/or its occupants. The horizontal dimensions of the building may be increased or reduced by means of a scale factor. An exit route may be "blocked" with a simple change to the network, forcing an alteration in people movement. The number of staff and/or residents in the building may be changed, as well as their initial locations and preparation times. The movement speed and disability type of each resident are also easily altered. Many other factors can be varied.

A survey of Board and Care Homes was recently conducted for NBS to aid in the calibration of the Fire Safety Evaluation System for Board and Care Homes. Some of the data in the survey was gathered for use in the development, calibration, and validation of the Escape and Rescue model. Daytime fire drills were run in most of the surveyed facilities, and the initial locations of the residents, their behavior in the drill, their preparation times, and their movement speeds were observed. A floor plan of the facility was included. For many facilities which held a fire drill, the drill information was employed by the Escape and Rescue Model in an effort to simulate the drill. The simulations almost invariably agreed well with the actual drills, which is not incredibly surprising due to the choice of input, but this result still tends to validate some of the assumptions built into the model. Finally, the Escape and Rescue Model was used to simulate nighttime emergency evacuations for some of the facilities which did not conduct fire drills.

CENTER FOR FIRE RESEARCH
NATIONAL BUREAU OF STANDARDS
FY 83

Institution: Brown University

Grant No.: NBS Grant NB80NADA 1024

Grant Title: Effects of Material Properties on Burning and Extinction-Fires on Vertical Fuel Surfaces

Principal Investigator: Professor M. Sibulkin
Division of Engineering
Brown University
Providence, RI 02912

Other Professional Personnel: S. Malary, Graduate Research Assistant
S. Tewari, Graduate Research Assistant
E. Oren, Graduate Fellowship Student

NBS Scientific Officer: V. Babrauskas

Technical Abstract:

The objective of this program is to determine the effects of changes in material properties on the burning rates and extinction limits for solid fuels. A vertical fuel configuration is used because it provides the best opportunity to compare experimental results with the detailed mathematical analyses of diffusion flames which have been developed. This year work has been completed on a study of the effects of incomplete combustion on the burning of methyl methacrylate. An analysis of the effects of external radiation has been made, with results calculated for PMMA. Our present emphasis has shifted from the study of "vaporizing" fuels (PMMA) to "charring" fuels (cellulose). An investigation of the effects of solid-phase fire retardants on the burning of cellulose is in progress.

One of the unsettled questions in the modeling of diffusion flames is the proper heat of combustion to use in comparing theory with experiment. Published calculations are based upon the use of heats of combustion for complete burning (i.e., bomb calorimeter values). This year a major task has been to finish a study of the degree of completeness of combustion in a wall fire, and to determine the effect of incomplete combustion on the burning rate. The apparatus used was a vertical, ceramic wick assembly burning liquid methyl methacrylate (MMA) to simulate the burning of PMMA. Using this apparatus, burning rate measurements have been made for an ambient oxygen concentration range of $Y_{O,\infty} = 0.20$ to 0.30. A procedure was developed to eliminate a ten percent uncertainty band in the burning rates obtained in previous liquid-fed wick measurements which were operated in a "zero dripping" mode. This was accomplished by measuring the difference between the fuel supplied and the unburned fuel collected in a trough below the

wick for a range of fuel supply rates. These results were then extrapolated to the zero dripping limit.

During the previous period a gas sampling system had been developed. This was used to obtain boundary layer profiles of the concentrations of CO_2 and CO using a two-channel nondispersive infrared analyzer. Results were obtained for the range $Y_{O,\infty} = 0.20$ to 0.30 at $x = 5.2$ cm from the leading edge of the wick, and at $x = 2.8$, 5.2, and 7.5 cm at $Y_{O,\infty} = 0.233$. These measurements were primarily made with a water-cooled, stainless steel probe (#1) having an outer diameter of 0.120 inches and an inlet diameter of 0.032 inches. The tip of this probe became blocked with soot in the luminous zone of the boundary layer. (The width of this high sooting region increased with increasing oxygen concentration.) Measurements were obtained in the sooting region with an uncooled quartz probe (#2) with an inlet diameter of 0.050 inches. Outside the sooting region measurements by both probes were in agreement. The dry gas concentrations X^D for CO_2 and CO are plotted against distance from the fuel surface y in Fig. 1 for $Y_{O,\infty} = 0.233$ at $x = 5.2$ cm. These results show that there are large concentrations of CO between the flame zone and the wall. The maximum value of the CO/CO_2 ratio increases from 0.8 at $Y_{O,\infty} = 0.20$ to 1.1 at $Y_{O,\infty} = 0.30$.

Because the cold trap in the gas sampling system removes both water and MMA vapor, the CO_2 and CO concentrations obtained from the IR Analyzer are on a dry gas basis. A data reduction procedure was developed to convert these concentrations to a total gas basis. The effective heat of combustion $h_{c,e}$ depends upon how much of the fuel goes to CO rather than CO_2. The total rates of CO and CO_2 production were calculated by integrating across the boundary layer using the measured concentrations and flow factors obtained from our diffusion flame computer program. Defining the ratio

$$R_{CO} \equiv \frac{\dot{n}_{CO}}{\dot{n}_{CO} + \dot{n}_{CO_2}}$$

where $\dot{n}$ is the production rate in moles per second, our results give values of R_{CO} which increases from about 0.3 at $Y_{O,\infty} = 0.20$ to 0.4 at $Y_{O,\infty} = 0.30$. When these results are used to calculate the heat of reaction, they give an effective heat of combustion $h_{c,e} \simeq 20{,}000$ kJ/kg which is approximately 20 percent less than the value for complete burning. The variation of R_{CO} and $h_{c,e}$ with $Y_{O,\infty}$ is shown in Fig. 2. These effective heats of combustion will be used as inputs to our diffusion flame computer program. The calculated results will be compared with our burning rate measurements. This work is being prepared for publication.

During this period an analytical study was made of the effects of external radiation on wall fires using our previously developed computer program for modeling this fire. The fuel considered was PMMA and results were calculated for external flux levels $\dot{q}''_{ex}$ from 0 to 40 kW/m^2 and for ambient oxygen concentration levels from $Y_{O,\infty} = 0.23$ down to extinction. Previous work had shown that the burning rate is nearly independent of the chemical reaction rate at oxygen concentrations above extinction. This result was checked and then used to significantly reduce the effort needed to obtain the burning rate results. The calculations for a fixed value of $Y_{O,\infty}$ show an almost linear increase in burning rate as $\dot{q}''_{ex}$ increased. However, the slope of the $\dot{q}''_{ex}$ vs. $\dot{m}''_b$ curve is not equal to the heat of pyrolysis of the fuel, as has been suggested, due to the great reduction in convective heat flux to the wall as $\dot{q}''_{ex}$ increases. A considerable effort was devoted to obtaining extinction limit results as a function of external flux level for finite chemical reaction rate. The kinetic parameters used were based on published results for PMMA. The variation in the nondimensional burning rate m^* is shown as a function of $Y_{O,\infty}$ in Fig. 3 for several external flux levels $\dot{q}''_{ex}$. The increase in burning rate with ambient oxygen concentration is linear. A major finding is that there is only a small decrease (about 2 percent) in the value of $Y_{O,\infty}$ at extinction as $\dot{q}''_{ex}$ is increased from 0 to 40 kW/m^2. These results are being prepared for publication.

Experimental work on the burning of pure and fire retarded cellulose cylinders is continuing. A preliminary investigation was made to evaluate methods for determining the heat of pyrolysis of cellulose. Our major effort in the next year will be on these problems.

Publication was completed this year of two papers whose findings were presented in the last conference abstract.

<u>Reports and Papers</u>:

Completed publications

"Free Convection Diffusion Flames with Inert Additives," M. Sibulkin and C. Y. Wang, Journal of Heat Transfer, <u>104</u>, 728 (1982).

"Nonsimilar Calculations for Free Convection Diffusion Flames," M. Sibulkin, A. K. Kulkarni, and S. F. Malary, Combustion and Flame, <u>50</u>, 59 (1983).

Publications in preparation

"Investigation of Completeness of Combustion in a Wall Fire," M. Sibulkin and S. F. Malary.

"External Radiation Effects on the Burning and Extinction of Wall Fires," M. Sibulkin and T. Gale.

Theses

"Calibration of Surface Temperature and Thermal Radiation Instruments," S. M. Schneider, Sc.M Thesis, Brown University (1982).

"Evaluation of the Heat of Pyrolysis for Cellulose," E. Oren, Sc.M Thesis, Brown University (1983).

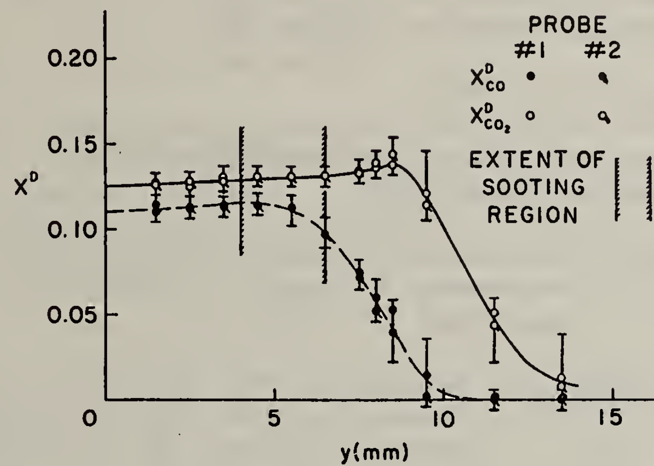

Fig. 1

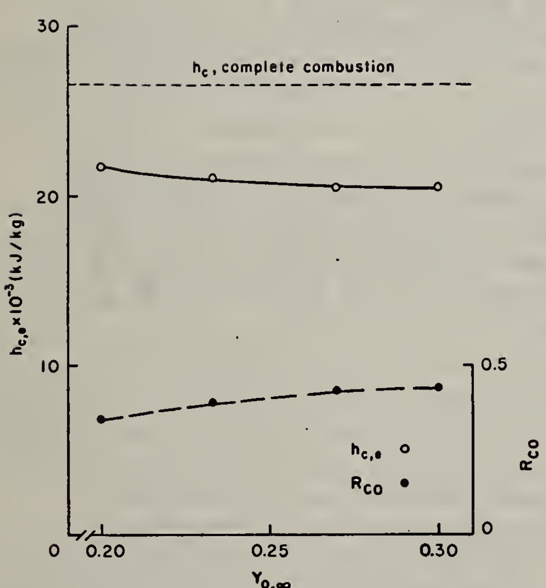

Fig. 2

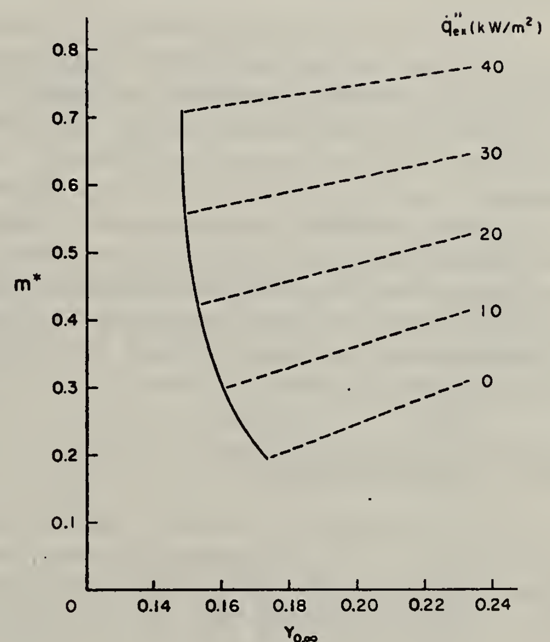

Fig. 3.

Institution: California Institute of Technology

Grant No.: NBS Grant NB82NADA3033

Grant Title: Experimental Study of Environment and Heat Transfer in a Room Fire

Principal Investigator: Professor Edward E. Zukoski 301-46
California Institute of Technology
Pasadena, CA 91125

Other Professional Personnel: Professor Toshi Kubota
Christopher Lim, Ph.D. Candidate
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Pasadena, CA 91125

NBS Scientific Officer: Dr. James Quintiere

Technical Abstract

Producing rational models of smoke movement in complex structures requires an understanding of a number of turbulent flow processes. We have been studying several of these processes and have also developed a simple computer model based on these results. We have been interested primarily in the plumes produced by a fire or by a flow of hot gas through openings, and have been investigating the entrainment rates of the plumes and the heat transfer rates produced by the impingement of the plumes on the ceiling of a room. A simple computer code has been developed which describes smoke movement in pre-flashover, two room configurations. This modeling effort has aided us in our selection of experimental problems. Some of our current work is described in the following paragraphs.

Experimental Progress

Heat Transfer. During the past year we have completed the documentation of the experimental work we have carried out on the heat transferred to the walls of a room as the result of a fire within the room. See Reference 1.

The primary data refer to steady state convective heat transfer to the ceiling but, in order to develop a rational description of this process, we were also forced to develop a model of the flow produced by the fire plume within the room and to compute radiant heat transfer between the surfaces forming the room. The flow field model includes a crude description of the plume-interface interaction region and a model of the hot ceiling jet formed by the plume impingement on the ceiling.

This flow field model is being modified to allow us to include in our Room Fire Model a calculation of heat loss to the walls, ceiling and floor. We are also in the process of including a calculation of the heat transfer to objects placed within the room such as a sprinkler head placed some distance below the ceiling.

The radiant heat transfer treatment is limited because, although radiant heat transfer between solid surfaces is taken into account, gas phase radiant transfer processes are not included. Thus, heat transfer between side walls, the ceiling and floor, and other solid objects within the room can be included in these calculations but heat transfer from a sooty gas to the wall cannot. The surfaces bounding the room are divided into a manageable number of flat elements and a single temperature is used to describe the surface condition of each element. View factors are calculated by a computer code given the room geometry and the temperature of each element is calculated from a transient heat transfer program. The calculation of the heat transfer into the wall is treated with a one-dimensional model and a single temperature distribution within the wall is required to describe each surface element.

We have had some success with early versions of this work in describing heat transfer in room fire tests carried out at the Lawrence Livermore Laboratory.

Combustion in a Fuel-Rich Ceiling Layer. We are also in the process of completing our work on the entrainment of fire plumes. The material, reported in Reference 2, has been incorporated in the Room Fire Model.

Current work includes an extension of our study of combustion in the fuel-rich ceiling layer. This work is a study of combustion which occurs in a diffusion flame which has its base in unvitiated air, but which extends for an appreciable fraction of its height into a ceiling layer composed of the products of combustion formed by the flame itself. We are examining the products of combustion formed by this system as a function of the height of the flame in the two regions, the temperature of the ceiling layer gas (which is fixed by heat loss from the layer) and the fuel flow rate or heat release rate of the diffusion flame.

Measurements are being made with a hood which is a cube with a side of 1.22 meters, heat release rates of 10 to 100 kW, and flame heights in unvitiated air as small as 20 cm. During the past year we have carried out measurements to develop a more accurate set of data than those previously reported. These data were substantially unaltered from those previously discussed. Thus, when the ceiling layer temperatures are in the range 750 to 900 K. the gas composition within the ceiling layer (i.e., the hood) has a composition which is, within our rather large experimental scatter, close to the corresponding equilibrium value. These results were obtained with methane as the fuel and for fuel-air ratios of the gases entering the hood which lie in the range of equivalence ratios between 0.1 and 2.20. In addition, we have ignored the contribution of the soot to the mass balances.

The products become combustible for values of the equivalence ratios which are greater than about 2.0 and, for this condition, vigorous burning of the products was noted in a door-jet flow configuration. Little combustion within the ceiling layer itself has been observed although the diffusion flame does act as an ignition source for the flame which is observed to lie at the horizontal interface between ceiling layer gas and unvitiated air.

The average height of the diffusion flames burning in the vitiated air within the hood were determined by observing the top of the flames through two 30 cm square pyrex windows located in the side of the hood. Average values determined by eye were the equal to the values determined for identical diffusion flames burning in unvitiated air to within our observational reproducibility of 5 to 10%. This surprising result was found to hold even for the very fuel-rich cases for which the ceiling layer gas had an oxygen mass fraction of less than 1%.

These studies also are giving us a better picture of the air entrainment process when the flame extends deeply into the ceiling layer.

Flame Dynamics. We have also started this year to study in a more detailed manner the large structures which are formed in the buoyant diffusion flames we have been using as a source for the buoyant plume entrainment work. These flames are characterized by a regular pulsation in the diameter of the flame near the burner which appears to be associated with the formation of vortical structures. See Reference 2.

We believe that these structures fix to a large degree the entrainment processes in the fire itself and perhaps also in the plume above the visible flame. This year, we initiated a study of these structures which have involved the use of simultaneous direct and shadowgraph photographs of the flame and near field of the plume. High speed motion pictures and short duration spark techniques are being used.

Door Way Entrainment. We are investigating the entrainment from the hot ceiling layer of a room into the floor layer by the action of the flow in and out of a doorway which is itself fixed by a fire within the room. The experiments are being carried out in a half scale room model, a room 1.22m high by 1.22m wide by 2.4m long, and with doors which are in the center of the 1.22 by 1.22m end. Entrainment rates are inferred from a mass balance made on a tracer which is introduced into the ceiling layer gas at a known rate.

We have had considerable success in correlating the results of this work with a parameter similar to a Richardson number. This is a continuing project and the final analysis has not been completed.

<u>Reports and Papers</u>

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CENTER FOR FIRE RESEARCH
NATIONAL BUREAU OF STANDARDS
FY 83

Institution: Case Western Reserve University

Contract Number: NB82NADA3028

Contract Title: Experimental and Analytical Study of Fire Sprinkler Scaling Laws

Principal Investigator: Joseph M. Prahl, Ph.D., P.E.
Associate Professor of Engineering
Dept. of Mechanical and Aerospace Engineering
Case Western Reserve University
Cleveland, Ohio 44106

NBS Scientific Officer: David D. Evans

Technical Abstract

The objective of this project is to develop an experimental base that will delineate the relevant scaling parameters that govern the ultimate performance of a wide class of fire sprinklers. The sheet trajectory, sheet breakup, and subsequent droplet size distribution and droplet trajectories will be related dimensionlessly to the mechanical and thermal properties of the liquid and gaseous fluids, the geometry, and the initial dynamics of the liquid and gaseous streams.

An apparatus has been designed and built to study the axisymmetric jet impingement on a flat disk which can be vibrated axially at a given frequency and chosen amplitudes. Several nozzle and disk sizes can be interchanged as well as varying the initial fluid velocity and distance between the nozzle and disk. The fluid itself can ultimately be varied as the flow system is recirculating. At present, the system is being preliminarily tested with water. A 22 and 1/2 degree sector of the axisymmetric discharge pattern will be studied intensively. The effects of surface characteristics of the disk as well as frequency and amplitude of vibration will be considered in detail first to specify the effect these parameters have on the sheet breakup location and the droplet size distribution that results. The droplet trajectories will be determined by catching the spray in a series of rain gutters spanning the floor of the sector in question.

If consistent results are obtained with water, other fluids with different surface tension properties will be tested in the rig to build confidence in the dimensionless parameters that appear to govern the behavior of the resulting sprays.

The tests planned for summer, 1983, are preliminary in nature and will be used to guide the investigators as to the appropriate level of instrumentation required to completely characterize the phenomenon.

Reports and Papers

No reports and/or papers have resulted from this work as yet.

CENTER FOR FIRE RESEARCH
NATIONAL BUREAU OF STANDARDS
FY 83

Institution: Case Western Reserve University

Grant No.: NB83NADA4002

Grant Tltle: Flame Spread and Spread Limits

Principal Investigator: Professor James S. T'ien
Department of Mechanical and Aerospace Engineering
Case Western Reserve University
Cleveland, Ohio 44106

Other Professional Personnel: Charlie Chen (Graduate Student)

NBS Scientific Officer: Dr. James G. Quintiere

Technical Abstract

The overall objective of this research program is to develop basic understanding of flame spread with special emphasis on flame spread limits. The work involves experimental and theoretical modeling efforts for both downward (opposed flow) and upward (concurrent flow) flame spreads.

During this report period, the fire plume region along a vertical wass was ivnestigated theoretically. The fire plume plays an important role in fire growth and upward flame spreading processes because it determines the heat flux level to the unburnt fuel surface. Furthermore, the quenching of chemical reactions near the tip of the combustion plume results in the escape of the unburnt fuel or combustion intermediates from the flame which produces them. These escaped pyrolyzates can either constitute as air pollutants or serve as fuels to be burnt later elsewhere (such as in the smoke layer in a room). Thus the study of the fire plume can have a number of practical implications to fire research.

Previous investigations on wall fire plume have employed the assumption of infinite-fast chemical kinetics [1, 2]. The present work emphasizes the effects of finite-rate gas-phase chemical reactions. The model assumes a naturally-convective laminar boundary layer along a vertical surface. The chemical reactions include two semi-global steps: in the first, fuel is oxidized to form carbon monoxide and water vapor and, in the second, carbon monoxide is oxidized to form carbon dioxide. Four important nondimensional kinetic parameters are identified: two dimensionless frequency factors (Damkohler numbers) and two dimensionless activation energy. A parametric study is used to investigate the effect of these parameters. The computed results indicate that by slowing down the relative kinetic rates in the gas-phase reactions, the

total heat transfer rate and the preheating distance are decreased (Fig. 1). Furthermore, slowing down the kinetics also increases the amount of unreacted combustibles which escape from the flame (Fig. 2).

The result of this plume model will be used to study the upward flame growth or spread rates and the spread limiting phenomena.

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1. Ahmad T. and Faeth, G.M., "An Investigation of the Laminar Overfire Region Along Upright Surfaces", vol. 100, 1978, J. of Heat Transfer, pp. 112-119.

2. Pagni, P.J. and Shih, T.M., "Excess Pyrolzate", 16th Sym. (Int.) on Combustion, The Combustion Institute, Pittsburgh, 1977. pp. 1329-1343.

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Borgeson, R.A., "Flame Spread and Spread Limits", NBS-GCR-82-396, July 1982.

Borgeson, R.A. and T'ien, J.S., "Modelling the Fuel Temperature Effect on Flame Spread Limits in Opposed Flows", Combustion Science and Technology, 32, 125 (1983).

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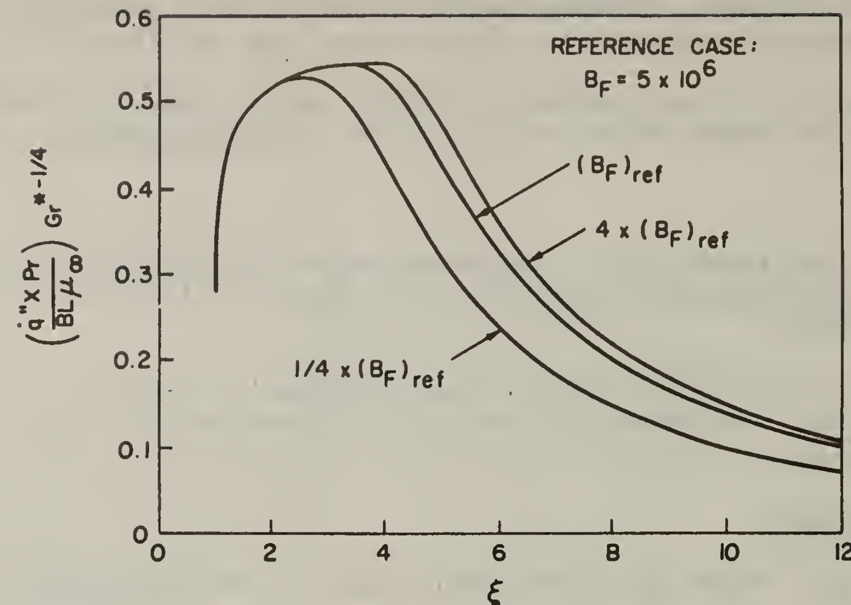

Fig. 1 Nondimensional surface heat transfer rates vs. nondimensional distance ξ, the effect of non-dimensional fuel frequency factor variation. The plume starts at ξ=1, pyrolysis region is from ξ=0 to ξ=1.

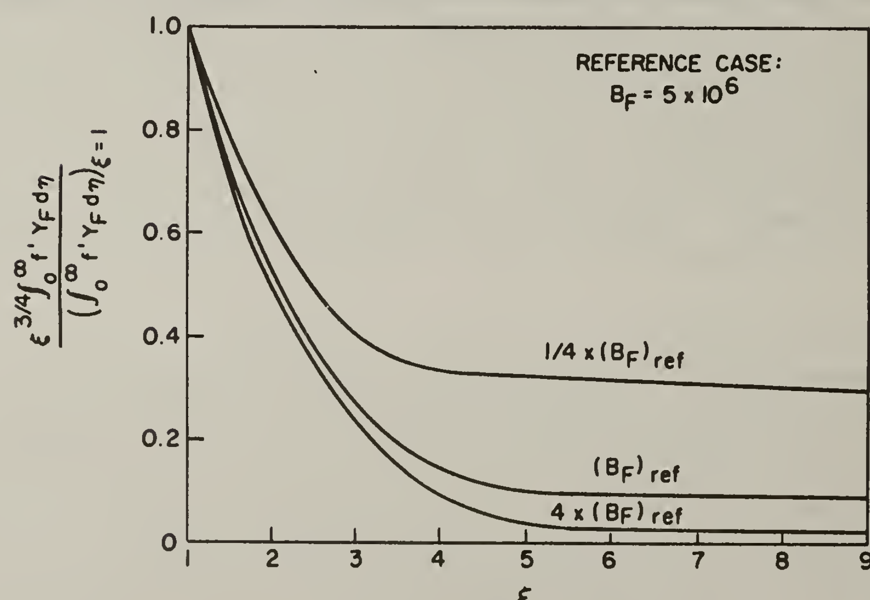

Fig. 2 Fuel mass flux ratio (fuel mass flux divided by fuel mass flux at the plume starting plane) vs. ξ: the effect of nondimensional fuel frequency factor variation. The flatten curves indicate the chemical-frozen region and give the ratios of unburnt fuel escaped from the flame.

CENTER FOR FIRE RESEARCH
NATIONAL BUREAU OF STANDARDS
FY 83

Institution: Clemson University

Grant No: NBS Grant NB80NADA1042

Grant Title: Ternary Reactions Among Polymer Substrate-Organohalogen-Antimony Oxides in the Condensed Phase Under Pyrolytic, Oxidative and Flaming Conditions.

Principal Investigator: Dr. M. J. Drews
School of Textiles
Clemson University
Clemson, South Carolina 29631

Other Professional Personnel: Dr. C. W. Jarvis, Co-principal Investigator
Dr. J. Reece, Post-doctoral Research Associate
Mr. T. Gilstrap, Graduate Assistant
Ms. B. Lee, Graduate Assistant

NBS Scientific Officer: Dr. G. Mallard

Technical Abstract:

The objective of this study is to determine the contributions of the solid phase interactions, occuring in antimony oxide/organohalogen/thermoplastic polymer substrate compositions, to the overall system chemistry during combustion. Of particular interest is the role of the polymer substrate in the generation of volatile antimony and halogen containing species. Small scale degradation data are to be integrated with the results from laboratory scale flaming combustion experiments conducted at the Center for Fire Research of the National Bureau of Standards. The flaming combustion and degradation data are to be used in an attempt to develop a comprehensive model for the chemistry which occurs in the condensed phase, under both flaming and non-flaming degradation conditions. This model is to be used in the identification of the controlling parameters for optimizing the efficiency of organohalogen/antimony oxide flame retardant combinations in specific polymer substrates.

The research plan has been divided into two concurrent pathways. The first pathway consists of small scale degradation studies to be conducted throughout the lifetime of the project. These degradation studies are designed to characterize the thermally initiated ternary reactions, which could affect halogen and antimony release in the condensed phase, occuring in mixtures of polymer substrate/organobromine additive/antimony oxide. These data will then be correlated with the previous results obtained in studies of the reactions

involving the individual components and binary mixtures. From these two data sets, the changes in the rates of antimony and/or bromine volatilization, the temperature profiles for antimony and bromine release, and the relative concentrations for the various volatilized bromine and antimony species will be used to define the role of the polymer substrate structure in the halogen and antimony loss from the solid phase. Three polymer substrates are being studied: polymethylmethacrylate (PMMA), polypropylene (PP) and polyethylene terephthalate (PET). Three organo bromine compounds are being used as model organohalogen additives: hexabromocyclododecane (HBCD), tetrabromobisphenol-A (TBBPA) and decabromodiphenyl oxide (DBDPO). The study of mixtures of each of the above with antimony trioxide or antimony pentoxide consists of a sequence of experiments including but not limited to, dynamic (at three different heating rates) and isothermal (at two different temperatures) decomposition studies in three different atmospheres; pyrolytic (nitrogen), catalytic (1% oxygen) and ambient (21% oxygen).

The second pathway in the research plan includes laboratory scale flaming combustion experiments conducted at the Center for Fire Research at the National Bureau of Standards during the project. In these experiments, the effects on combustion parameters such as sample thickness and geometry, as well as polymer substrate additive concentrations are to be studied. The apparatus to be used for these flaming combustion experiments is the cone calorimeter developed by Parker, Babrauskas, and Swanson. Several combustion parameters are measured for each sample including; time to ignition, rate of heat release, mass consumption rate, and the gravimetric smoke yield.

While the combustion data gathered to date represent a limited sampling, they clearly indicate that the solid state chemistry can not be completely isolated from the gas phase reactions. In particular these data reflect the effects of the relative additive stabilities on the overall ability of a halogen/antimony system to disturb the combustion envelope as represented by oxygen depletion and carbon monoxide/dioxide formation. That these effects occur, even in the downward burning candlelike geometry using thermally thick samples is surprising but in accord with the basic hypothesis of this work. Perhaps even more surprising is the observation that the closer the match between the substrate and organohalogen stabilities, the less the base burning behavior, in terms of these gases, is disturbed. One would have initially expected a maximum deviation for this case. In addition, these data show that significant changes in flame height, smoke generation and incomplete combustion as measured by CO formation may occur while the mass consumption rate remains essentially unchanged.

While these results obtained on the cone calorimeter so far are extremely interesting, because such a limited amount of data is available, it is difficult to draw any concrete conclusions regarding some of the observations that have been made. It appears more promising than ever, however, that when combined with the thermal analysis results these data will lead to a significant increase in the understanding of the effects of antimony/halogen systems on the combustion performance of polymer substrates.

From the initial experiments until the present time difficulties have been encountered in obtaining complete mass balances of the reactive components in the ternary mixtures. As a result, during the past project year a decision has been made to begin larger scale pyrolysis in a tube furnace apparatus. In order to maintain the experimental consistency which has been designed into this work, it therefore became necessary to repeat some of our earlier single component and binary mixture studies in the tube furnace. These data were consistent with the thermal analysis experiments in that, only in the ternary mixture and melt (melt blended mixture) has any evidence for significant chemical reaction and antimony volatilization been observed.

To date, however, even in the tube furnace experiments, mass balances of the additives and antimony have been obtained in only a limited number of cases. Consequently, the research plan for the current project year has undergone substantial modification with respect to the pyrolysis work. New polymer substrates and organohalogen additives will be screened in an attempt to discover a system more amenable to analysis by the techniques which have been developed during the course of this work.

The results of this systematic investigation are intended to make available new basic information in several important areas: formation of volatile antimony species from reactions of antimony oxides with organo halogens that cannot by themselves eliminate hydrogen halide; the effect of the polymer substrate on the reactions which produce volatile antimony halides and oxy halides; and the first systematic study on the controlled combustion of thermoplastic materials containing organohalogen/antimony oxide flame retardants. The systems description which this research program seeks to develop should make it possible to model more accurately combustion performance of these materials in fire situations and lead to a greater understanding of the thermal characteristics necessary for the more efficient flame retardation of thermoplastic materials.

Reports and Papers:

Drews, M. J., Jarvis, C. W., Leibner, E. A., "Organobromine/Antimony Oxide/Polymer Substrate Interactions in the Solid Phase. Part I. Binary Interactions," Organic Coatings and Plastics Preprints, 43, 181 (1980).

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CENTER FOR FIRE RESEARCH
NATIONAL BUREAU OF STANDARDS
FY 83

Institution: Colorado School of Mines

Grant No.: NBS1NADA2020

Grant Title: Characterization of Aerosols from Fires

Principal Investigator: Professor Kent J. Voorhees
Department of Chemistry and Geochemistry
Colorado School of Mines
Golden, CO 80401

Other Professional Personnel: Dr. R. Tsao, Post-Doctoral Associate
Mr. S.A. Durfee, Ph.D. Candidate

NBS Scientific Officer: Ms. Maya Paabo

Technical Abstract

The objective of this research program is to determine, using pyrolysis/mass spectrometry (Py-MS)/pattern recognition procedures, the composition of the polymeric materials in combustion aerosols and relate this information to the fuels involved in the combustion process. Single polymer and wood samples have been individually decomposed in both flaming and nonflaming modes and the aerosols collected. The pyrolysis/mass spectra have been recorded as reference spectra for these materials. Polymer and wood mixtures have also been decomposed and the aerosols investigated by Py-MS. Various pattern recognition procedures with and without reference spectra have been used to determine the number of components as well as identification of the components of the mixture. A similar procedure has also been applied to single polymer and wood samples and combination mixtures where gasoline was present. The results in these areas will be individually discussed.

1. Aerosols from Flaming and Nonflaming Degradation

The aerosols collected from 11 polymer samples, 3 wood samples and gasoline all produced pyrolysis/mass spectra which were unique for the original sample. Differences were noted between the aerosols produced from flaming and nonflaming conditions. All of the individual samples were either extracted or vacuum treated to remove the volatile (low molecular) portion. In many cases, particularly in the nonflaming aerosols, the pyrolysis/mass spectra were quite similar to the pyrolysis/mass spectra of the original polymers.

2. Pattern Recognition

Four pattern recognition procedures have been applied to mixture aerosol Py-MS data. Multivariate statistics have been used for

differentiating between samples; abstract factor analysis for determining the number of components; and least squares fitting and targeted factor analysis, both using reference spectra, for identifying and quantifying the components in the mixtures. The ARTHUR package (1) for multivariate statistics has been extensively proven reliable in our laboratory. The other three approaches have been carefully tested using synthesized data from the individual reference spectra. For the test data, abstract factor analysis (1) predicted the correct number of components in a set of spectra almost routinely. Both the least squares approach (2) and the targeted factor analysis (3) have correctly identified species in the mixtures with a 90 percent record. Quantitation for the synthesized data was acceptable and follows the values originally reported by Fausett and Weber (2).

3. Factor Analysis of Nonflaming Mixture Analysis

Twenty mixtures (2 unique sets) each containing up to 4 components were formulated at various compositions from the 10 original polymers. Analysis of the pyrolysis data from these 20 mixtures by multivariate statistics showed that each mixture produced a unique Py-MS pattern. The spectrum for each mixture was first visually analyzed using the mass spectral peaks characteristic of the components of the mixture. Next, principal components factor analysis was done. In order to extract the chemical information, a series of graphical rotations were performed on the first six factors. Figure 1 represents the spectrum generated by rotation of factor 1 by 135° with respect to factor 2. The upper part of this spectrum corresponds to polyurethane GM-29. The spectrum of the original GM-29 is shown in Figure 2. Similar data was extracted for most species contained in the mixtures. In general, this approach was used to predict the components in the mixtures with 88 percent correctness.

A least squares approach was also applied to the pyrolysis data for quantitation (3). The program used reference spectra for a best fit to the mixture mass spectrum. The results of the least squares analysis showed that some materials such as PVC in relation to the amount in the mixture produces large quantities of polymeric aerosol. Others are affected by accompanying materials in the mixture and show no predictable trend.

In addition, a series of aerosols collected from flaming combustion has been analyzed using a similar approach. The data generated from aerosols from the Potts furnace were extremely variable and gave factor analysis results which were difficult to interpret. Aerosols from the NBS furniture calorimeter were pyrolyzed to give data which were more like the results generated from the nonflaming experiments. In general, the data from the Potts furnace in the flaming mode showed a more complete degradation of the material.

4. Samples Containing Gasoline

A new approach has been developed for analyzing aerosol samples suspected of containing gasoline residues. In the past only the polymeric material has been used in the analysis. The new procedure now uses the volatile compounds. The filters after collection are placed in glass jars with a Curie point wire containing activated carbon glued on the end. Experiments have been completed on several mixture sets containing up to three components plus gasoline. Figure 3 shows the volatile spectrum of gasoline. Important in this spectrum are the peaks between m/z 130-160. Figure 4 shows the factor gasoline spectrum from one of the mixture sets spiked with gasoline. In all data examined to date, a factor gasoline spectrum has been obtained. Although some peaks may not appear, the gasoline spectrum can easily be recognized.

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"Characterization of Aerosols from Nonflaming Combustion," presented at American Society of Mass Spectrometry, Boston, Massachusetts (1983).

"Characterization of Aerosols from Nonflaming Combustion," submitted to Analytical Chemistry.

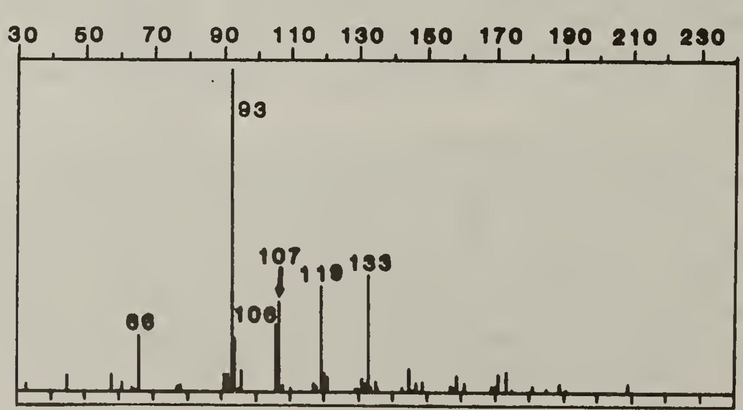

Figure 1. Factor spectrum of polyurethane.

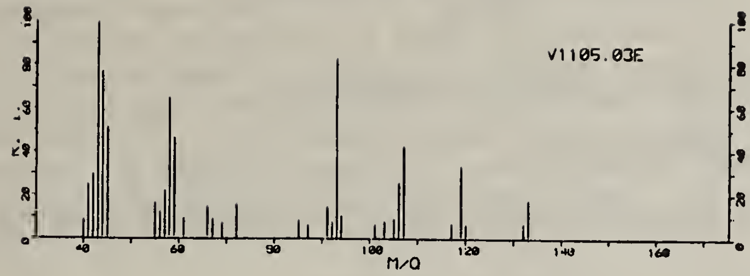

Figure 2. Py-MS spectrum of polyurethane

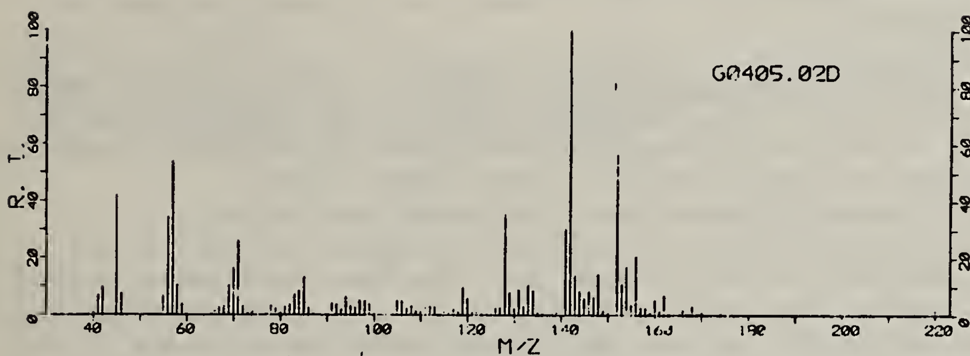

Figure 3. Spectrum of gasoline vapors.

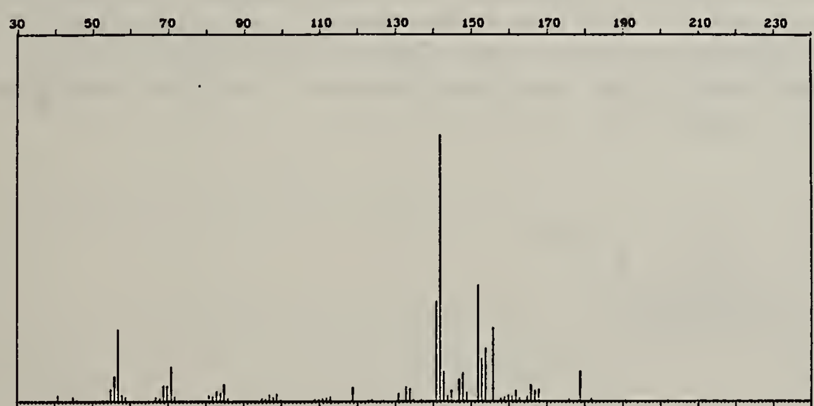

Figure 4. Factor spectrum of gasoline.

CENTER FOR FIRE RESEARCH
NATIONAL BUREAU OF STANDARDS
FY 83

Institution: Factory Mutual Research Corporation

Contract Number: NB 82-NADA-3041

Contract Title: Computer Modeling of Aircraft Cabin Fire Phenomena

Principal Investigator: Dr. M. A. Delichatsios
Research Specialist
Factory Mutual Research Corporation
Norwood, MA 02062

NBS Scientific Officer: Kenneth Steckler

Technical Abstract

The objective of this program is to develop simple integral models for wall and ceiling fires, including radiation effects which can be incoporated in the form of computer subroutines into existing codes for the prediction of fire growth in aircraft cabin fires.

The major accomplishments over the current period are:

1. The integral model for turbulent burning on a vertical wall, which was developed in the previous year, has been extended to include flame and external radiation interactions[1]. The predictions of the model agree within ten per cent with experimental measurements of the pyrolysis rate on vertical PMMA wall fires[1].

2. It has been shown, based on simple dimensional arguments, that for all buoyant diffusion flames (including wall fires) the flame height depends only on the heat release rate and it is independent of the stoichiommetry[2]. In addition, for laminar or turbulent, buoyant wall fires it has been shown by comparison with experiments (turbulent) or exact solutions (laminar) that the flame height is independent of the extent of the pyrolysis region if the flame extent is much larger (by a factor of 3) than that of the pyrolysis region. For this case the wall flame height, h_f is given by:

laminar flames:

$$h_f = 0.16 \left(\frac{Q_c'^4}{\rho_o^4 C_p^4 T_o^4 \nu_o^2 g} \right)^{1/3} \qquad (1)$$

turbulent flames:

$$h_f = 4.65 \left(\frac{Q_c'^2}{C_p^2 T_o^2 \rho_o^2 g} \right)^{1/3} \qquad (2)$$

In these equations, $\dot{Q}_c'$ is the heat release rate per unit width and the other parameters are properties of the ambient air; g is the gravitational constant.

3. Based on an analytical model of pyrolysis of charring materials (developed under another contract), critical conditions have been formulated for self-sustained burning and flame propogation on vertical charring walls[3]. The maximum depth of char before pyrolysis ceases is determined. In addition, critical conditions of flame propagation and extinction downstream of the pyrolysing segment are developed. Such parameters can be used to characterize the flammability of charring materials.

Reports and Papers

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2. Delichatsios, M.A., "Flame Heights in Buoyant Diffusion Flames and a New Material Flammability Number," FMRC Memorandum, March 30, 1983.
3. Delichatsios, M.A., "Critical Conditions for Sustained Burning and Flame Propagation on Vertical Charring Walls," for presentation at the ASME Meeting, Boston, MA, November 1983.

Institution: Factory Mutual Research Corporation

Grant No.: NB79NADA0014, Amendment/Modification No. 3

Grant Title: Determination of Fuel Parameters for Fire Modeling

Principal Investigator: Archibald Tewarson, Ph.D.
Manager, Flammability Section
Factory Mutual Research Corporation
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Norwood, MA 02062

Other Professional Personnel: J. Steciak and S.D. Ogden

NBS Scientific Officer: William J. Parker

Technical Abstract

The objective of the study was to examine the influence of air contaminants on the fuel parameters. Polymethylmethacrylate (PMMA), cellulose and polyvinylchloride (PVC) were used as fuels.

The replacement of nitrogen by CO_2 in concentrations of up to 7% did not significantly change the fuel parameters as long as the volume concentration of oxygen remained the same. The effect of CO_2 as a contaminate was important when it resulted in a reduction in O_2 concentration.

For enclosed spaces, a ventilation parameter, ϕ, was defined as the ratio of the total mass flow rate of oxygen introduced into the enclosed space to the mass consumption rate of oxygen for stoichiometric combustion. The flame height, combustion efficiency, product generation efficiencies and oxygen consumption in the combustion process were found to be proportional to ϕ^{-n}. For flame height, Pagni's relationships were used [1-4]. The flame height was found to vary with $\phi^{-1.5}$ and to depend on the fuel property $(L/k_{O2})^{-n}$; in agreement with Annamalai and Sibulkin [5], L is the actual heat of gasification and k_{O2} is stoichiometric mass oxygen-to-fuel ratio, although the value of n under our experimental conditions was different from the theoretical n value of Annamalai and Sibulkin for different geometry.

The flame height was found to vary with the 1.5 power of the net heat flux absorbed by the fuel. Air velocity was found to have a significant effect on the flame height.

The combustion efficiency was found to decrease with decrease in ϕ. The fraction of total mass flow rate of oxygen consumed in the combustion process was found to vary with $\phi^{-1.2}$.

The ratio of the generation efficiency of the product of incomplete combustion (CO, hydrocarbons and "smoke") to the generation of CO_2 was found to follow the relationship:

$$f_j / f_{CO2} \sim \phi^{-n} \quad (1)$$

where f is the generation efficiency, and j is either CO or hydrocarbons or "smoke."

The experimental n values are listed in Table 1 for PMMA and PVC.

Table 1

Experimental n Values in Equation (1)

	n	
	PMMA	PVC
f_{CO}/f_{CO_2}	~4	~1
$f_{hydrocarbons}/f_{CO_2}$	~4	~2
f_{smoke}/f_{CO_2}	~3	-
$f_{others*}/f_{CO_2}$	~2	-

*others: carbon compounds other than CO_2, CO, hydrocarbons and "smoke."

The data in Table 1 indicate that the generation of CO and hydrocarbons is more sensitive to ϕ for PMMA than it is for PVC. Also, for PMMA the generation of "smoke" or carbon compounds other than CO_2, CO, hydrocarbons and "smoke" is not as sensitive to ϕ as the generation of CO and hydrocarbons.

It should be pointed out that, although the data are useful for enclosure fire models, they are very limited and are only experimental. For general applicability, data for other fuels including larger-scale fire test data and calculations are needed.

Reports and Papers

Tewarson, A. and Steciak, J., "Fire Ventilation," National Bureau of Standards, Washington, D.C., Technical Report NBS-GCR-83-423, February 1983, National Technical Information Service, Springfield, Virginia, Order No. PB83-183293. (Paper based on the report is accepted for publication in Combustion and Flame).

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CENTER FOR FIRE RESEARCH
NATIONAL BUREAU OF STANDARDS
FY 83

Institution: Factory Mutual Research Corporation (Joint program with Harvard; see Harvard's summary)

Grant No.: NB82NADA3030 - NBS Scientific Officer: J. Quintiere

Title: Prediction of Fire Dynamics

Principal Investigator: R. Friedman (FMRC); H. W. Emmons (Harvard)

Other Professional Personnel: See individual tasks

Summary Comments:

The program consists of five tasks. The first task, by Harvard, is the refinement of a computer model of a growing fire in an enclosure; the remaining tasks, by FMRC, are to develop critical scientific knowledge elements needed to quantify a growing fire. The bulk of the work is concerned with a more accurate characterization of a fire plume with regard to entrainment rate, distribution of incompletely burned chemical species, and radiation emitted. One task is particularly concerned with charring combustibles, which are of great practical importance.

Task 1: The Prediction of Fire in an Enclosure (See Harvard's abstract)

Task 2: Vitiation and Entrainment in Pool Fires

Task Leader: Michael A. Delichatsios

Technical Abstract

The objectives are: 1) to measure precisely the entrainment rates in turbulent flames; 2) to measure the influence of vitiation in the air or fuel side on turbulent flames. A reliable procedure has been developed for measuring entrainment in turbulent jet flames. The entrainment rate in turbulent fires is required for implementation of computer codes concerning fire growth in enclosures; the entrainment rate affects fire growth rate and development of the smoke layer. In existing codes, entrainment in turbulent fires is calculated by using the Taylor hypothesis: entrainment velocity is proportional to maximum velocity at any height in the fire plume. Existing data are not sufficient to verify the Taylor hypothesis in turbulent diffusion flames. Recent data provided entrainment values varying by a factor of three for comparable diffusion flames.

In our setup, a buoyant flame jet burned under quiescent

conditions inside the enclosure[1] constructed for this project. The supply air is provided by a blower at the bottom of the enclosure through four 15 cm ducts, a stone-bed and a screen. The supply air flow rate can be varied by using a variable-voltage motor to drive the blower. The air flow rate is measured at the inlet of the tank by concentration measurements of a diluent injected upstream of the blower. At the upper part of the tank an orifice plate has been installed with a variable opening size: 15, 20, 25, 30.5, 40.6 and 56 cm. The base of the turbulent jet flame can be moved relative to the orifice plate. We have taken extreme measures to eliminate scatter in the data due to (thermal) gravity effects; these measures include the cooling of the pressure tubes, the orifice plate, and the walls of the tank.

The principle of the measuring technique is the following: the mass entrainment rate is that flow rate of the supply air for which the pressure differential across the orifice plate is zero. This technique will measure the true entrainment rate only if the orifice size is somewhat larger than the plume dimensions at the orifice level. In this case, large-scale eddies associated with the plume will flow freely through the opening.

Figure 1 shows measurements of the entrainment rate for two orifice openings as a function of the distance from the source of the buoyant jet plume. We think that the reason the entrainment rates differ for the two orifices is that there are still some residual disturbances in the ambient flow. Presently, two modifications are being made in order to eliminate any such effects:

a) two additional screens at the entrance of the supply air are being installed in order to further reduce large-scale vorticity in the ambient air;

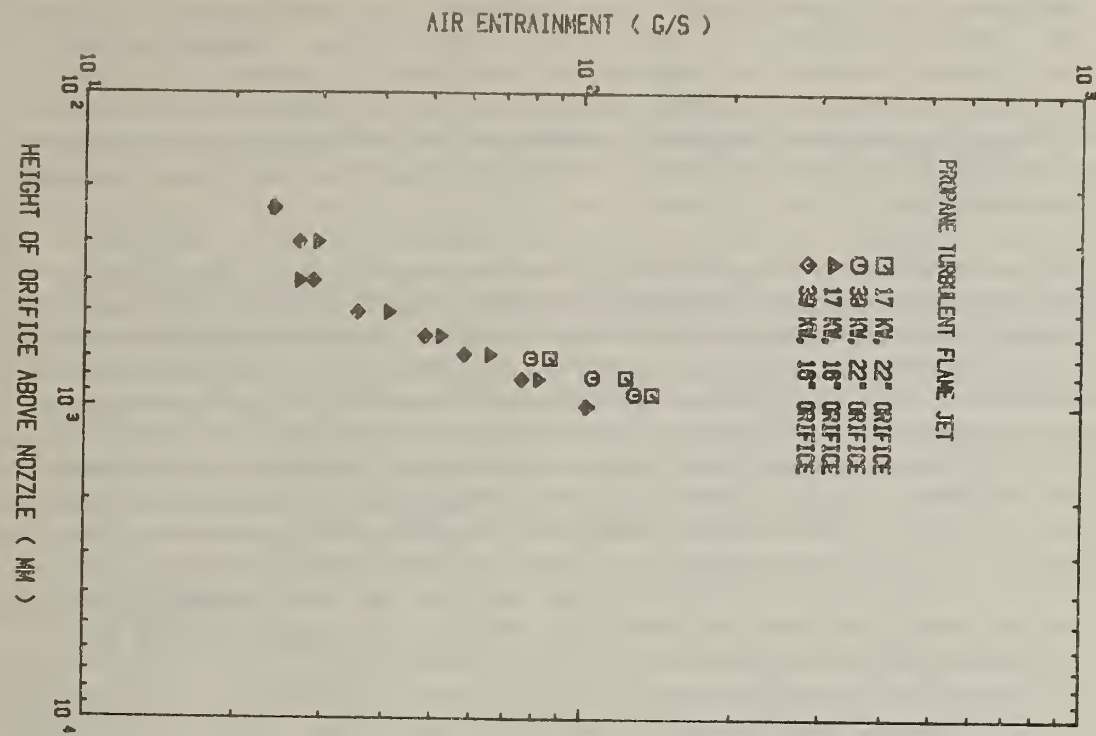
b) The water-cooled walls will be maintained at the identical temperature as the supplied air, in order to eliminate any buoyant drafts coming from the walls of the tank.

In conjunction with previous measurements[2] of the heat release rate as a function of distance from the nozzle, the entrainment measurements will be used also to determine the effectiveness of mixing and combustion in a turbulent jet flame. Once we have completed these entrainment measurements we will examine the effects of ambient/fuel vitiation on the radiation from the same buoyant turbulent fuel jets.

Reports and Papers

1. Santo, G. and Delichatsios, M.A., "Effects of Vitiated Air on Radiation and Completeness of Combustion in Propane Pool Fires," submitted for publication in Fire Safety Journal.

2. Tamanini, F., "Direct Measurements of the Longitudinal Variation of Burning Rates and Product Yield in Diffusion Flames," accepted for publication in Combustion and Flame (summer 1983).



Task 3: Chemical Scaling of Pool Fires

Task Leader: Lawrence Orloff

Technical Abstract:

The objective is to model the burning of large pool fires by using chemical concentration profiles of major species (O_2, CO_2, CO, H_2O, H_2, THC) obtained from corresponding medium-scale fires. By recourse to Froude modeling, these concentration profiles are expected to be scaled in large pool fires.

Accurate gas sampling and species concentration techniques were developed in 1982. A special water-cooled sampling probe was tested in order to ensure constant mass flow sampling in sooty fires. The probe features a narrow passageway in order to very rapidly cool the gases to achieve constant mass flow sampling of the fluctuating composition. Heavily soot-laden sample gases present unusual challenges of flow restriction and filtration. The experimental methods developed here with propylene fires should also apply to many real-world combustibles.

Soot concentration profiles have been measured in Task 4. Such soot data is important to the current chemical scaling and material flammability studies because it is the thermal radiation from soot that controls burning. Markstein has observed a knee in curves of soot concentrations at a fixed location vs. pyrolysis rate. There appears to be a critical fuel blowing rate that engenders reduced oxygen concentration, reduced burning and lower soot temperatures. Concentration data for gaseous species in experiments replicating Markstein's pool fires are being measured in this study in order to describe the conditions enhancing or retarding soot formation in turbulent fires. This aspect of the study should provide insights to effects of fuel blowing on flammability.

The molecular species directly measured are O_2, CO_2, CO, H_2O and total hydrocarbons; H_2 is inferred from the sample thermal conductivity and from gas chromatographic analysis; soot concentrations were measured by a fiber-optic probe measurement in Task 4; an average flame temperature is inferred from a thermocouple attached to a 6 mm copper sphere. Measurements of species concentration profiles have been obtained for 38 cm diameter propylene, propane, and methane pool fires with and without a lip. There is some indication that species concentrations correlate with oxygen depletion, and that CO_2 concentration correlates well with measurements of soot concentration carried out in Task 4. Further work to establish the validity of the concentration data and to test the chemical modeling concept with measurements in 0.8 m diameter fires is planned.

Task 4: Radiation from Flames

Task Leader: George H. Markstein

Technical Abstract

In many fires, energy transfer from the flame to the fuel and to the surroundings occurs predominantly by thermal radiation. The main objective of the present task is the development of techniques for measuring the pertinent radiative properties of fires, and to provide a quantitative basis for predicting the resulting radiative energy transfer. The rate of fire growth and the spread of fire to new fuel elements depends critically on this energy transfer, and its quantitative assessment is thus essential for estimating fire losses and threat to life safety.

Recent work under this task has concentrated on measurements with a fiber-optic absorption probe on gaseous-fuel pool fires. Deficiencies of an earlier design of the probe caused by thermal expansion effects on optical alignment were eliminated by extensive redesign of the device.

The scaling of the radiative absorption coefficient with pool size was investigated by performing vertical centerline traverses with propylene pool fires of 381 mm dia for fuel flow rates ranging from 230 to 1400 mℓ/s (18 to 110 kW fires) and of 762 mm dia for flow rates ranging from 1300 to 3465 mℓ/s (102 to 273 kW fires). It was found that the maximum values of the absorption coefficient scaled with the square of pool diameter so that the data for this set of measurements fell on a single graph when plotted against fuel flow velocity. An abrupt decrease of slope of the plot above a velocity of 5 mm/s was tentatively interpreted to correspond to the flow above which air cannot penetrate to the pool surface.

The influence of fuel type was studied by performing vertical centerline traverses with 50 kW 381 mm dia pool fires of ethane, propane and ethylene in addition to propylene. It was found that the logarithm of the maximum absorption coefficient correlated linearly with the length of laminar diffusion flames at the soot point. Although currently established only for a single rate of heat release and for four fuels, this finding opens up the important possibility of predicting radiative properties of large turbulent fires from data obtained with small laminar flames. A major portion of future work under this task will therefore be concerned with the extension of such correlations to a wider range of fuels and burning conditions. Work currently under way has already shown that a similar correlation exists between the radiative fraction of total heat release rate of turbulent fuel-jet diffusion flames and soot-point flame length of laminar flames.

Reports and Papers

1. Markstein, G.H., "Measurements on Gaseous-Fuel Pool Fires with a Fiber-Optic Absorption Probe," FMRC Technical Report RC83-BT-1, March 1983; also, paper to be presented at this conference.

Task 5: Flame Radiation from Charring Fuels

Task Leader: J. de Ris, R. L. Alpert

Technical Abstract

There is a demonstrated need for a standardized measurement to characterize radiative emission from the flames of a burning material. Such flame emission is the critical factor in determining material flammability. Accordingly, a new flammability apparatus employing a 0.3 m x 0.3 m vertical sample is being developed for the accurate measurement of heat transfer to a vertical surface above the sample and flame emission-absorption coefficient and radiation temperature in this region. Measurements of piloted ignition time, transient heat release rates, and turbulent flame heights will also be obtainable. These measurements will serve as an input to our recently developed analytical models[1,2] for the transient pyrolysis rate of charring materials and for the critical conditions which allow charring materials to undergo sustained burning and wind-aided flame spread. The calculated critical conditions based on measured properties of the .3-m-high charring material should enable predictions to be made of material flammability under a variety of end-use conditions.

Construction of the new flammability apparatus is not yet complete. However, the instrument to be used for the critical flame radiation measurement in the heat feedback region has been constructed and

is ready for testing. This radiometer will simultaneously measure flame absorption coefficient and radiation temperature profiles across a two-dimensional wall fire. We have also been developing, in consultation with NBS personnel, a high-intensity, gas-fired radiant panel as an appropriate source of external radiation for the flammability apparatus.

In the program for theoretical prediction of material flammability from property measurements, several analytic expressions were obtained for the various stages of transient charring. These expressions are being used to infer effective charring properties from rate-of-heat-release measurements. It is planned to compare the analytical expressions with exact numerical solutions of a set of idealized equations using the SPYVAP code[3] developed previously.

Reports and Papers

1. Delichatsios, M.A. and de Ris, Jr., "An Analytical Model for the Pyrolysis of Charring Materials," paper to be presented at the CIB Meeting, Sweden, May 1983.

2. Delichatsios, M.A., "Critical Conditions for Sustained Burning, and Flame Propagation on Vertical Charring Walls," paper submitted for presentation at the ASME Winter Annual Meeting, Boston, MA, November 1983.

3. Tamanini, F., "A Numerical Model for One-Dimensional Heat Conduction with Pyrolysis in a Slab of Finite Thickness," Appendix A of The Third Full-Scale Bedroom Fire Test of the Home Fire Project - Vol II," Ed. by A.T. Modak, Factory Mutual Research Corporation Technical Report, Serial No. 21011.7, November 1976.

CENTER FOR FIRE RESEARCH

NATIONAL BUREAU OF STANDARDS

FY 83

Institution: Harvard University

Grant No.: NB82NADA3030

Grant Title: The Prediction of Fire Dynamics

Principal Investigators: Professor Howard W. Emmons, Division of Applied Sciences, Harvard University, Pierce Hall, Cambridge, MA 02138

Dr. Raymond Friedman, Factory Mutual Res. Corp., 1151 Boston-Providence Tn., Norwood, MA 02062

Other Professional Personnel: Dr. Henri E. Mitler, H.U.
Mr. Richard I. Land, H.U.
Mr. Arvind Atreya, Ph.D. Candidate, H.U.

NBS Scientific Officer: Dr. John Rockett

Task 1: The Prediction of a Fire in an Enclosure

Task Leaders: Dr. H.E. Mitler, Prof. H.W. Emmons

Technical Abstract:

An integral model analysis of the time-dependent ceiling-jet produced by the hot plume ascending from a fire in a corridor has been published as a technical report. It is preliminary, because it makes a number of simplifying assumptions, two of which are quite unrealistic: entrainment of the adjacent gas layer (air for the initial stages and a hot layer for the later stages, for the confined-ceiling case) has been neglected, as well as heat transfer to the surroundings. This preliminary analysis already shows, however, that the buoyant acceleration of the "jet" is substantially greater than the Reynolds stresses at the ceiling and confining walls, and that inertia cannot be ignored. Another interesting finding is that even for the steady-state case, no analytic solution of the equations is possible when there is friction. Hence a numerical technique must be used to solve the coupled PDE's describing the flow. The method used here is a generalization of one developed by Lax and Wendroff. The results of this limited analysis are reasonable, but well-known difficulties produced by the large gradients at the front end of the jet make the technique less than wholly adequate, so that further refinements will be required before the inclusion of more realistic physics is undertaken.

A restructured, multi-room version of Computer Fire Code V (Mark 5) was completed last year, and dubbed Mark 6. Not much has been done with it since, except that a number of bugs have been found and fixed. A "handbook" of materials properties needed by the model - mostly for flammable materials - has been started, and incorporated for use by

Mark 6 as a separate file which can be accessed by the input program. At the moment, it gives relevant thermophysical data for methane, propane, acetone, propanol, kerosene, heptane, methanol, PE, P.U. foam #7004, POM, PMMA, PP, PS, red oak, and marinite.

A number of additions have been made to Mark 5, on the other hand. Among them: the algorithms used there for convective heat transfer to objects, walls, and ceiling were very crude, and there was none at all for heat exchange between a heated floor and the adjacent - generally cooler - layer. The latter is needed in order to permit the lower layer to heat up (the other mechanism being mixing at the doorway). Reasonably good though simple expressions were found from the literature for the convective heat transfer to horizontal surfaces, vertical surfaces, floor, and lower and upper walls; these have been put into new algorithms. For the convective heating or cooling of horizontal surfaces, it was found necessary to assume that the gas temperature varies gradually from hot to cold in a transition zone (as is indeed the case in reality). L. Cooper's algorithm for the convective heat transfer from a fire to a confined ceiling has been slightly simplified and generalized. Three of these algorithms have been incorporated into a version now called Mark 5.2, and the rest will soon follow. Mark 5.2 also has a photoelectric detector response algorithm now, as well as a much-improved contact-ignition algorithm. A forced-vent algorithm was devised and inserted into the program as subroutine FORV. Any desired time-dependent volumetric flow through that vent, $\dot{V}(t)$, can be approximated as a piecewise linear function, and is prescribed through INPUT. VENT interpolates the values of $\dot{V}(t)$ at any time t, and (as usual) finds the pressure in the room required to give that flow through the unforced vent(s), which balances mass. Runs with this new algorithm are now (May 1983) being compared with a set of forced-vent experiments carried out at Lawrence Livermore National Labs, and preliminary analysis is very promising.

Technical Reports and Papers

1. Mitler, H.E., "The Time-Dependent Ceiling-Jet in a Corridor," H.F.P. Technical Report #55 (Dec. 1982)
2. Emmons, H.W., "The Ingestion of Flames and Fire Gases into a Hole in an Aircraft Cabin for Arbitrary Tilt Angles and Wind Speed," H.F.P. Technical Report #52 (1982)
3. Emmons, H.W., "The Analysis of a Tragedy," to be published in Fire Technology, NFPA (1983)

Task 1a: Pyrolysis, Ignition, and Fire Spread on Horizontal Surfaces of Wood

Task Leader: Arvind Atreya

This study is an attempt to understand the complicated process of transient fire growth on horizontal surfaces of wood and the related phenomena of pyrolysis and ignition under the conditions of externally supplied radiation. The anisotropic, inhomogeneous and charring properties of wood made this work especially challenging.

In this work, experimental techniques and methods were developed. Numerous experiments on ten different kinds of wood were conducted under various levels of external radiation, with the purpose of identifying the controlling mechanisms for spread, and to obtain reliable chemical and physical data. The problem was divided into three components:

(a) Solid phase thermal decomposition (PYROLYSIS)
(b) Conditions for flame spread (IGNITION)
(c) Heat and mass transfer to the unburned zone (FIRE SPREAD)

These component phenomena were then investigated both theoretically and experimentally.

Finally, with the understanding of the controlling mechanisms discovered for fire spread on wood, these component phenomena were recombined to solve the overall transient fire spread problem. Since we are now able to predict the flame radius as a function of time by an appropriate transient flame spread theory, and mass flux by a pyrolysis theory, then the correlations of experimental results can serve as a basis of obtaining other physical and chemical quantities of interest, like burning efficiencies, chemical species production rates, etc.

Technical Reports and Papers

1. Atreya, Arvind, "Pyrolysis, Ignition, and Fire Spread on Horizontal Surfaces of Wood," Ph.D. Thesis, 1983.

CENTER FOR FIRE RESEARCH
NATIONAL BUREAU OF STANDARDS
FY 83

Institution: National Fire Protection Association, Quincy, MA

Contract No.: EMW-C-0874

Contract Title: Investigation and Analysis of Major Fires

Principal Investigators: A. Elwood Willey, Project Administrator
Thomas J. Klem, Division Director, Fire Investigations and Applied Research Division
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Other Professional Personnel: James R. Bell, Legislative Technical Specialist
James K. Lathrop, Life Safety Code Specialist
Wilbur Walls, Flammable Gases Specialist
Martin Henry, Flammable Liquids Specialist
Charles E. Zimmerman, Fire Protection Engineer
Robert Benedetti, Chemical Specialist
Robert Carter, Chief Fire and Arson Investigations Specialist

NBS Scientific Officer: Richard Bukowski
Edward Wall, Chairman, Working Group
United States Fire Administration
Federal Emergency Management Agency
National Emergency Training Center

Technical Abstract: Under a cost-sharing contract between the National Fire Protection Association, National Bureau of Standards and Federal Emergency Management Agency, in-depth field investigations are

conducted of selected fire incidents. For each investigation an analysis is made of fire causal factors, spread factors, materials contributing to fire and smoke propagation, people movement and actions taken, fire propagation as a function of time, factors affecting fire propagation, performance of fire protection equipment, key life safety and property protection problems and of contributing factors resulting in loss of life and property damage. In addition to field work by investigators with fire protection engineering background, other specialists are consulted, including NBS researchers. In some cases, samples from fire scenes are tested for fire hazard characteristics at NBS and results included in reports. Briefings by fire investigators are provided FEMA/NBS regarding incident facts and technical aspects of interest.

Following submittal of contract reports to FEMA/NBS, reports are published and distributed by NFPA to ensure that the facts and lessons learned are made available to the fire community in a timely manner. In addition to the literature, background data from the investigations is available at NFPA for research purposes.

This contract is the sixth in a series of NFPA/NBS fire investigation contracts since 1972. The four most recent contracts have also involved the FEMA, with funding shared between the two agencies and NFPA in a cooperative effort. Since the original contract, 91 incidents have been investigated and reports prepared.

Potential Applications

This in-depth investigation and analysis activity gives an improved understanding of fire growth and development, smoke development and spread, and the actions of people in actual fire situations. The information gained has many uses both in the fire safety field and in the research community.

Reports contain commentary on the performance of fire detection and extinguishing equipment, building assemblies and systems and various measures of fire control. The studies provide an opportunity to measure the performance of requirements in national consensus fire safety codes and standards. Lessons learned from these investigations are of use to fire safety practitioners and researchers. Indicators for additional research are often included in reports.

In addition to the use of information by NFPA technical committees and in technical programs, information from investigations is utilized in training films and slide packages for use by the fire service and fire safety practitioners.

Future Milestones

Investigations are in progress of six incidents and reports will be prepared. These active studies include:

- An early morning fire in the Harrison County Jail in Biloxi, Mississippi, on November 8, 1982, was responsible for the deaths of 29 inmates and injury to 59 others including inmates, jail officers, sheriff's deputies, police officers and fire fighters. The fire, reported to the Biloxi Fire Department at 1:31 a.m., originated in an occupied isolation cell. The isolation cell walls and door were padded with a sprayed-on rigid foam material tentatively identified as polyurethane foam.

  Although the fire was confined to the cell of origin, thick, black smoke was able to spread rapidly throughout the jail, trapping inmates in their cells. The jail officer attempting to unlock cell doors to release inmates was overcome in the smoke filled corridors.

  The fire, of suspicious origin, was fed primarily by the padding materials of the isolation cell. The rapid spread of fire beyond the room of origin soon resulted in untenable conditions throughout the jail. Delays were experienced in the release of remaining prisoners once the fire reached this magnitude.

- Gasoline vapors cascading from a storage tank during a filling operation in Newark, New Jersey on January 7, 1983 were ignited and ultimately resulted in several small explosions and one large explosion. As a result, an oil company employee was killed. Further, the explosion resulted in the destruction of four gasoline storage tanks and consumed approximately 3 million gallons of gasoline before being brought under control.

  The explosion occurred on Thursday, January 7, 1983 during a tank filling operation. The scheduled delivery was for approximately 1.6 million gallons that would be completed within approximately six hours. At the time of the filling operation, two terminal operators visited the tank as the expected fill time approached. Upon arriving at the scene, the operators discovered that the tank was overflowing. Terminal operators began the emergency shut-down procedures for the tank. Sometime during the fire department response to the scene, ignition occurred. The blast had a great deal of force in that a remote storage tank was flattened by the impact. In addition, other reported damage included flattened railroad cars, destruction of a drum refinishing plant, a truck terminal building, and the destruction of several trucks and automobiles which were incinerated in the general area of the fire. In addition, the impact of the blast damaged several structures surrounding the industrial area.

- An early morning fire in the Jefferson Dormitory on the campus of the College of William and Mary, Williamsburg, Virginia, on January 20, 1983, forced the evacuation of the building's 184 occupants into 15 degree Fahrenheit weather and led to an estimated $4 million loss to the structure and contents. Prompt reaction to the manual fire alarm system and to the sounding of evacuation of the dormitory resulted in no injuries to any of the occupants. The fire was reported to the Williamsburg Fire Department at 1:13 a.m. The fire spread through the sprinklered building in concealed combustible spaces beyond the reach of the building's sprinkler system. Efforts of fire fighters to locate and extinguish fire in concealed spaces above ceilings and behind wall surfaces were unsuccessful. After approximately 2 hours of interior fire fighting efforts, fire fighters were forced to withdraw from the building when the corridor floor on the first floor collapsed and cracks formed in the exterior bearing walls. The developing fire caused the loss of the entire west wing of the building and all of the attic and roof, with extensive damage to the remaining east wing of the structure.

- An early morning fire in a community-based residential facility (boarding home) resulted in six elderly residents losing their lives. The fire occurred on Monday evening, February 7, 1983, in Eau Claire, Wisconsin, a small college community 85 miles southeast of the Minneapolis - St. Paul area. The building was a 100-year old Victorian-style, 2 1/2-story frame dwelling which had recently been converted from a single family structure to a boarding home. The facility provided care for eleven elderly residents occupying rooms on the first floor and second floor.

The cause of the fire is currently listed as undetermined by the Eau Claire Fire Department. The investigation is continuing but it is believed to have been an accidental ignition of furnishings. The fire was discovered when one of the night managers was awakened by a smoke detector operating on the first floor. Leaving her second floor room, and descending to the first floor, she observed a developing fire within the living room (lounge) portion of the building. At the time of discovery, the manager could see a "glow" in the area of a couch and feel the heat from the fire on her face. She returned to her second floor room to arouse the other night manager. A phone call was made to the owner of the facility and evacuation procedures were then initiated.

- Another in a long series of untreated wood-shingle roof fires in Texas and Southern California occurred in Dallas, Texas on March 21, 1983. The fire at the Willow Creek Apartments in Dallas started in an unoccupied apartment, caused by a malfunction of electrical wiring in an exterior apartment wall. The fire spread upward into the attic and advanced rapidly both internally and externally along the roof. The fire spread to another building downwind and against the wind to an adjoining building to the north. The roof of the building to the north had burned previously in August of 1980.

  The Dallas Fire Department controlled the fire with a five-alarm response supplemented by two special calls for equipment and with effective use of a helicopter for observation. Four buildings were severely damaged. Another seven buildings had minor roof damage or roof spot fires that were extinguished. The preliminary estimate of damage to approximately 125 apartments units was $6.6 million.

  Although the City of Dallas has an ordinance requiring fire retardant Class C roofing on new construction, this fire shows that the problem of untreated wood-shingle roofs on existing buildings will continue in Dallas for many years.

- A half-way house fire in Worcester, MA, resulted in 7 fatalities and injuries to 26 persons. Apparently, the occupants of the half-way house were deinstitutionalized mental patients from a nearby facility.

The fire, accidental in nature, was reported at 02:21 on the second floor of the converted single-family dwelling, three stories in height. Early reports indicate that the dwelling was a complying facility to the lodging home occupancy of the State of Massachusetts Building Code. There were smoke detectors and a fire alarm system within the building.

Reports and Papers: Under this contract the following investigation reports have been submitted to FEMA/NBS:

Bell, James R., "Rockefeller Park Towers - Cleveland, Ohio - January 5, 1982 - 5 Fatalities. (Summary Investigation)

Best, Richard, "Star Elementary School BLEVE - Spencer, Oklahoma - January 19, 1982 - 7 Fatalities". (Limited Investigation Report)

Bell, James R., Klem, Thomas J., and Willey, A. Elwood, "Westchase Hilton Hotel - Houston, Texas - March 6, 1982 - 12 Fatalities."

Best, Richard L., "K Mart Corporation - Distribution Center Fire - Falls Township, PA - June 21, 1982".

Bell, James R., "Dorothy Mae Apartment Hotel Fire - Los Angeles, CA - September 4, 1982 - 25 Fatalities." (Summary Investigation Report)

Bell, James R., "Perrys' Domiciliary Care Home - Pittsburgh, PA - October 28, 1982 - 5 Fatalities." (Summary Investigation Report)

Bryan, Dr. John L., "An Examination and Analysis of the Dynamics of the Human Behavior in the Westchase Hilton Hotel Fire, Houston, Texas on March 6, 1982".

Preliminary Reports

"The Westchase Hilton Hotel Fire, Houston, TX, March 6, 1982"

Published Reports

Best, Richard L., Reconstruction of a Tragedy - Beverly Hills Supper Club Fire, NFPA, 1978.

Demers, David P., Fire In Syracuse: Four Fire Fighters Die, NFPA, 1979.

A Study of the Baptist Towers Housing for the Elderly Fire, NFPA, 1973.

Best, Richard L. and David P. Demers, Investigation Report on the MGM Grand Hotel Fire, Las Vegas, Nevada, November 21, 1980, NFPA, 1982.

Bryan, John L., An Examination and Analysis of the Dynamics of the Human Behavior in the MGM Grand Hotel Fire, Clark County, Nevada, November 21, 1980, NFPA, 1982.

Bell, James R., Klem, Thomas J. and Willey, A. Elwood, Investigation Report, Westchase Hilton Hotel Fire, Houston, Texas, March 6, 1982, NFPA, 1982.

Bryan, John L., An Examination and Analysis of the Dynamics of the Human Behavior in the Westchase Hilton Hotel Fire, Houston, Texas on March 6, 1982, NFPA, (Publication pending).

Swartz, J. A., Fahy, R. F. et al, Final Technical Report on the Building Fire Simulation Model, NFPA, 1983.

Articles in NFPA Publications

Fire Investigations Department. "Fire at the MGM Grand." Fire Journal January 1982.

Fire Investigations Department. "Investigation Report on the Las Vegas Hilton Hotel Fire." Fire Journal, January 1982.

Bryan, John L. "Human Behavior in the MGM Grand Hotel Fire." Fire Journal, March 1982.

Hill, Steven. "19 Die in Chicago Hotel Fire." Fire Journal, March 1982.

Bell, James R. "Investigation Report of the Fire at Stouffer's Inn of Westchester." Fire Journal, May 1982.

Fire Investigations Department. "The MGM Hotel Fire - Part 1." Fire Service Today, January 1982.

Fire Investigations Department. "The MGM Hotel Fire - Part 2." Fire Service Today, February 1982.

Fire Investigations Department. "Hilton Fire: A Tragedy Revisited." Fire Service Today, March 1982.

Fire Investigations Department. "Westchase Hilton Fire Claims 12 - A Preliminary Report." Fire Service Today, July 1982.

McKiernan, James V. and Peterson, Carl E. "The Lynn Conflagration - Part 1." Fire Service Today, July 1982.

McKiernan, James V. and Peterson, Carl E. "The Lynn Conflagration - Part 2." Fire Service Today, August 1982.

Best, Richard L. and Walls, Wilbur L. "Hot Water Heater BLEVE in School Kills Seven." Fire Journal, September 1982.

Fire Investigations Department. "Tragedy in Kentucky" (Beverly Hills Supper Club). Fire Journal, November 1982.

Fire Investigations Department. "Fire at the MGM Grand Hotel." Fire Journal, November 1982.

Fire Investigations and Applied Research Division. "Westchase Hilton Investigation. "Fire Service Today, January 1983.

Bell, James R., Klem, Thomas J. and Willey, A. Elwood. "Twelve Die in Fire at Westchase Hilton Hotel." Fire Journal, January 1983.

Fire Investigations and Applied Research Division. "K Mart: Sprinklers vs. Aerosols." Fire Service Today, March 1983.

Best, Richard. "$100 Million Fire in K Mart Distribution Center. "Fire Journal, March 1983.

Bell, James R. "Five Die in Rockefeller Part Towers Fire, Cleveland, OH." Fire Journal, March 1983.

Bell, James R. "24 Die in Los Angeles Residential Apartment Fire." Fire Journal, May 1983.

Best, Richard. "Fire Walls That Failed: The K Mart Corporation Distribution Center Fire." Fire Journal, May 1983.

Recent Papers

Willey, A. Elwood, "Lessons from Recent Hotel Fires", presented before the Opening Session, May 18, 1981, at the 85th NFPA Annual Meeting, Dallas, TX.

Best, Richard L., "Mississauga Train Derailment", presented at the Annual Meeting of the Union of Furtherance of Fire Protection, Leverkusen, Germany, June 16, 1981.

Willey, A. Elwood, "A Preliminary Report - The Westchase Hilton Hotel Fire, Houston, Texas, March 6, 1982", paper presented at the Opening General Session, 86th NFPA Annual Meeting, San Francisco, CA, May 17, 1982.

Case Study NFPA Films and Slide Packages based on contract investigations:

Case Study Slide Packages:

SL - 13, "LP-Gas Explosion, Kingman, Arizona, July 5, 1973"
SL - 22, "Hospital Fire, Osceola, MO., December 3, 1974"
SL - 26, "Three Nursing Home Fires" (Wincrest Nursing Home, Chicago, Illinois, January 30, 1976; Cermack House, Cicero, Illinois, February 4, 1976; Plaza Nursing Centre, Niles, Illinois, February 18, 1976)
SL - 38, "Reconstruction of a Tragedy - The Beverly Hills Supper Club Fire"
"Four Hotel Fires: An Investigative Analysis", Fire Investigations and Applied Research Division

Films:

FL - 35, "Incendio!" (High-rise fire, Sao Paulo, Brazil, February 1, 1974)

FL - 50, "The Beverly Hills Supper Club Fire . . . A Case for Code Enforcement"

FL - 58, "Fire at the MGM Grand"

CENTER FOR FIRE RESEARCH
NATIONAL BUREAU OF STANDARDS
FY 83

Institution: The Pennsylvania State University

Grant Number: NB81NADA2044

Grant Title: An Investigation of Turbulent Fires on Vertical and Inclined Walls

Principal Investigator: Professor G. M. Faeth
Department of Mechanical Engineering
The Pennsylvania State University
214 Mechanical Engineering Building
University Park, PA 16802

Other Professional Personnel: S-M. Jeng, Research Assistant
M-C. Lai, Graduate Assistant

NBS Scientific Officer: H. Baum

Technical Abstract

Introduction - The objective of this investigation is to study the structure and radiation properties of turbulent fires along walls at various inclinations. The findings can be applied to modeling fires within structures, the development of material test codes and the development of fire detectors.

Measurements in both noncombusting and combusting flows along plain surfaces are used to evaluate models of mean and turbulent structure as well as flame radiation properties. Correlations of the results, useful for comprehensive fire models, are also being sought. Combusting flows are emphasized--noncombusting flows are considered to provide systematic model evaluation. Various wall inclinations provide information on stratification--an important aspect of fires within structures.

During this report period, test apparatus was assembled for measurements in noncombusting buoyant flows along surfaces and measurements were initiated. Earlier work with axisymmetric flames was also extended--to aid development of theoretical and experimental techniques.

Apparatus - An infrared monochrometer system (1.8 - 5.5 microns) was developed to measure spectral radiation intensities from flames. Satisfactory operation was verified by initial measurements in axisymmetric flames.

The apparatus for studying noncombusting buoyant flows along surfaces was developed. To avoid errors due to parasitic heat losses in thermal plumes, these buoyant flows are formed with mixtures of air

and sulfur hexafluoride or carbon dioxide. Mean and fluctuating velocities are measured using laser Doppler anemometry. Mean and fluctuating concentrations are measured by Rayleigh scattering. Both techniques are nonintrusive and have excellent frequency response.

Theory - The analysis is based on numerical solution of the boundary layer equations. The conserved-scalar method is used in conjunction with a k-e-g turbulence model. The original version of this model was converted to Favre averaging and recalibrated successfully so that a single set of empirical constants applies for both noncombusting and combusting flows.

State relationships giving scalar properties as a function of instantaneous mixture fraction are needed for analysis. Two methods are being considered: (1) the laminar flamelet method--where properties are found by measurements in laminar diffusion flames; and (2) the partial equilibrium method--where properties are found assuming thermodynamic equilibrium for fuel equivalence ratios less than some critical value and frozen adiabatic mixing for high fuel equivalence ratios.

A narrow-band radiation model is used to predict spectral radiation intensities. The Goody statistical model, in conjunction with the Curtis-Godson approximation for nonhomogeneous radiation paths, is used. Two methods of treating turbulent fluctuations are being examined: (1) use of mean properties--ignoring turbulent fluctuations; and (2) use of a stochastic model where turbulent fluctuations are treated by random sampling.

Results and Discussion - Predictions of scalar properties using the laminar flamelet method were in good agreement with earlier measurements in buoyant methane flames. Based on these present findings, the laminar flamelet method has good potential for predictions of temperature and the concentrations of major gas species in flames. The partial equilibrium method yielded fair results for the same properties when thermodynamic equilibrium was frozen at a fuel equivalence ratio of 1.2. While less effective, the partial equilibrium approach should be valuable in frequent instances where laminar flame data is unavailable for a particular fuel.

Figure 1 is an illustration of predicted and measured monochromatic spectral radiation intensities in a highly buoyant, axisymmetric turbulent methane diffusion flame. This flame appears yellow to the eye and contains measurable quantities of soot, but effects of continuum radiation from soot are small. Therefore, gaseous radiation bands at 1.88 microns (H_2O), 2.7 microns (CO_2 and H_2O) and 4.3 microns (CO_2) are clearly evident. The results are for a radial path at the flame tip--where the mean temperature along the axis is a maximum.

Three predictions are illustrated in Fig. 1, based on: (1) measured mean properties; (2) mean properties using the laminar flamelet method; and (3) fluctuating properties using the laminar flamelet method and the stochastic analysis. Predictions based on stochastic analysis are reasonably good--which is most encouraging. Predictions based on mean properties are lower than both the stochastic analysis and the measurements. This is expected, since radiation is not a linear property in flames; therefore, mean radiation levels are not properly functions of mean properties alone.

Both measurements and analysis indicate that spectral intensities increase when burner flow rates are increased in buoyant flames--in agreement with earlier findings of Markstein.

Conclusions - The present Favre-averaged, k-e-g model provides reasonable predictions of flow structure for flows ranging from forced constant density jets to buoyant flames--with a single set of empirical constants. The laminar flamelet method is promising as a method for handling effects of finite-rate chemistry and differential diffusion in turbulent flames--circumventing near-term difficulties in analyzing turbulent reacting flows. The partial equilibrium method is useful for the many instances where laminar flame data is unavailable.

The structure predictions yielded reasonably good predictions of nonluminous flame radiation properties in conjunction with the stochastic analysis which allows for effects of turbulent fluctuations. As expected, use of predicted or measured mean properties caused radiation intensities to be underestimated.

These methods established for axisymmetric flames are now being applied to fires along surfaces. Measurements are currently in progress for noncombusting flows to initiate model evaluation.

Reports and Papers

Jeng, S-M., Chen, L-D. and Faeth, G. M., "The Structure of Buoyant Methane and Propane Diffusion Flames," Nineteenth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, pp. 349-358, 1982.

Jeng, S-M., Chen, L-D. and Faeth, G. M., "Predictions and Measurements of Turbulence Properties in Buoyant Diffusion Flames," Proceedings of the Fifteenth Fall Technical Meeting, Eastern Section of The Combustion Institute, Pittsburgh, pp. 31.1-4, 1982.

Jeng, S-M., Chen, L-D. and Faeth, G. M., "The Structure of Axisymmetric Buoyant Diffusion Flames," Report No. NBS-GCR-83-422, February 1983.

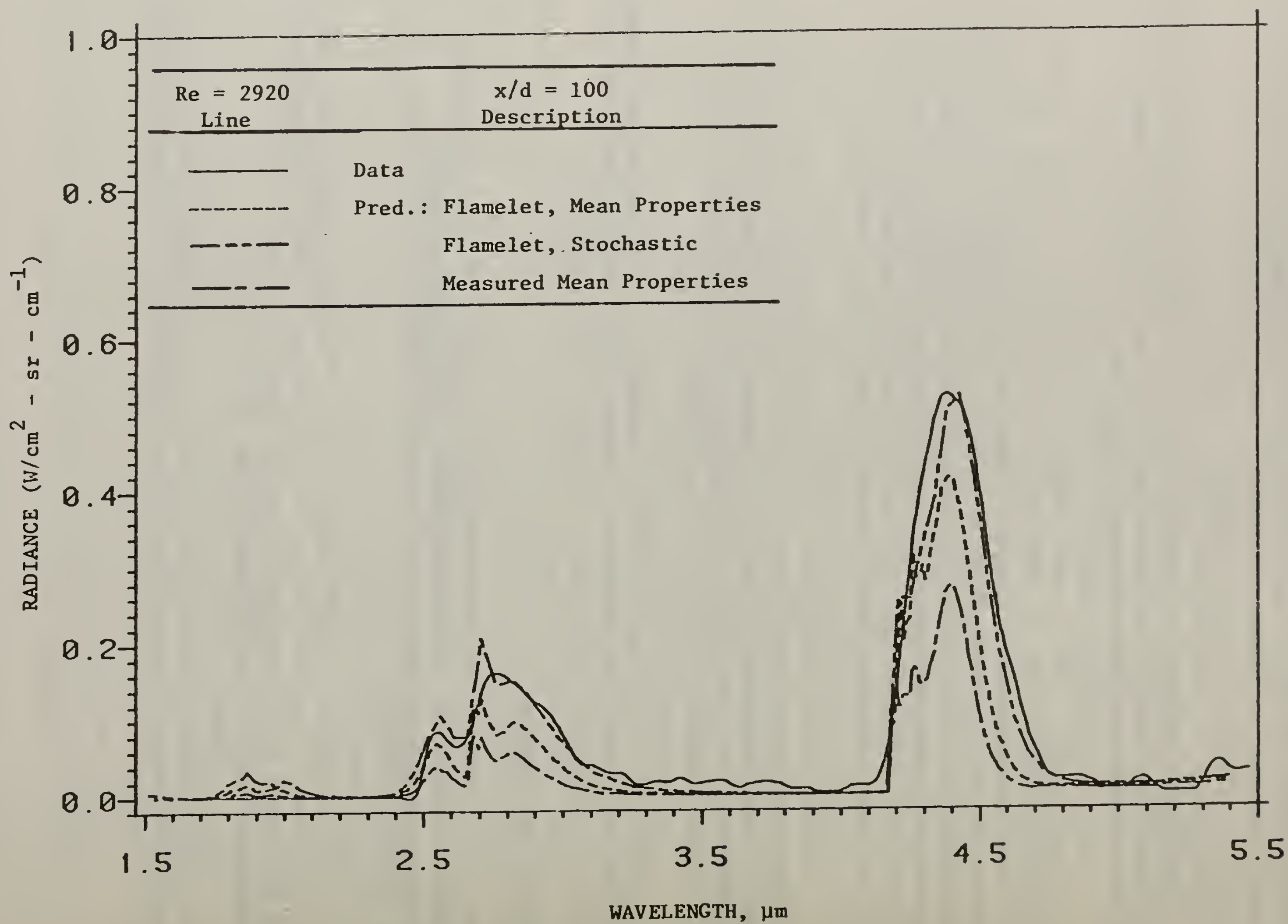

Fig. 1 - Spectral radiation intensities.

CENTER FOR FIRE RESEARCH
NATIONAL BUREAU OF STANDARDS
FY 83

Institution: Princeton University

Contract Number: NB83NADA4007

Contract Title: Flow Field Effects on the Sooting Structure of Diffusion Flames

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NBS Scientific Officer: Bernard McCaffrey

Technical Abstract

In major, as well as minor, fire conflagrations, smoke inhalation is a primary contributor to the casualty rate. The particulate matter in smoke is soot formed during the burning of the fuel mass in a diffusion controlled combustion system. Earlier Princeton work on soot formation in both pre-mixed and diffusion controlled combustion systems has established the fuel pyrolysis rate as a dominant factor in a system's propensity to soot. It follows then that temperature is an important parameter with regard to a combustible material's tendency to soot. However, it is the time that a fluid element is exposed to pyrolysis temperatures in a flame that determines the amount of particulate matter formed. This time, and other factors in flame configurations, are controlled by the overall flow situation in the combustion system. In order to evaluate how control of the fluid mechanical situation could affect the extent (and character) of the soot process, the present program was undertaken.

As inferred, the production of soot in diffusion flames can be influenced significantly by the flow field in and around a flame. The convection of particles by the flow can also determine their residence time in regions of growth and oxidation and, in addition, in many experimental configurations the fuel stream entrains oxidizer at the base of the burner. These latter effects serve to complicate the interpretation of soot measurements in arrangements such as Wolfhard-Parker and tubular burners. Consequently, it is necessary to have a well-controlled and well-defined flow field in which the interaction of fluid flow and chemistry on soot production in a diffusion flame can be clearly elucidated. Thus we have chosen the following "opposed jet"

diffusion flame configuration.

Fuel is ejected uniformly from a porous cylindrical, ceramic burner which is housed in a low turbulence wind tunnel supplied with oxygen and nitrogen. A laminar diffusion flame is stabilized in the forward stagnation region of the burner. Measurements of the flow and temperature fields are obtained along the stagnation streamline with an LDV system and a radiation-corrected thermocouple. A laser light scattering - extinction measurement yields data on soot particle number density, particle size and soot volume fraction. Measurements of the soot characteristics are made along the stagnation streamline from their region of formation on the fuel side of the flame up to the stagnation point. Along the stagnation streamline the flow is one-dimensional and the velocity data permit the interpretation of the light scattering measurements in terms of time rather than distance. Consequently, rates of formation, surface growth and coagulation in the diffusion flame can be inferred from the data. More complex, two-dimensional flow fields do not readily permit the interpretation of soot behavior in these terms.

Measurements have been made on the effect of varying the oxygen index (the oxygen mole fraction) in the oxidizer flow. The initial fuels chosen were ethene and propane and the oxygen index range selected varied from 0.18 to 0.28. Maximum flame temperatures increased about 400° K over this range of oxygen concentration. From the experiments soot volume fractions were found to increased by an order of magnitude with increasing oxygen index.

Concisely, the results to date obtained from the light scattering data reveal that with increasing oxygen index there is a) an increase in the number density of particles at all locations, b) an increase in the soot volume fraction at all locations, c) a maximum soot particle diameter near the stagnation point which is unchanged at around 60 nm, and d) an increase in the soot production rate (rate of increase of soot volume fraction) at any given location.

The one-dimensional nature of the flow along the streamline also permits the calculation of soot volume fraction growth rates. In the absence of significant particle generation, which appears to be the case at the locations of interest, the measurements yield an indication of surface growth rates for soot particles. Apparent values of surface growth rates are around 10^{-3} g/cm^2-sec near the flame front, and this value decreases by about a factor of 5 towards the stagnation point. These results reflect the well-known decrease in apparent surface reactivity of soot particles as they age. In addition, there is a trend to higher surface growth rates as the oxygen index is increased.

Arrhenius-type plots of overall soot volume increase through the flame against a reciprocal average temperature have yielded typical values for the apparent activation energy. The activation energies were 48 kcal/mole for ethene and 20 kcal/mole for propane.

Reports and Papers

Kennedy, I.M., Vandsburger, U., Dryer, F.L. and Glassman, I., "Soot Formation in the Forward Stagnation Region of a Porous Cylinder", Western States Section/Combustion Institute Paper 82-39, 1982.

Vandsburger, U., Kennedy, I.M., Dryer, F.L. and Glassman, I., "The Effect of Oxygen Index on the Sooting Structure of a Diffusion Flame", Eastern States Section/Combustion Institute Meeting, Paper No. 8, 1982.

CENTER FOR FIRE RESEARCH
NATIONAL BUREAU OF STANDARDS
FY 83

Institution: SRI International

Contract Number: NB81NAHA2005

Contract Title: Continued Development of Residential Fire Decision Analysis Model

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Menlo Park, California

NBS Scientific Officer: Alan Gomberg

Technical Abstract:

The objective of this project is to develop and demonstrate a decision analysis model for evaluating residential fire loss reduction strategies. The modeling approaches developed for this project are to contribute to CFR's more general effort to develop fire risk assessment methodology.

The decision analysis model provides an analytic framework for evaluating loss reduction strategies. The framework includes a loss model for calculating deaths, injuries, and property losses under various intervention strategies. A cost model calculates the costs of implementing each alternative. From an economic standpoint, the most attractive alternative is the one that results in the least cost plus loss.

The rudiments of the fire loss model were developed in late FY 82. Most of the work this past year has been spent refining and verifying the model. The model is now functional and is being used to evaluate several alternatives, including conventional sprinklers, fast-response sprinklers, and smoke detectors. Other alternatives will be evaluated as time permits.

The loss model represents a major breakthrough in fire loss modeling. Most previous models have calculated fire losses as a direct function of final flame extent. Whereas this is a reasonable approach for property losses, it is unsatisfactory for fatalities, as many deaths occur during the early stages of a fire. The deficiency is especially

apparent when modeling the impact of alternatives which reduce the extent of fire damage, but which have little effect on life safety.

The innovative feature of our fire loss model is the representation of critical events in a fire and the modeling when fatalities occur by critical event. Critical events are defined as key changes in fire conditions such as occurrence of flashover or major changes in suppression systems status such as sprinkler operation. Algorithms have been developed to combine NFIRS casualty data with expert judgment to distribute the fire losses according to the critical event at which they occurred. Other NFIRS statistics are used in conjunction with the same algorithms to determine the fire growth transition probabilities between critical events. Alternatives are modeled by adjusting the transition probabilities to reflect the action of the intervention strategy in question.

The model has been tested and calibrated using 1980-81 NFIRS data. Results are being reviewed by interested parties. A final report will be issued in late 1983.

Reports and Papers:

Gomberg, A., Buchbinder, B., and Offensend, F., "Evaluating Alternative Strategies for Reducing Residential Fire Loss--The Fire Loss Model," Interim Report, National Bureau of Standards, NBSIR 82, Summer 1982.

Gomberg, A., and Offensend, F., "Evaluating Fire Safety Alternatives: A Probabilistic Approach to Decision Making," paper presented at annual NFPA meeting, St. Louis, Missouri, May 1983.

CENTER FOR FIRE RESEARCH
NATIONAL BUREAU OF STANDARDS
FY 83

Institution: SRI International

Grant No.: NBS Grant NB80NADA1003

Grant Title: Polymer Degradation During Combustion

Principal Investigator: Dr. S. K. Brauman
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Technical Abstract

The degradation of burning polymers is being investigated to provide understanding of the detailed degradation processes occurring in the condensed phase of a burning polymer that result in fuel production and to allow prediction of the effect of certain thermal or chemical variables on the rate or mechanism of fuel production. We are using a novel driven-rod apparatus with superimposed radiant heating to study steady-state linear regression of vertically mounted polymer rods degrading under nonflaming conditions that simulate those of combustion. Absence of the flame simplifies experiments and analysis.

Previously, we used this driven-rod, radiant pyrolysis technique to study steady-state linear regression of vertically mounted polystyrene rods degrading under nonflaming conditions that simulate those of combustion. Using this technique, we demonstrated that a combustion process can be successfully isolated and simplified for detailed study. The same mass loss rate (0.06 cm/min) and temperature-depth profile (surface temperature T_s = 446° ± 3°C) obtained for combustion of polystyrene in air in the driven-rod configuration were achieved for nonflaming pyrolysis of polystyrene in air and nitrogen by using superimposed radiant heating. The required radiant flux is independent of the atmosphere, indicating that polymer surface oxidation is unimportant during pyrolysis and, presumably, during combustion. The lack of oxygen incorporation in the pyrolysis residues substantiates this conclusion. Furthermore, we successfully calculated the observed mass loss or fuel production rate using the temperature-depth profile and gravimetric kinetic parameters obtained isothermally under slow heating conditions in an inert atmosphere. The success of these calculations coupled with the observed monomer-to-nonmonomer ratio (33:67) in the volatile pyrolysis products indicates that the mechanism of degradation of polystyrene under our combustion conditions is similar to that under

more conventional slow-heating conditions in the absence of air.

During the present year, determination of the high-boiling volatile products and the heat of gasification concluded our studies on polystyrene. To identify the composition of the fuel entering the flame during combustion, we analyzed all the products volatilized from the surface under our combustion-like (nitrogen) radiant pyrolysis conditions. The high-boiling volatiles were identified by field ionization mass spectrometry (FIMS). Oligomers as high as heptamer are detected; volatile products larger than tetramer have not been reported previously. The trend for distribution of monomer, dimer and trimer (monomer > trimer > dimer) has been observed previously for certain pyrolysis conditions. Based on the FIMS results, the molecular weight of volatiles for the mass range 100-800 is $\bar{M}_n = 220$, $\bar{M}_w = 289$.

The heat of gasification, L, for polystyrene was determined from the dependence of the mass loss rate on the incident flux. The heat of gasification (472 cal/g or 1.98 kJ/g) generally agrees with other values available in the literature for polystyrene.

The investigation of polypropylene was initiated during the current year, and steady-state combustion and radiant pyrolysis studies have been completed. In contrast to the results for polystyrene, oxidation is important in the condensed phase degradation of polypropylene burning in this configuration. Thus, we are unable to make the pyrolysis and combustion temperature profiles very similar for the desired mass loss rate. Compared to the combustion profile, the air pyrolysis profiles are low and the nitrogen pyrolysis profiles are very high. Agreement between calculated and observed rates for radiant pyrolysis in nitrogen is excellent, however, agreement is poor for both air pyrolysis and combustion using kinetic parameters for air or nitrogen. The oxygen involvement implied by this poor agreement is further substantiated by the finding of oxygen incorporation in the combustion residue.

The information obtained from this research will contribute to reducing the nation's fire loss by providing understanding of the chemistry of the combustion process of fuel production. With this knowledge, understanding of the effectiveness of and even prediction of improved fire retardants used to control fires by altering fuel production become possible.

<u>Reports and Papers</u>

Brauman, S. K., Matzinger, D. P., and Berg, R. A., "Polymer Degradation During Combustion," SRI International Annual Report, April 11, 1983.

Brauman, S. K., Chen, I. J., and Matzinger, D. P., "Polystyrene Degradation During Combustion," J. Polym. Sci., Polym. Chem. Ed., <u>21</u>, 000 (1983).

CENTER FOR FIRE RESEARCH
NATIONAL BUREAU OF STANDARDS
FY 83

Institution: TRW

Contract Number: NB82SBCA1662

Contract Title: Modeling of Wind-Aided Flame Spread

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Other Professional Personnel: George Carrier, Harvard University
Phillip Feldman and Stanton Fink, TRW

NBS Scientific Officer: Howard Baum

Technical Abstract

1. Introduction. A major goal of fire dynamics is prediction of the rate of fire spread from knowledge of (1) the physicochemical properties of the combustible materials and (2) the thermohydrodynamic environment. Flame-propagation rates become particularly significant under wind-aided conditions; in general, far more rapid fire advance is associated with situations in which hot gaseous products of homogeneous combustion preheat (by conduction, convection, and/or radiation) still uninvolved downwind combustible materials. In contrast, in spread against the wind, fire advance usually is much slower because combustion products flow over already involved portions of the combustibles, and only gas-phase radiation and solid-phase conduction can effect preheating.

With the more rapid advance connected with wind-aiding, quasisteady approximation tends to be inadequate and explicit accounting for temporal derivatives is required; thus, even the simplest scenarios in wind-aiding spread entail dependence on two spatial coordinates and on time. Accordingly, progress to date in quantifying wind-aided flame spread is modest. Here, the goal is to provide enough quantitative accuracy to permit correct ordering of materials with respect to supporting of fire spread, even if the predicted rate of spread is not precise. It may be worth noting that consistent orderings of materials, but not precise quantitative values, are reproduced by purportedly standardized laboratory testing of materials in a severe fire environment.

At the rudimentary present state of quantitative analysis, there are three geometric arrangements that would appear to warrant attention. One may distinguish usefully (1) fire spread across a horizontal solid slab constituting the ceiling of a room or corridor, such that forced-convection arising from a boundary constraint is the source of the aiding wind; (2) fire spread up a vertical wall, such that free convection is a source of the aiding wind; and (3) fire spread across a horizontal solid slab constituting the floor of a room or corridor or forest, such that a boundary constraint is the source of the aiding wind but buoyancy plays a crucial role. While perhaps the first two cases are of primary interest within a structure and while perhaps the third case is of primary interest in wildlands and in spread between structures, nevertheless comparing the cases is mutually illuminating. Of course, the generalities presented here find many exceptions; for example, the torching out of a single tree in a so-called passive crown fire entails many features in common with case (2). In this discussion, primary attention is to be placed on case (1), which (for all its difficulties) may be the most straightforward of the three cases, and which seems the most tractable of the three cases. Space precludes comments concerning the other two, less advanced cases. However, before any of the cases are discussed, some general remarks on formulation are apropos.

2. Formulation. A formulation is sought in which all the significant phenomena are incorporated in the simplest reasonable form, such that convection, diffusion, radiative transfer, chemical exothermicity, buoyancy, pyrolysis, char formation, and char erosion are all treated to a comparable degree of accuracy. The framework for such a formulation is furnished by the so-called Shvab-Zeldovich approximation, in which the dynamics and energetics are decoupled as much as reasonably possible, and in which a generic fuel vapor is taken to react exothermically with oxygen in a direct one-step irreversible rapid homogeneous chemical reaction.

One advantage introduced by wind-aiding is that the flow speeds, and hence the Reynolds number, tend to be large enough to permit adoption of the boundary-layer approximation: diffusion transverse to streaming is retained, but diffusion in the streamwise direction may be omitted, in the lowest order of approximation. Furthermore, with the streaming well defined, it is possible to approximate convective transport of mass, momentum, and heat in the manner of Oseen; that is, it is possible to linearize the streamwise convective transport. It should be noted, however, that in free-burning problems, in which the fuel vapor usually is either pyrolyzed from a solid or evaporated from a liquid pool, the convective transport transverse to the principal streaming warrants careful treatment. Indeed, where there is interphase mass transfer (at a rate that appears as an eigenfunction to be identified in the course of solution), the convective transport transverse to streaming entails nonlinearity.

The conventional Shvab-Zeldovich formulation concerns gas-phase phenomena. A consistent level of accuracy is required for the formulation of the solid phase. It is suggested here that the often-adopted two-parameter (gasification temperature, specific endothermic heat of gasification), sublimation-type (or evaporation-type) model of gasification may not be adequate to recover behavior of a char-forming body. Upon heating to a fairly well-defined temperature, the preponderance of synthetic and natural polymers undergo thermal degradation partially to a carbonaceous, porous matrix, and partially to (in part, combustible) vapor that traverses the (usually relatively thin) porous matrix to reach the gas phase. The heat-retention properties of the matrix are crucial under forced-convection-extinction conditions, and probably warrant retention under vigorous-burning conditions as well. Furthermore, at high-enough temperature, the carbonaceous char layer erodes; this may be owing to loss of mechanical strength such that spalling occurs, or it may be due to chemical attack (such as reduction by the char of carbon dioxide, and, to a lesser degree, of water vapor). In any case, the char layer tends not to increase indefinitely in thickness, but to remain thin relative to the depth of the gas phase and of the pristine solid (such that an approximate integral-type treatment of the char layer suffices). The point to be emphasized is that a formulation, consistent with the Shvab-Zeldovich spirit, is available that encompasses the usually endothermic onset of char formation and gasification, the onset of char erosion, and the heat-retention properties of the char, but that does not introduce spatially distributed, finite-rate processes of uncertain rate and mechanism and of limited generality.

Radiative transfer involves reradiative cooling of the gas-solid interface, radiative heating of the gas-solid interface from cooling of vitiated bulk-gas air, and radiative heating of the gas-solid interface from nonconductive transport from the gas-phase flame (probably in the presence of soot). It is the last of these three processes that probably presents the greatest challenge in seeking a compromise between fidelity to the physics and tractability of the formulation. In this regard, the recent work of Howard Baum of the Center for Fire Research is noteworthy.

In summary, wind-aided flame challenges modeler to incorporate tractable formulation of charring and radiative transfer in an explicitly unsteady, spatially (at least) two-dimensional problem involving close coupling of the solid and gas domains.

3. <u>The Ceiling Geometry</u>. Wind-aided flame spread along a thick semi-infinite horizontal slab (such that burn-through, and thus exhaustion of outgassing capacity, is not achieved), entails a parabolic boundary/initial-value problem. In particular, one may envision the initiation of a hot vitiated air stream over the leading edge at time zero, displacing the prior stagnant, thermodynamically benign environment downwind. One seeks the rate at which the char-formation front at the solid-gas interface, and the rate at which the char-erosion front at the solid-gas interface, progress downwind, as a function of the thermohydrodynamic environment and the physicochemical slab properties; these fronts characterize the extent of slab "involvement". While knowledge of the progression rates of these fronts does not constitute a complete solution throughout the three-independent-variable space, such knowledge does provide the knowledge of particular engineering significance, and theoretically one can later ascertain meticulous details if one wishes.

Either by use of point-source solution for a second-order parabolic operator, or alternatively by Weiner-Hopf-like arguments in the inversion of Fourier transforms, Volterra integral equations have been derived that relate the dependent variables and their fluxes <u>in the gas-solid interfacial plane</u>; of course, such relations reduce the three-independent-variable problem to a two-independent-variable (time and streamwise distance) problem. These integral equations are supplemented by locally appropriate algebraic relations between the dependent variable and their fluxes in the interfacial plane; the phrase <u>locally appropriate</u> alludes to the fact that different algebraic relations pertain to the preheat, char formation, and char erosion zones. The integral equations are also supplemented by an ordinary differential equation, evolved from a transversely averaged (i.e., approximate integral-type) treatment of the conservation-of-energy equation for the (relatively thin) char layer. In fact, the problem as rephrased in the interfacial plane is of hyperbolic character, with fluid-particle paths and fixed downwind stations delineating a characteristics grid on which the char-formation front and char-erosion front are shock-like loci, i.e., loci noncoincident in general with a characteristic curve. Cauchy (boundary) data, specified along the boundaries of the two-dimensional (streamwise-distance/time) solution space, is propagated across the characteristics mesh in customary, node-to-node, stepwise procedure (with iteration).

The boundary data consists partly of the temporal (downwind) history of the first hot particle of vitiated-air flow across the leading edge at the starting instant; the requisite Abel integral equation is treated by known procedures. The boundary data consists partly of the selfsimilar solution to the steady flow past a semi-infinite, fully involved charring slab (in the absence of any radiative transfer); this steady solution holds instantaneously at the leading edge (since there is no upwind transfer of information in the formulation). Solution to this generalized Emmons problem has been thoroughly explored, not only because it furnishes requisite boundary data for initiating the complete solution for all sites and times in the interfacial plane, but also because it permits solution even upon relaxation of approximations required for tractability under nonselfsimilar conditions. For example, it is possible to investigate the consequences attendant on adoption of the Oseen approximation of convective transport, of Lewis-Semenov number unity, of approximate integral treatment (rather than exact treatment) of the char layer, of a sublimating pseudomechanism (rather than diffusively controlled chemical reduction) for char erosion, etc. The findings, documented in a publication listed below, are, succinctly, that none of the approximations compromise trends at all, but quantitative precision is sacrificed.

Attention is now being turned to propagating the solution across the characteristics mesh, so that the variation of rate of fire spread with physical parameters (gas-phase flow speed, pristine solid heat capacity, etc.) may be ascertained.

In the presentation comments about the anticipated adaptability of the formalism to spread up a vertical wall, but the major modification required for wind-aided spread along a floor slab, will be included.

Reports and Papers

Carrier, G., Fendell, F., and Fink, S. (1983), "Towards Wind-Aided Flame Spread Along a Horizontal Charring Slab: The Steady-Flow Problem," Combustion Science and Technology 32, 161-210.

Carrier, G. and Fendell, F. (1982), "Crown Fires," Report 38095-6001-UT-00, TRW Space and Technology Group, Redondo Beach, CA, October.

CENTER FOR FIRE RESEARCH
NATIONAL BUREAU OF STANDARDS
FY 83

Institution: University of California, Berkeley

Grant No: NB81 NAHA 2038

Grant Title: "Dynamics of Smoke and Inert Tracers Produced in Porous Fuels"

Principal Investigator: Professor Simon L. Goren
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Other Professional Personnel:
Warren Friedman, Postdoctoral Research Assistant
Peter Lipowicz, Graduate Research Assistant

NBS Scientific Officer: Dr. George Mulholland

Technical Abstract:

The objective of this research is to quantify the mass generation rate and the size distribution of smoke aerosols produced by smoldering porous fuels. These variables are to be related to the chemical and physical properties of the fuel and to the combustion conditions. Since temperature, gas velocity and location of pyrolysis change during the course of smoldering, the amount and other characteristics of the emitted smoke also vary with time. Our approach to this dynamic process is a coordinated theoretical and experimental study.

Time dependent rates of release and size distributions of smoke aerosols produced by smoldering cellulosic insulation are being measured. The fuel is supported on an array of screens in a pyrex combustion chamber 178 mm in diameter and 330 mm in length. Air is introduced below the screens and caused to flow upwards through the fuel. Most of the combustion gases are vented to a hood through a chimney. A small sample of the gases is withdrawn and diluted for analysis by a Royco model 236 Laser Particle Counter. This instrument counts the particles and sorts the counts according to size into sixteen channels; the smallest detectable particle is 0.12 µm in diameter. Because of the high concentration of smoke, we had to design a sampler which permits dilutions of 100 to 10,000 fold. The chamber has an array for ports for insertion of thermocouples into the fuel to monitor the pyrolysis propagation rate. The output from the Royco and the thermocouples are recorded at about one minute intervals by a microcomputer and are stored on floppy disk. We will be recording the concentrations of oxygen, carbon monoxide, carbon dioxide and water vapor using various instruments and also the mass

loss of the fuel using a load cell. The mass of smoke emitted is measured at several times during the course of a burn by recording the mass gain of filters.

For burns ignited from a "point" source at the top of the bed, the smolder propagation speed is almost independent of the superficial gas velocity U at an average value of 0.057 mm/s for air velocities from 1.2 to 2.7 mm/s. The weight percent of cellulose lost at the completion of the burn increased somewhat with increasing air velocity; at U = 1.2 mm/s the percent weight loss was 46% whereas at U = 2.7 mm/s the weight loss was 55 to 59%.

For each of these experiments a burst of smoke is detected by the optical counter upon ignition. The smoke concentration then rapidly decreases. Later, the smoke concentration is observed to increase with time reaching a maximum concentration approximately 25 to 35 minutes after ignition. Thereafter, the smoke concentration decreases almost experimentally with time, but there is usually at least one subsequent time for each run when the smoke concentration increases abruptly. Following the abrupt increase, the smoke concentration again decreases exponentially with time with approximately the same slope as before the abrupt increase. We believe the abrupt increases coincide with sudden changes of the bed structure due to slumping and opening of fissures. Post burn examination of these beds showed that each bed developed a conical crater with fissures. These structural defects were more pronounced the higher the air velocity.

The slopes of the logarithm of concentration versus time for the decreasing concentration regime was determined for each particle size range of the optical counter where significant counts were recorded. An example is Figure 1 for the burn at U = 2.0 mm/s. The slope shows a minimum for particle diameter D_p of about 0.7 μm. The form of this curve is consistent with particle removal by filtration. Small particles are efficiently removed by Brownian diffusion and large particles are efficiently removed by sedimentation leaving an intermediate size particle less efficiently captured. Similar plots for the other flow rates showed similar trends with a more pronounced minimum at U = 2.7 mm/s and a less pronounced minimum at U = 1.2 mm/s. In general, for a given particle size, the slope decreases with increasing gas velocity. This is consistent with the two collection mechanisms postulated because of the decreased residence time within the bed with increasing gas velocity.

For top ignited burns, we fitted the formula $c = c_o t^n$ for the concentration c of particle of a given size as a function of elapsed time t from ignition for the regime where the concentration increases with time. For the most part, values of n were independent of particle size although significant scatter was found especially at the highest gas velocity. The weak dependence of n on D_p suggests that early in a top ignited burn very little filtration of the smoke produced occurs because of the short distance the smoke needs to travel to reach the top of the bed. Apparently, the concentration increases because the volume undergoing smoldering increases. We found the exponent decreases with increasing gas velocity. At U = 1.2 mm/s the exponent n = 2.3; at U = 2 mm/s the exponent n = 1.2; and at U = 2.7 mm/s the exponent is between 0.4 and 1.

We have filtered the smoke passing up the chimney to determine the time dependence of the mass of smoke emitted. The filters were changed at twelve minute increments during the course of the burn. Figure 2 shows the time history of the mass concentration of aerosol computed from the weight gains on the filters after drying by exposure to a flow of dry air at 2ℓpm for 10 minutes. Superimposed on this graph is the mass concentration induced by the Royco optical counter integrated for the corresponding time periods, corrected for dilution, and assuming the particle density is 1 g/cm^3. There is good correspondence between these two measurements when the mass gain is above our level of resolution of 2 mg. We have improved our technique and believe we can achieve a resolution of 0.2 mg.

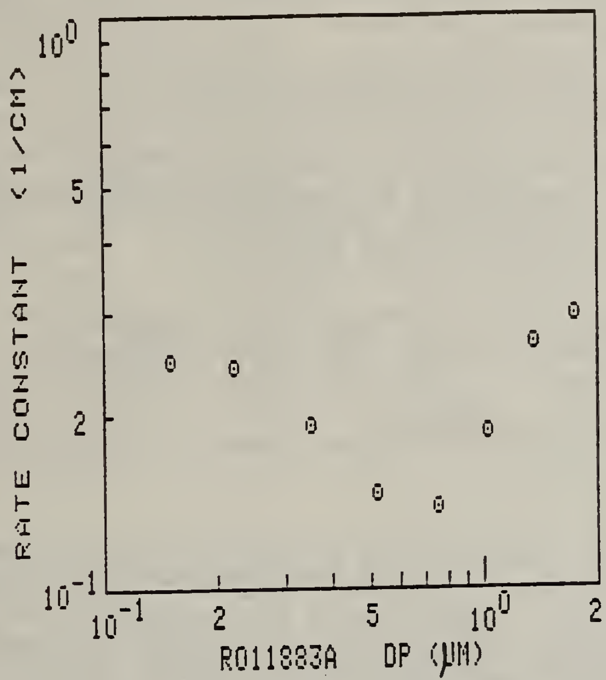
A plot of the weight gain of each filter determined immediately upon removal from the experiment versus the weight gain after drying is found to be very nearly a straight line. If we assume that the mass of water on each filter is the same because each filter is exposed to 100% humid air produced in the burn and if we assume that there is a constant fraction f_{nv} of non-volatile organics in the organics produced as smoke, then we can derive the following formula:

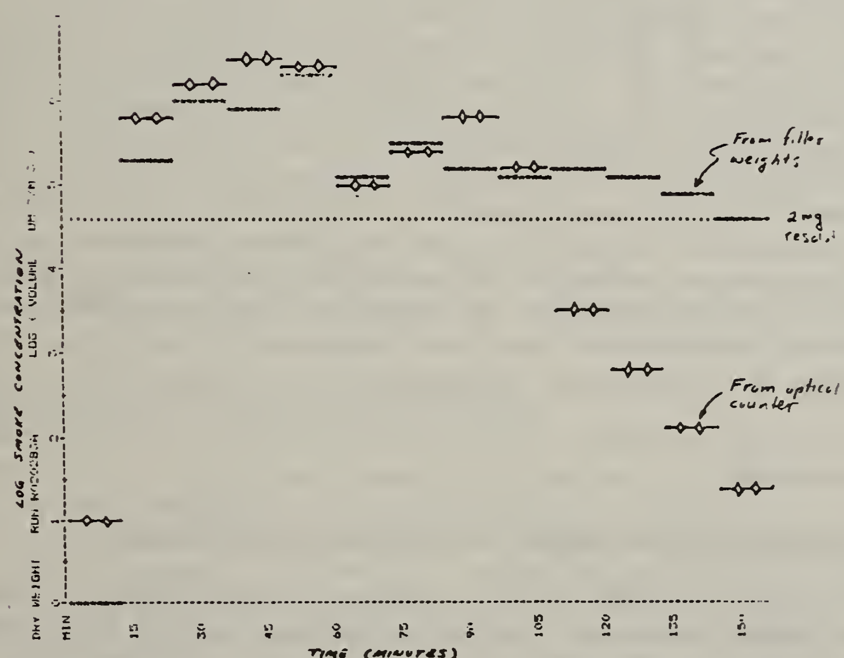
$$W_{immediate} = (1/f_{nv})\, W_{dry} + W_{water}$$

The measured slopes give a range of f_{nv} from 0.4 to 0.6 for the several burns which have employed filters.

Considerate effort was spent in calibrating the Royco aerosol counter and in developing a sampling and dilution probe to be delivered to the NBS for it's in house smoke research.

The information to be obtained on time dependent rates of production, size distributions and other properties of smoke aerosols emitted from smoldering porous fuels is important for improved fire detection and smoke hazard assessment. A significant fraction of fire related deaths, injuries and property losses are due to fires that originate as slow smoldering combustion of porous fuels. Early and reliable detection of smolder generated smoke could reduce these losses by enabling automated countermeasures. This research also is important for the development of models for estimation of fire hazards. Smoke reduces visibility, making evacuation or rescue more difficult. Inhaled smoke may have a debilitating effect by inducing choking and a long term health effect as a carrier of toxic chemicals. Smoke also alters the development of fire by modifying the heat transfer through radiation. Smoke is a reservoir of highly combustible fuel and is important in flashover. All of the effects depend on both the quantity and size of the smoke aerosol. Any modeling of the smoke aerosol in the air spaces must have information on the source term.





CENTER FOR FIRE RESEARCH
NATIONAL BUREAU OF STANDARDS
FY 83

Institution: University of California, Berkeley

Grant No.: NB80NADA1064

Grant Title: Fire Propagation in Concurrent Flows

Principle Investigator: Professor A.C. Fernandez-Pello
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Other Professional Personnel: C.-P. Mao, Ph.D. Candidate
H.-T. Loh, Ph.D. Candidate

NBS Scientific Officer: W.J. Parker

Technical Abstract

A study is being performed of the process of fire spread in gaseous flows moving in the direction of flame propagation, i.e.: concurrent or flow assisted flame spread. This mode of fire spread is very rapid and hazardous, and consequently of great interest in the fire safety field. The study includes two research efforts: 1) Natural convection, flow assisted, flame spread over enclosure's walls; 2) Flame spread over a flat surface in a concurrent forced flow. During this reporting period, a numerical analysis has been performed of the natural convection, steady burning of combustible surfaces of varied length and composition forming the walls of an enclosure. The analysis represents an intermediate step toward the development of a theoretical model of the spread of fire in enclosures. The results for the location and length of the flame agree well with experimental data. Measurements of the rate of flame spread in a concurrent forced flow of varied velocity and oxygen concentration show that the spread process is controlled primarily by heat transfer from the flame to the fuel. The measured rate of spread of the pyrolysis front, V_p, can be correlated in terms of the free stream gas velocity u_∞, and mass transfer number B, by using an expression of the form $V_p/B^2 \sim u_\infty$, which agrees with the predictions of thermal theories of the flow assisted mode of flame spread.

Steady, Free Convective Burning of Surfaces in Enclosures:

A numerical analysis of the steady, laminar, non-radiative burning of surfaces in a partial enclosure has been completed during this period. To perform the analysis, a computer code to solve the two-dimensional, elliptic, buoyant, laminar, non-reactive conservation equations was modified to include the vaporization of a surface and the flame sheet combustion of the pyrolyzed fuel. Theoretical predictions of the velocity and temperature fields, and of flame contours were obtained for fires in enclosures of varied soffit and pyrolyzing lengths, and with PMMA or POM as combustible materials.

A representative example of the results obtained in this work is presented in Figs. 1 and 2. The figures show the characteristics of the predicted velocity and temperature fields in a compartment fire and the comparison of the flow structures for fires generated by PMMA or POM burning. In Figs. 1a and 1b the predicted flow velocity and temperature profiles are presented for a PMMA compartment fire with a pyrolyzing length of 7 cm and in Figs. 2a and 2b the corresponding distributions are presented for a POM compartment fire with the same pyrolyzing length. Comparison of Figs. 1a and 2a show that the flow structures are quite similar for both cases. However, for POM the two vortices in the center region of the compartment are stronger than those predicted for PMMA. The top vortex tends to roll the flame backwards so that the tip of the flame does not emerge through the compartment opening as occurs with PMMA. For POM fire, the flame size is smaller than for the PMMA fire suggesting that POM is a less hazardous material than PMMA. The results of this work have been reported in a paper entitled "An Investigation of Steady Wall-Ceiling and Partial Enclosure Fires". To be published in the J. of Heat Transfer.

<u>Fire Spread in a Concurrent Forced Flow</u>:

Measurements are currently underway of the rate of flame spread over PMMA sheets in a forced flow of varied velocity and oxygen concentration moving in the direction of flame propagation. The experimental installation consists of a small scale combustion tunnel and its complementary instrumentation. The test section of the tunnel is 61 cm long and has a rectangular cross section 12.7 cm by 7.6 cm. It is made of Marinite and has Pyrex windows to permit optical access to the experiment. The sheet of PMMA is embedded flux in the Marinite and placed at the entrance of the test section so that a flat plate flow is developed. The gaseous flow consists of a mixture of O_2 and N_2 which flow rates are previously metered with critical nozzles. The flow velocity is currently being measured with a pitot tube until a LDV system is made operational. Surface temperature histories provided by thermocouples embedded at fixed distances along the PMMA surface are used to calculate the rate of spread from the time lapse of pyrolysis arrival to consecutive thermocouples and the known distance between thermocouples.

The results of the measurements of the rate of spread of the pyrolysis front over PMMA sheets 1.25 cm thick as a function of the flow velocity are shown in Fig. 3 for several oxygen mass fractions of the gas flow. It is observed that for all oxygen concentrations tested, the spread rate is linearly proportional to the flow velocity with the slope increasing with the oxygen concentration. In Fig. 4 the data of Fig. 3 are correlated using V_p/B^2 as ordinate and u_∞ as abcissa. V_p is the spread rate, B is the mass transfer number and u_∞ the free stream velocity. The correlation is suggested by present thermal models of the flow assisted mode of flame spread. It is seen that the experimental results correlate quite well, indicating that thermal models can describe correctly the mechanisms controlling the flame spreading process. It is believed that the observed scatter in the correlation of the data is due to flame length effects not included in the correlating parameters.

Mixed Convective Burning of Surfaces with Arbitrary Inclination:

An analysis has been developed for the mixed, forced and free, convective combustion on a flat fuel surface of arbitrary inclination. A mixed-convection parameter $(Re_x^n + Gr_x^m)^{1/2n}$ which properly scales the dependent and independent variable fields and a mixed convection ratio $(Gr_x^m/Re_x^n)^{1/2}$ which plays the role of the downstream local similarity coordinate are introduced in the nondimensionalization of the equations. It is shown that these two parameters, rather than the standard Reynolds, Re_x, and Grashof, Gr_x, numbers are the optimum choice of governing nondimensional groups for this problem. The values of m and n are selected to obtain a similarity solution of the governing equations for the limiting cases of pure forced and pure free convection. This occurs at the particular cases of a vertical (m = 2, n = 4) and a horizontal (m = 2, n = 5) surface, which are the cases that have been solved in this work. With this formulation, the solution of the problem provides for both cases smooth transition of all physical variables from one convective limit to the other. Results obtained from numerical integration of the governing equations and from application of the local similarity approximation show that the range of validity of local similarity is extended beyond that obtained with alternate formulations and that the proper limits are approached.

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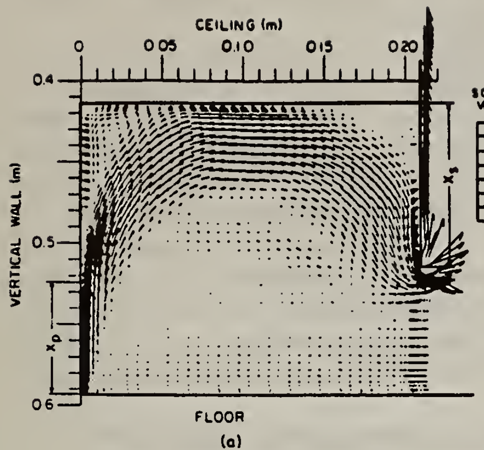

Fig. 1a

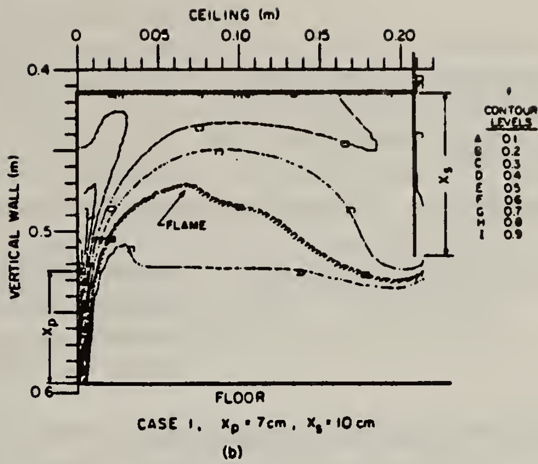

Fig. 1b

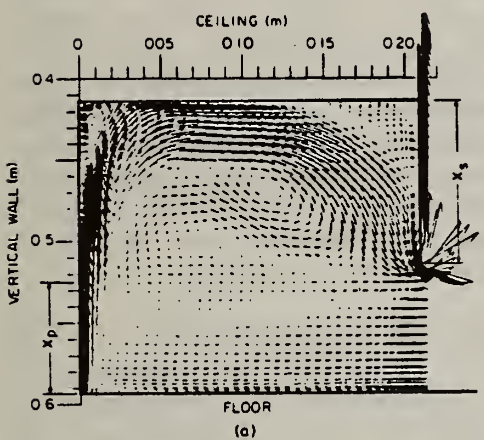

Fig. 2a

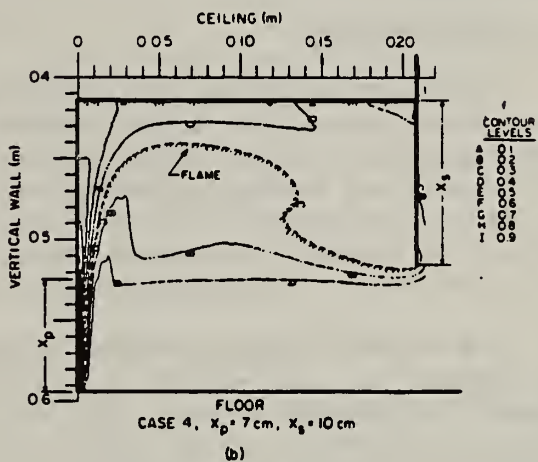

Fig. 2b

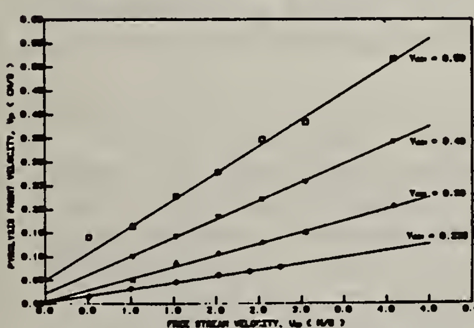

Fig. 3

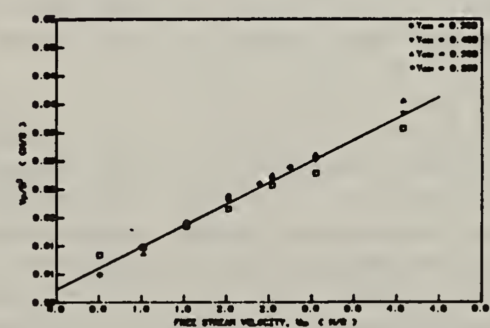

Fig. 4

CENTER FOR FIRE RESEARCH
NATIONAL BUREAU OF STANDARDS
FY 83

Institution: University of California, Berkeley

Grant No.: NB80NADA1072

Grant Title: **Intralaboratory Evaluation of a Standard Room Fire Test**

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Other Professional Personnel: Fred L. Fisher, Development Engineer
Fred Mowrer, Associate Specialist

NBS Scientific Officer: William J. Parker

Technical Abstract:

The characterization and regulation of the fire growth characteristics of interior finish materials have been of concern for many years. Since the early 1970's it has been recognized that small scale test methods are unable to accurately predict the fire growth potential of certain types of interior finish materials, particularly those composed of synthetic polymers. This recognition has led to an interest in the use of full scale room fire tests for this purpose.

In November 1982 a Room Fire Test Method was published, for information only, in Part 18 of the ASTM Book of Standards[1]. This proposed test method appears very promising as a means of providing a realistic assessment of the fire growth characteristics of interior finish materials in their end-use configuration. This experimental program has been one of the primary sources of information for the ASTM Task Group which produced the method as published. Until a series of smaller, less expensive fire tests, can be developed and validated, it is likely that the Room Fire Test Method will be one of the primary test method for evaluating the fire growth characteristics of interior finish materials.

The Room Fire Test is now standardized to a test compartment which is 2.4m (8 ft) wide, 3.7m (12 ft) long, and 2.4m (8 ft) from floor to ceiling. The ignition source is a propane-fired sand burner placed in one corner of the compartment. The test is conducted by igniting the burner and measuring the following data: temperature 100 mm (4 in.) below the ceiling, the rate of heat release (RHR) by oxygen depletion in the stack, the heat flux to the floor and the light transmission through the smoke in the stack. Once the test compartment has been constructed and the instrumentation has been calibrated, the test is only slightly more difficult to conduct than

other standard fire tests, such as ASTM E119.

The results of room calibration experiments and of experiments in which the room was lined with 6 mm thick plywood at relatively low moisture content were presented in in the previous summary and an NBS GCR Report[2]. This year additional experiments were conducted using 6 mm thick plywood at higher equilibrium moisture contents (18% and 24%) as well as experiments using 6 mm thick pressure treated fire retardant plywood. In addition, a "screening test" protocol was developed that may be useful for evaluating prototype materials and conducting interlaboratory studies with limited amounts of standard materials. Finally, new experiments with a line burner at the back wall of the compartment will be briefly described.

The results from four room fire experiments of 6 mm (0.25 in.) thick A-D Douglas fir plywood are presented below. The experiments provide a comparison of the fire behavior of 6 mm thick plywood in an untreated, high equilibrium moisture content (EMC) state (experiments C-215 and C-216) versus pressure treated fire retardant wood (experiments C-219 and C-220). Experiments C-215 and C-219 provide this comparison for the case in which the ceiling is covered with plywood and the walls with gypsum wallboard. Experiments C-216 and C-220 provide the comparison when both the ceiling and walls are covered with plywood. Table I provides a summary of the plywood treatment and location within the room for each of the experiments.

TABLE I: Materials Used as Interior Finish for the Room Fire Experiments

Experiment Number	Interior Finish Material	
	Walls	Ceiling
C-202	13 mm Gypsum Wallboard	6 mm Plywood @ 10% EMC
C-212	6 mm Plywood @ 10% EMC	13 mm Gypsum Wallboard
C-213	6 mm Plywood @ 10% EMC	6 mm Plywood @ 10% EMC
C-215	13 mm Gypsum Wallboard	6 mm Plywood @ 18% EMC
C-216	6 mm Plywood @ 24% EMC	6 mm Plywood @ 24% EMC
C-219	13 mm Gypsum Wallboard	6 mm Plywood-Fire Retardant Treated @ 9.1% EMC
C-220	6 mm Plywood-Fire Retardant Treated @ 11.3% EMC	6 mm Plywood-Fire Retardand Treated @ 11.3% EMC

In the proposed test method the following three criteria are associated with "flashover": (1) an average ceiling temperature above 600°, (2) a heat flux of greater than 20 KW/M^2 measured in the center of the floor, and (3) the first observation of flames out the top of the door. It is interesting to compare the times at which each of these criteria is reached in these room fire experiments. A comparison of the flashover criteria is presented in Table II.

TABLE II: Critical Times and Heat Release Rates for the Room Fire Experiments

Experiment Number	Time (Min:Sec) to Reach:			Approximate Maximum Rate of Heat Release Prior to Flames Out Door (KW)
	600° C.Av. Ceiling Temp.	20 KW/M^2 Heat Flux at Floor center	Flames Out Top of Door	
C-202	3:50	---- $13KW/M^2$ @5:23	4:35	800
C-212	2:55	3:50	3:30	950
C-213	1:55	3:25	2:50	950
C-215	4:40	---- $12KW/M^2$ @6:30	8:50	750
C-216	3:20	6:15*	4:48	950
C-219	---- 590° @5:00	---- $4.5KW/M^2$@4:30	----	400
C-220	3:35	6:35	5:35	800

*Cooling water not flowing - time possibly longer.

During experiment C-215 the high moisture content of the plywood delayed ignition of the ceiling and reduced the rate of flamespread as compared to experiment C-202. However, the additional moisture in the plywood delayed burnthrough of the ceiling in the corner for a long enough time to establish burning away from the corner prior to burnthrough of the ceiling above the burner. This ultimately enabled a large enough area of the ceiling to become covered with visible flaming (as observed from the door opening) to cause flashover as defined by two of the three criteria. The maximum RHR during this experiment was 1175 kW and it occurred at an elasped time of about 10:00 minutes. The plywood contribution to the peak rate of heat release was on the order of 1000 kW.

Experiment C-216, in which both the walls and ceiling were lined with plywood, indicated a delay in the time to reach flashover of approximately 2 minutes as compared to a similar experiment[2] conducted at 10.1% EMC. The two minute difference can be considered as "drying time" for the plywood. During this period the burner released on the order of 19 MJ (18,000 Btu) of energy into the room.

The fire retardant treated plywood ceiling evaluated during experiment C-219 did not spread fire away from the corner area above the ignition source. The RHR produced by the ceiling only was relatively small. The peak RHR due to combustion of the ceiling was on the order of 240 kW. The fire did not spread and once the plywood located above the burner had been consumed, the total RHR decreased to a level only slightly greater than that produced by the ignition burner. During experiment C-220 the fire retardant treated plywood walls and ceiling did lead to flashover of the room. However, flashover was delayed by approximately 2 minutes, 45 seconds as compared to untreated plywood at 10% EMC, and 47 seconds as compared to the untreated plywood at 24% EMC shown in experiment C-216. Another notable difference between the fire retardant treated and untreated plywood experiments is in their maximum RHR. In tests of untreated plywood maximum rates of heat release of about 4 MW were recorded before the test was terminated. It is probable that these rates of heat release would have greatly exceeded 4 MW had the experiments not been terminated; however, the maximum capacity of our experimental facility is only about 4 MW. The maximum RHR recorded during experiment C-220 was about 3.1 MW, of which only slightly more than 2.9 MW was the result of plywood combustion. Thus the fire retardant treated plywood indicated two definite effects; increased time-to-flashover, and a reduced maximum RHR.

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2. Fisher, F.L. and Williamson, R.B., "Intralaboratory Evaluation of a Room Fire Test Method," NBS-GCR-83-421, National Bureau of Standards, Washington, D.C., January 1983.

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1. Fisher, F.L. and Williamson, R.B., "Intralaboratory Evaluation of a Room Fire Test Method," NBS-GCR-83-421, National Bureau of Standards, Washington, D.C., January 1983.

2. Fisher, F.L., Mowrer, F.W., and Williamson, R.B.,"A Room Fire Screening Test Procedure", Western States Section, Combustion Institute, Paper 83-7, April, 1983.

CENTER FOR FIRE RESEARCH
NATIONAL BUREAU OF STANDARDS
FY 83

Institution: Lawrence Berkeley Laboratory, University of California, Berkeley

Grant No.: NB 80 NAG-E6839

Grant Title: Fire Modeling

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NBS Scientific Officer: Dr. Gary Mallard

Technical Abstract:

The overall goal of this project is to develop physical and mathematical models of the detailed combustion phenomena which control a fire's growth through a structure. These experimental and theoretical studies will provide bases for code development and for evaluation of the real fire hazard of materials. This year's report focuses on incorporating experimental results for flame soot volume fractions in radiative combustion modelling [1-4], and on obtaining the variable fields profiles required for reconstructing the evolution of individual soot particles in a flame.

An analytical technique has been developed for combined force and free convection on a flat fuel surface of arbitrary inclination. The analysis uses a laminar boundary layer approximation for the gas flow, and the flame sheet approximation for gaseous reactions at the flame. Two new parameters are introduced: $(Gr_x^m + Re_x^n)^{1/2n}$, a mixed convection parameter which scales the dependent and independent variables, and a mixed convection ratio, $(Gr_x^m/Re_x^n)^{1/2}$ which plays the role of a streamwise local similarity coordinate. These two parameters are shown to be the optimum choice of governing nondimensional groups. m and n are chosen to obtain solutions for the limiting cases of horizontal (m = 2, n = 5), and vertical (m = 2, n = 4) convection. In each case, the new formulation enables a smooth transition of all physical variables solutions from one convective limit to the other. Results have been obtained

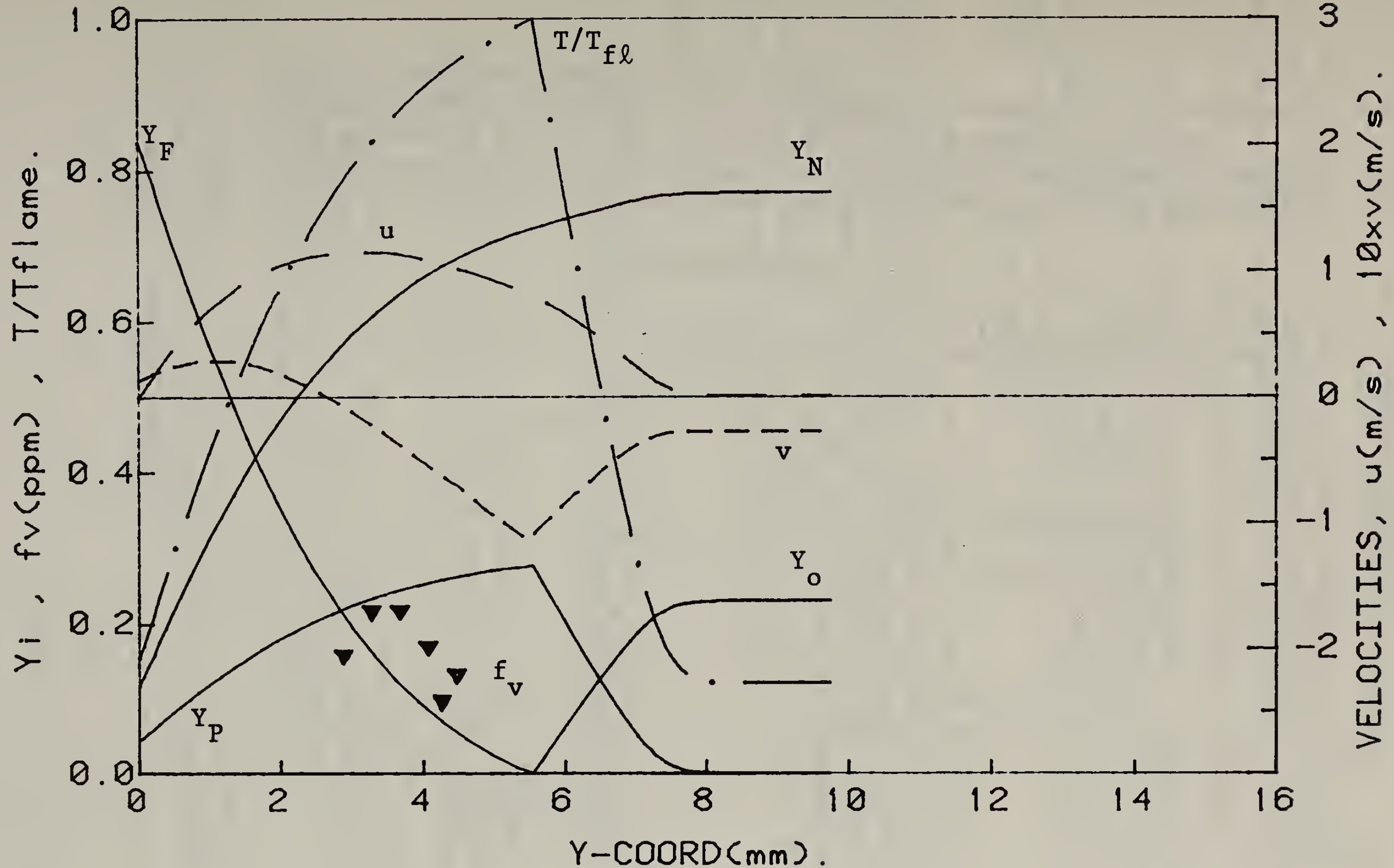

Fig. 1a. Velocity, temperature, species, and soot profiles in an n-heptane/air free flow boundary layer flame at 20 mm from the leading edge. Radiation effects are included. The calculated non-adiabatic flame temperature is Tflame = 2424 K. The pertinent dimensionless parameters are B = 5.6, D_c = 29.0 and r = 0.078.

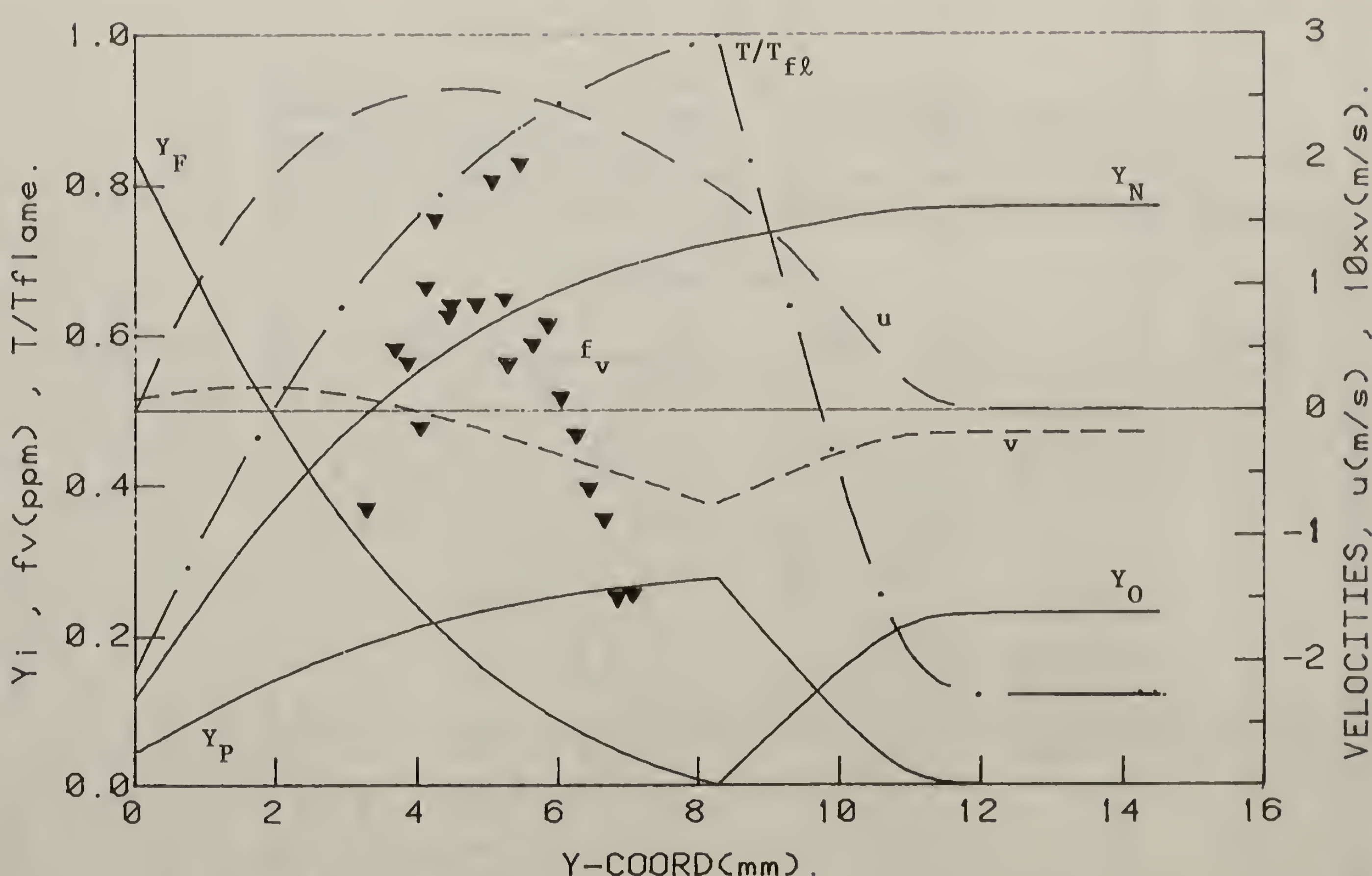

Fig. 1b. Velocity, temperature, species, and soot profiles as in Fig. 1a, except here the distance from the leading edge is 100 mm to show the evolution of the soot volume fraction profile. The soot exists primarily in the region between the converging streamline ($v = 0$) and the flame ($Y_F = Y_O = 0$).

by numerical integration of the governing equations, and from a local similarity approximation. It has been determined that buoyancy is a non-negligible effect in our horizontal forced flow combustion tunnel, primarily due to elevated $Y_{O\infty}$. We are now attempting to incorporate radiation in the mixed flow combustion analysis.

In the pure free flow case, the scaling of the physical variables in real space depends on the reference viscosity, ν_∞, and the profile shapes depend on the absorption coefficient, κ, through the coordinate, $\xi = 2^{1/2}\kappa x/Gr_x^{1/4}$. These properties have been obtained in free flow, for 5 liquid hydrocarbon fuels, and plexiglass. ν_∞ was obtained by matching flame standoff against analytical predictions at streamwise distances of x = 2,4, and 10 cm. The absorption coefficient, κ, was obtained by using experimental soot volume fractions adjusted to the optically thin approximation. These values of κ and ν_∞ have been used to calculate the variable fields shown in figs. 1a and 1b.

It has been possible to measure and quantify carbon particulates in laminar diffusion flames, and to compute detailed profiles of species and temperature, needed for modelling oxidation-formation reactions; as well as detailed 2-dimensional velocity profiles, enabling the construction of streamlines in free flow. Upon inclusion of thermophoretic forces and free-molecular drag and heat transfer, the particle paths may be traced and the development of each particle analyzed.

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4. C.-P. Mao, A.C. Fernandez-Pello and P.J. Pagni, "Mixed Convective Burning of a Fuel Surface with Arbitrary Orientation," submitted to the Journal of Heat Transfer.

CENTER FOR FIRE RESEARCH
NATIONAL BUREAU OF STANDARDS
FY 83

Institution: Lawrence Berkeley Laboratory, University of California, Berkeley

Grant No.: GE 1653-3

Grant Title: Flame Radiation

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K.Y. Lee (Ph.D. student)

NBS Scientific Officer: Dr. Takashi Kashiwagi

Technical Abstract:

The current objective of this project is to establish a simple physical framework for the calculation of radiation from complex fire phenomena. The basic research approach aims at developing approximate formulations by systematic experimentation and analysis of the fundamental aspects of the problem. The present research is focused on two primary topics: 1) Experimental and theoretical determination of radiative properties of gases evolved from burning condensed fuels, principally PMMA, and 2) Development of a simple calculation scheme for radiation absorption in a thin non-isothermal layer composed of these gases.

Radiation of Gases Evolved from Condensed Fuels. A significant energy input is required to ignite and maintain continuous burning of a condensed fuel. It has been found that this energy is primarily transported to the fuel by means of thermal radiation from the flame zone. As a result of the heating process, numerous gas species evolve from the solid fuel and act as strong absorbers to the incoming radiation. These gases therefore strongly influence the ignition and burning process. The gases of interest are principally complex hydrocarbons of which very little is known concerning the thermal radiation characteristics. A combined analytic and experimental research effort is therefore being directed toward the determination of the infrared radiation characteristics of the evolved gases. The experimental phase consists of the determination of the spectral absorption of several hydrocarbons commonly evolved from condensed fuels. These gases in-

clude methyl methacrylate ($C_5H_8O_2$), propane (C_3H_8), propylene (C_3H_6), ethane (C_2H_6), ethylene (C_2H_4), acetylene (C_2H_2), and methane (CH_4). Infrared measurements are being made for 1 atm. pressure and a temperature range of 300 to 900°K. Typical absorption curves obtained in this research for propylene (C_3H_6) are shown in Figs. 1 and 2 for a spectral range of 1200 to 4800 cm^{-1} (8.33 to 2.0 μm). The figures indicate the overlapping nature of the various absorption bands. The analytic portion of this project is then to develop a simple modeling scheme to specify the absorption of the overlapping bands and determine the overall radiation characteristics for the entire infrared region. A preliminary model has been developed which successfully groups the primary infrared bands of H_2O and CO_2 and accurately predicts the radiation behavior. It will be applied to the complex hydrocarbon data in an effort to describe the infrared radiation characteristics of the gases.

Radiative Energy Absorption in a Non-Isothermal Layer. Based on the information gained for the radiation properties of the hydrocarbon gases, a simple calculation scheme is being developed for radiation absorption in thin non-isothermal layers of these gases. The analytic study involves two steps. First, the gas properties for non-isothermal conditions will be determined by generalizing the existing methods for total band absorptance of non-isothermal gas layers to account for the overlapping bands of the various hydrocarbons. The combined band model previously mentioned can then be extended for non-isothermal conditions. The second phase then focuses on the calculation of the radiative energy absorption in the layers based on the equation of radiative transfer with radiative properties of non-isothermal gas mixtures. The net result will be to provide fundamental information to and complement the existing radiation measurements and radiation modeling for large pool fires.

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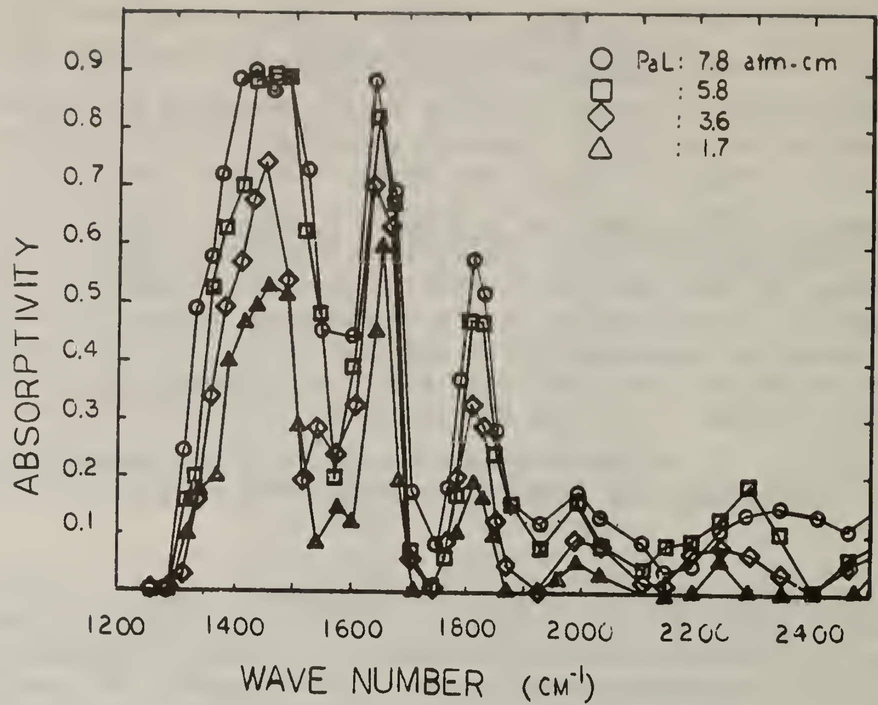

Fig. 1: Spectral absorption of Propylene near the ν_7 (1473 cm^{-1}) and ν_6 (1651 cm^{-1}) fundamental bands and the $2\nu_{19}$ (1825 cm^{-1}) first overtone band.

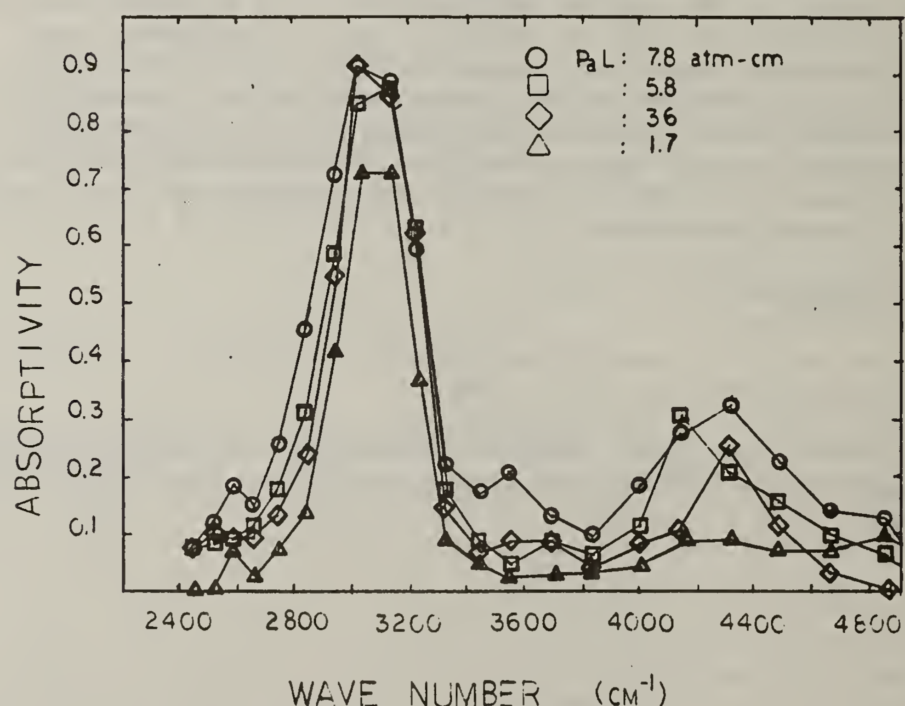

Fig. 2: Spectral absorption of Propylene near the combined ν_4, ν_3, ν_2, and ν_{15} fundamental bands (2950 cm^{-1}) and the two combination bands of ν_{9+5} and ν_{4+15} (4300 cm^{-1}).

CENTER FOR FIRE RESEARCH
NATIONAL BUREAU OF STANDARDS
FY 83

Institution: University of Florida

Grant Number: NB81NADA2057

Title: Network Models of Building Evacuation: Development of Software System - Year Two

Principal Investigators: Thomas M. Kisko and Richard L. Francis, Ph.D.
Industrial and Systems Engineering
University of Florida
Gainesville, FL 32611

NBS Scientific Officer: Leonard Cooper, Ph.D.

Technical Abstract:

This report summarizes the efforts of a two year project to develop user friendly software for the network modeling of building evacuation.

When the evacuation of a building involves the flow of people through well defined passageways, it is natural to consider the evacuation problem to be a network flow problem. EVACNET+ is a user friendly interactive computer program that accepts a user defined network model of a building, converts that model to a time expanded dynamic "transshipment" network, and solves the dynamic network using a capacitated minimum cost network flow algorithm. The solved dynamic network gives a time-dependent plan to evacuate the building in a minimum time, and identifies building evacuation bottlenecks.

The first year's effort of the project involved the development of the interactive computer program called EVACNET+. The second year's effort involved coding a post-processing routine, implementing and testing EVACNET+ on several types of computers, writing a user's guide, and testing the system with a sample of potential users.

The user defined network representation of a building is called a static model. A static model consists of a set of static nodes connected by static arcs. The nodes represent building components such as rooms, halls, landings, stairs and lobbies. The arcs represent the passageways between the building components. Nodes have two attributes: capacity and initial contents. The attributes of arcs are traversal time and capacity per unit time.

A static model is constructed by relating the building components and passageways of a building to nodes and arcs of a static model. The attributes of the nodes and arcs are estimated by

utilizing the dimensions of the building and the distribution of people in the building at the time of the evacuation.

When the EVACNET+ is run, the static model is converted to a time expanded network called a dynamic model. A dynamic model is a representation of the building where each node of the static model is expanded into a series of dynamic nodes. Each dynamic node represents a building component at the end of a time period. Dynamic nodes associated with a specific static node are connected with hold-over arcs. The hold-over arc flows represent people staying in a room for the unit time period associated with the specific hold-over arc.

The dynamic nodes are also interconnected by movement arcs. Flows in these arcs represent, for a specific time period, the movement of people from one building component to another building component. There are a series of movement arcs for each individual static arc. Movement arcs proceed from a dynamic node at one time period and to a dynamic node for a later time period; the later period is determined by the traversal time of the associated static arc.

The dynamic model is solved using NETFLO as a subroutine to EVACNET+. NETFLO is a primal network code for the solution of capacitated network flow problems. The principal limitations of the model are as follows: (1) it is a linear model; (2) it does not represent behavioral aspects.

EVACNET+ is an interactive computer package that is user friendly. The input is free format. Static nodes and arcs are referred to using a special form. For example, WP2.3, refers to the second workplace on the third floor. WP2.3-HA4.3 refers to a static arc from the workplace to a hall on the same floor.

A user running EVACNET+ sits at a computer terminal and first enters the static nodes and arcs representing the building of interest. The process is totally "menu driven", in the sense that all the user has to do is select options and answer associated questions. The model is also run interactively. Results can be displayed on a terminal or printed. If the user wishes, the static model may be modified and rerun.

Figure 1 is the master option list of EVACNET+. When the option list is displayed, the user has twelve alternatives to select from. Upon entering a valid option code, the system will display a suboption list. From the suboption list the user may select any of the desired actions presented, including returning to the master option list.

```
                    EVACNET+
   BUILDING EVACUATION ANALYSIS PROGRAM
             MASTER OPTION LIST

CODE             REQUESTED ACTION

EN   - ENTER NODE DEFINITIONS
EA   - ENTER ARC DEFINITIONS
LN   - LIST NODES
LA   - LIST ARCS
DN   - DELETE NODES
DA   - DELETE ARCS
SYS  - DEFINE OR REDEFINE SYSTEM ATTRIBUTES
RM   - RETRIEVE DEFINED MODEL
RUN  - RUN MODEL
EXAM - EXAMINE RESULTS
QUIT - TERMINATE EXECUTION OF EVACNET
HELP - WHENEVER YOU HAVE QUESTIONS

ENTER CODE OF REQUESTED ACTION
```

FIGURE 1 - EVACNET+ MASTER OPTION LIST

Figure 2 is an example of a suboption list. It is the option list produced by the EXAM master option and allows the user to select any of 14 specific results.

EVACNET+ is a powerful tool that will allow fire safety engineers to make objective decisions about the evacuability of buildings.

REPORTS AND PAPERS:

Chalmet, L. G., Francis, R. L., and Saunders, P. B., "Network Models For Building Evacuation", Management Science, Vol. 28, No. 1, pp. 86-105, January, 1982.

Also reprinted in Fire Technology, Vol. 18, No. 1, pp. 90-113, February, 1982.

Kisko, T. M., and Francis, R. L., "Network Models of Building Evacuation: Development of Software System", Final Report - Year One, National Bureau of Standards, NB81NADA2057, December, 1982.

Kisko, T. M., and Francis, R. L., "EVACNET+: A Network Model of Building Evacuation", Proceedings of the Conference on Computer Simulation in Emergency Planning, San Diego, January, 1983.

Kisko, T. M., "EVACNET+ Implementation Guide", Industrial and Systems Engineering Department, University of Florida, Gainesville, FL, August, 1983.

Kisko, T. M., and Francis, R. L., "EVACNET+ User's Guide", Industrial and Systems Engineering Department, University of Florida, Gainesville, FL, August, 1983.

```
                 PRIMARY EXAM OPTION LIST
     FORM MODEL ID - "EXAMPLE THREE STORY BUILDING"

1   SUMMARY OF RESULTS:
         BASIC STATISTICS OF EVACUATION
2   DESTINATION ALLOCATION:
         NUMBER OF EVACUEES BY DESTINATION
3   TOTAL ARC MOVEMENT:
         TOTAL MOVEMENT THROUGH AN ARC BY ARC
4   BOTTLENECKS:
         IDENTIFICATION OF BOTTLENECK ARCS
5   FLOOR CLEARING TIME:
         TIME TO CLEAR A FLOOR BY FLOOR NUMBER
6   UNCONGESTED TIMES:
         UNCONGESTED EVACUATION TIME BY NODE
7   NODE CLEARING TIME:
         TIME TO CLEAR A NODE BY NODE
8   BUILDING EVACUATION PROFILE:
         NUMBER OF EVACUEES BY TIME PERIOD
9   DESTINATION EVACUATION PROFILE:
         NUMBER OF EVACUEES BY TIME PERIOD FOR EACH DESTINATION
10  NODE CONTENTS PROFILE:
         PEOPLE WAITING AT END OF TIME PERIOD BY TIME PERIOD
11  NODE CONTENTS SNAPSHOT:
         PEOPLE WAITING AT END OF THE PERIOD BY NODE
12  ARC MOVEMENT PROFILE:
         MOVEMENT THROUGH AN ARC BY TIME PERIOD
13  BOTTLENECK PROFILE:
         BOTTLENECK ARC INFORMATION BY TIME PERIOD
14  NON-EVACUEE ALLOCATION:
         NUMBER OF NON-EVACUEES BY NODE

ENTER OPTION NUMBER, OR 'END' TO RETURN TO MAIN MENU
```

FIGURE 2 - EVACNET+ EXAM OPTION LIST

CENTER FOR FIRE RESEARCH
NATIONAL BUREAU OF STANDARDS
FY 83

Institution: University of Maryland, College Park

Grant No.: NB80NADA1067

Grant Title: The Determination of Behavior Response Patterns in Fire Situations, Project People II

Principal Investigator: Dr. John L. Bryan, Professor and Chairman
Department of Fire Protection Engineering
University of Maryland
College Park, MD 20742
(301) 454-2424

Other Professional Personnel: Mr. James A. Milke, Lecturer

NBS Scientific Officer: Dr. Bernard Levin

Technical Abstract

The progress involved in the final phase of this study involved the analysis of the behavior response patterns identified from in-depth, open-ended interviews with supplemental structured questionnaires. The study interviews were conducted by University of Maryland personnel at the scene of the fire incident in the time period from one to four weeks following the occurrence of the fire incident.

The objectives of this research study were established in the initial phase of the study, and were continued during the final phase of the study with the emphasis during this reporting period on objectives 2 and 3:

1. To analyze the established variables of building occupants in fire situations as these variables have been established and identified in the previous project people studies primarily concerned with the residential occupancies and the project people II studies primarily concerned with the health care occupancies.

2. To attempt the evaluation of the existing models of human behavior in these fire incidents. The premodel concepts of Archea and Withey were analyzed with the models of Bickman, Edelman, and McDaniel. The computer models of Stahl and the model of Berlin were evaluated with the conceptual models of Canter.

3. To compare the developed human behavior response patterns to the provisions of the Life Safety Code and the model building codes.

The research study has evaluated the preconceptual models, the conceptual models and the computer models of human behavior response with the observed and documented behavior response patterns established from the study populations of both the Project People and the Project People II research studies. The Project People study involved 335 fire incidents with questionnaire responses from 584 individuals. The Project People II study involved 65 fire incidents confined to health care, educational, correctional and large residential occupancies with a total questionnaire and interview population of 880 individuals. Thus, the total study population utilized in the analysis was obtained from a total of 400 fire incidents and 1,464 individual behavioral response patterns.

The established and analyzed human behavioral response patterns were compared with the provisions in the 1981 edition of the Life Safety Code, the 1981 edition of the Basic Building Code, the 1982 edition of the Uniform Building Code and the 1979 edition of the Standard Building Code. The behavior response patterns indicated few of the participants observed exit signs, varying between 6 and 8 per cent. The participants tended to move through smoke to obtain egress, and the behavior in the majority of the fire incidents would be classified as information seeking and objective orientated in contrast to the sterotyped accounts of individuals panicking and competing for escape. Altrustic behavior was frequent, involving the notification of others, assistance to others, and reentry of the fire incident building to assist others.

The features of the codes that would appear to require further study from the analysis of the behavior response patterns involved; the color, location and design of exit signs; the utilization of audible signaling devices rather than verbal communicative devices for evacuation notification; and the provision of the floor level illumination specified in the codes at the floor level.

The most effective and productive behavioral responses in the health care occupancies involved the closing of patient room doors by staff personnel. Staff personnel in health care occupancies were alerted to the fire incidents by the automatic closing of smoke barrier doors in addition to the conventional signaling devices.

Reports and Papers

Bryan, John L., Implications for Codes and Behavior Models From The Analysis of Behavior Response Patterns in Fire Situations as Selected From The Project People and Project People II Study Programs. NBS GCR-83-425, March 1983.

CENTER FOR FIRE RESEARCH
NATIONAL BUREAU OF STANDARDS

Institution: The University of Michigan

Grant No.: NBS Grant NB80NADA1054

Grant Title: Degradation of Mechanical Properties of Wood During Fire

Principal Investigator: Professor George S. Springer
Department of Mechanical Engineering and Applied Mechanics
The University of Michigan
Ann Arbor, Michigan 48109

Other Professional Personnel: M.H. Do
N.H. Jin
C.H. Tsai

NBS Scientific Officer: William J. Parker

Technical Abstract:

The objectives of this investigation were to evaluate the decrease in mechanical properties of wood exposed to fire, and to develop a method that can be used to predict the failure time of loaded structural members during fire exposure. In order to achieve these objectives, tests were performed measuring the thermal response as well as changes in the mechanical properties of wood exposed to flames or to a radiant heat source. In conjunction with the test, models were developed for describing the behavior of the wood exposed to high temperature environments and for predicting the failure time.

An important part of the pyrolysis of wood is the heating up of wood and the evaporation of volatiles from the material. The heating up is characterized by a temperature rise inside the material. The evaporation of volatiles is represented by a mass loss. In this investigation the temperature response and mass loss of wood were measured at heat fluxes which result in surface temperatures of 100 to 800°C. Data were obtained for southern pine and douglas fir. These types of wood were selected for the tests because of their wide use in the building industry. The measurements were performed by placing 100 mm long and 25.4 mm wide test specimens in a temperature controlled oven. The weight (mass) losses of the specimens and the centerline temperatures were recorded as a function of time. The oven temperatures were 100, 160, 245, 400, 600, and 800°C. Specimens of different thicknesses were used in the tests, the thicknesses being 6.35, 12.7, 19.05, and 25.4 mm. The weight loss and the thermocouple data were compared to the results of the analytical

model described subsequently. Good agreement was found between the data and the results of the model.

Tests were also performed to assess the influence of the ambient oxygen concentration on the mass loss. In these tests the oven was filled with either pure oxygen or with pure nitrogen. Mass losses were measured in these two environments at 100 and 245°C. The mass loss was somewhat higher in the pure oxygen environment. However, the maximum difference in the mass loss in pure oxygen and in pure nitrogen environments was only about 25 percent.

The tensile, compressive, and shear properties of southern pine and douglas fir were also measured after the test specimens were heated at either 100, 160, 245, 400, 600, or 800°C for different lengths of time. The strengths and the moduli in the directions both parallel and transverse to the grain were then measured at room temperature. The longitudinal and the transverse tensile strengths and moduli of southern pine and douglas fir were measured as functions of exposure time at all six of these temperatures. In addition, the longitudinal and transverse compression, and the longitudinal shear strengths and moduli of southern pine were measured at 400, 600 and 800°C. Specimens with different dimensions were used in the tests. Thus, the data provide the longitudinal and transverse strengths and moduli as functions of specimen geometry, exposure temperature, and exposure time. It is noted that longitudinal tensile strengths of southern pine were also measured with specimens kept at elevated temperatures during the tests. The strengths of the specimens tested "hot" and "cold" agreed closely.

The strengths and the moduli were also calculated by the model described below. The results of the model and the data agree well, creating confidence in the validity of the model.

In addition to testing, analytical models were developed to simulate the response of wood to fire exposure. The major goals in constructing the models were to describe changes in the thermal and mechanical properties and, most importantly, to predict the time of failure. The model was developed in three steps: a) calculation of the temperature distribution and the mass loss, b) prediction of the changes in the tensile, compressive, and shear properties, and c) prediction of the failure time.

In the first part of the model the temperature distribution inside the wood and the mass loss are calculated. This part of the model is based on the law of conservation of energy, with the chemical reactions being represented by a single step Arrhenius bulk reaction. As noted above, the results of the model agreed well with the data generated in this study.

The second part of the model is used to estimate changes in the strengths and the moduli. This part of the model is based on the hypothesis that degradation in the mechanical properties is related to the mass loss due to volatilization of the wood. Using the model, together with data obtained in this program, correlations were developed which show the changes in the tensile, compressive, and shear strengths and moduli of southern pine and douglas fir in the temperature range 100 to 800 °C. As pointed out above, the strengths and moduli of southern pine and douglas fir specimens exposed to elevated temperature predicted by the model were in good agreement with the data.

The third part of the model provides the failure time of loaded beams during fire exposure. The model employs the flexure formula modified to account for changes in the strength with exposure time. In addition to the failure time, the model also yields the changes in the safety factor with time before failure occurs.

On the basis of the model, a "user friendly" computer code was developed. All three steps of the model are incorporated into this code. The computer code can be applied to loaded wooden beams exposed to elevated temperature and provides the following parameters as functions of exposure time: a) temperature distribution inside the wood, b) mass loss, c) longitudinal and transverse tensile strength and modulus, d) longitudinal and transverse compressive strength and modulus, e) longitudinal shear strength and modulus, f) safety factor, and g) failure time.

Failure times calculated by the model were compared a) to failure times (measured in this study) of 19 x 19 mm and 1200 mm long simply supported southern pine beams exposed to fire, and b) to failure times (measured by NBS) of southern pine ceiling joists during the fire of a full scale room. Reasonable agreements were found between the calculated failure times and the data.

The results of this investigation provide a means for estimating the failure time of loaded wooden beams during fire. This information can be utilized in designing wooden structural members so as to minimize losses resulting from failure.

Reports and Papers

G.S. Springer, and M.H. Do, "Degradation of Mechanical Properties of Wood During Fire". Report submitted to Center for Fire Research, National Bureau of Standards, May 1983.

R.M. Dastin, D.A. Stanke, and G.S. Springer, "Mechanical Properties of Southern Pine and Douglas Fir at Elevated Temperatures" Journal of Fire and Flammability, (in print).

M.H. Do and G.S. Springer, "Mass Loss of and Temperature Distribution in Southern Pine and Douglas Fir in the Range 100 to 800°C" Journal of Fire Sciences (submitted).

M.H. Do and G.S. Springer "Model for Predicting Changes in the Strengths and Moduli of Wood Exposed to Elevated Temperatures", Journal of Fire Sciences (submitted).

M.H. Do and G.S. Springer, "Failure Time of Loaded Wooden Beams during Fire", Journal of Fire Sciences (submitted).

CENTER FOR FIRE RESEARCH
NATIONAL BUREAU OF STANDARDS
FY 83

Institution: University of Montana, Missoula, MT 59812

Contract Number: NB81NADA2066

Grant Title: Chemistry of Smoldering Combustion and its Control

Principal Investigator: Professor Fred Shafizadeh
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University of Montana
Missoula, MT 59812
(406) 243-6212

Other Professional Personnel: Dr. Yuki Sekiguchi

NBS Scientific Officer: Dr. Thomas J. Ohlemiller

Technical Abstract

The general objective of this project is to develop a molecular understanding of smoldering combustion and possible methods for controlling it. The present studies are aimed at determining the chemical changes in composition and structure of the substrate and correlation of these structures with the reactions involved in smoldering combustion.

It has been shown that smoldering combustion of cellulosic materials involves (a) pyrolysis of the substrate to provide a highly reactive pyrophoric char, (b) chemisorption of oxygen on the fresh char, and (c) gasification of the char from sites containing chemisorbed oxygen, resulting in the creation of new active sites and propagation of the combustion process.

Heating of cellulosic materials leaves a solid residue, which is neither intact substrate nor pure carbon, but a different material at various stages of charring and carbonization. The intermediate chars are characterized by the functional groups present, including aromatic and paraffinic structures, a high concentration of free spins trapped in a rigid structure or stabilized by aromatic structures, a large surface area, and a high degree of reactivity, all of which depend on progression of the secondary reaction in the solid phase. Development of these structures and functionalities has been investigated by several chemical and physical methods and related to the pyrolysis conditions, particularly heating, the presence of inorganic catalysts, and the reactivity of the products. These experiments were conducted with cellulose, lignin and wood heated for 5 min at temperatures ranging from 300-600°C.

Development of aromaticity was established by permanganate oxidation of chars which gives benzene polycarboxylic acids derived from the aromatic nuclei, indicating the extent of aromaticity and crosslinking

of the carbon chain in polycyclic aromatic structures. FTIR was used to show the disappearance of the hydroxyl and glycosidic group at ~3500 and 900-1200 cm^{-1} and the formation of C=C and C=O groups at 1600 and 1700 cm^{-1}, respectively. Quantitative data on the concentration of various carbon species was obtained by CP/MAS ^{13}C-NMR. These species included paraffinic (0-60 ppm), glycosylic (60-110 ppm), aromatic and olefinic (100-170 ppm), carboxyl and ester (170-190 ppm) and carbonyl carbons (190-220 ppm).

These data indicated a rapid weight loss at temperatures up to 400°C which is accompanied by destruction of the anhydroglucose units in cellulose through dehydration, rearrangement and development of C=C, C=O and COO groups, forming a relatively stable char containing aromatic and aliphatic groups. The "stable" char formed at 400 °C contained 69% aromatic, 27% paraffinic and no glycosylic carbons (see Figure 1). Heating at higher temperatures resulted in preferential loss of the paraffinic groups through homolytic cleavage, forming highly condensed polycyclic aromatic structures and resonance stabilized free radicals. At 500 °C the char contained 88% aromatic carbon with 12% intermittent paraffinic groups (see Figure 1), and nearly a maximum concentration of free spins.

Surprisingly, the lignin and wood chars prepared at 400°C had about the same aromatic content as the corresponding cellulosic char, although the char yields were substantially higher from lignin and wood as compared to cellulose. Therefore it was concluded that the presence of preformed aromatic groups (guaiacyl groups) does not increase the aromaticity of the chars from lignin. The char from lignin and wood showed distinct NMR peaks for the methoxy phenyl groups of lignin (guaiacyl units) from which the char yield of the lignin component of wood could be estimated.

DSC and TG studies simulating smoldering combustion of cellulose and chars prepared at temperatures up to 600°C showed that the heat release associated with the oxidation reactions takes place in two stages corresponding to the rapid weight loss at ~350°C and to combustion of the stable char at 500°C. Furthermore the magnitude of the oxidation isotherms was highly dependent on the progress of charring and carbonization of the substrate. As shown in Figure 2, the second isotherm (at ~500°C) is very small for cellulose but gradually expands as the charring reaction proceeds and the aliphatic carbons are converted to polycyclic aromatic carbons. Graphite, which is highly crosslinked behaves quite differently and does not show either of the two isotherms. It appears that the first isotherm is caused by oxidation of the more reactive aliphatic component and the second isotherm is due to the oxidation of the more stable and resistent aromatic groups in the char; thus, the intermediate chars are more reactive and are oxidized at lower temperatures to provide the driving force for smoldering combustion.

Reports and Papers

W.F. DeGroot and F. Shafizadeh, "Effect of Inorganic Additives on Oxygen Chemisorption on Cellulosic Chars", Carbon 21, 61-67 (1983).

F. Shafizadeh and Y. Sekiguchi, "Development of Aromaticity in Cellulosic Chars", Carbon, in press.

F. Shafizadeh, "The Chemistry of Fire Retardants", Proceedings of the Conference on Chemical Aspects of Wood Technology by Ingvar Johansson and Solveig Johansson, Swedish Forest Products Research Laboratory, Stockholm, Sweden, June (1982).

F. Shafizadeh, "Pyrolytic Reactions and Products of Biomass", Proceedings of the 1983 Fundamentals of Thermochemical Biomass Conversion, an International Conference, Estes Park, Colorado, in press.

F. Shafizadeh, "Chemistry of Pyrolysis and Combustion of Wood", Progress in Biomass Conversion, 3, 51-76 (1982).

Y. Sekiguchi, J.S. Frye, and F. Shafizadeh, "Structure and Formation of Cellulosic Chars", J. Appl. Polym. Sci., submitted for publication.

F. Shafizadeh, "The Chemistry of Pyrolysis and Fire Retardants", ACS Advances in Chemistry: The Chemistry of Solid Wood", Roger M. Rowell, ed; Academic Press, submitted for publication.

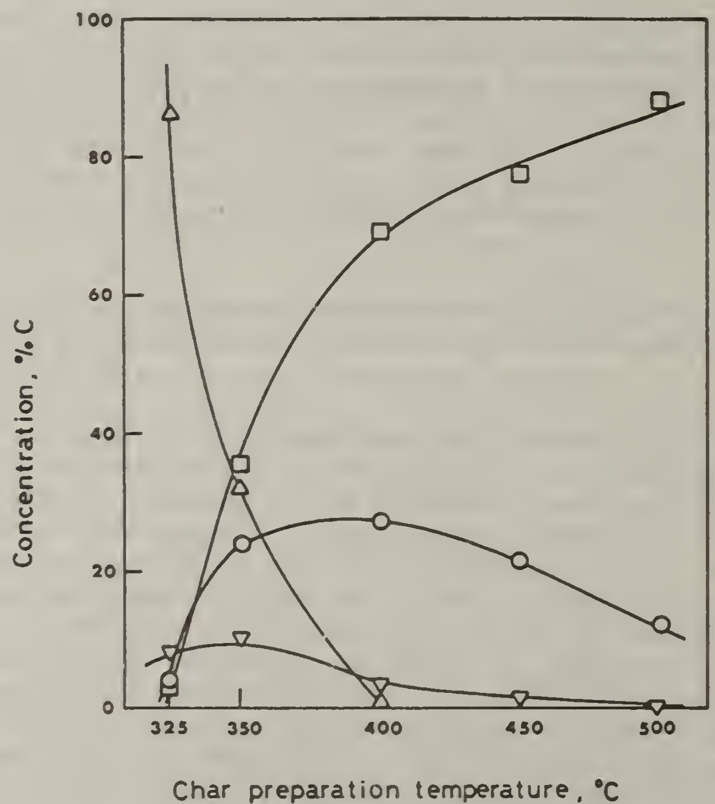

Figure 1. Concentration of different carbon species in char prepared at 325-500°C: glycosylic, —△—; aromatic, —□—; paraffinic —○—; and carbonyl and carboxyl, —▽— .

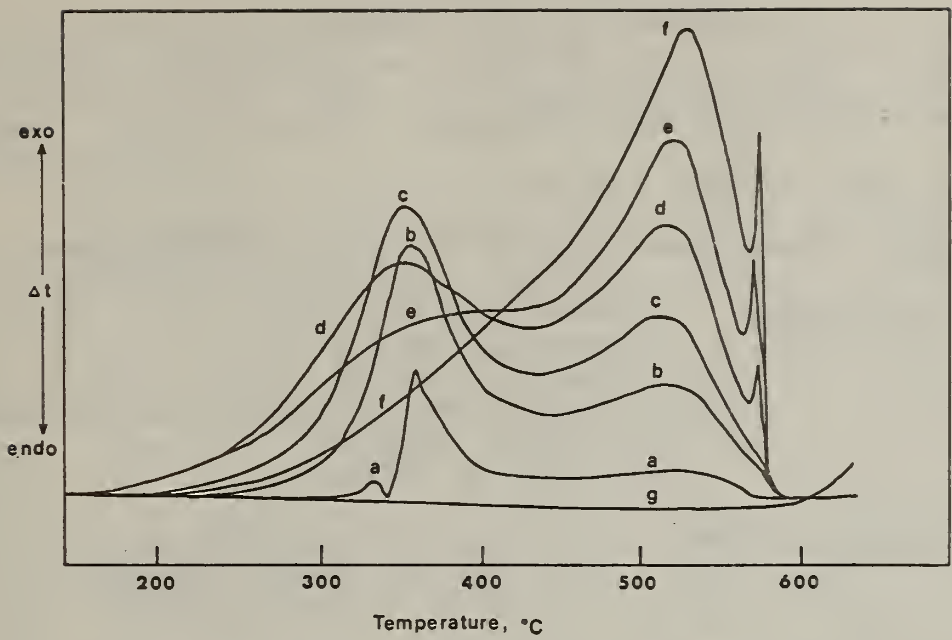

Figure 2. Differential scanning calorimetric curves of cellulosic chars measured in a stream of air. a = cellulose; b-f = cellulosic chars prepared by 5 min heating in N_2 at 340(b), 350(c), 400(d), 500(e), and 600°C(f), respectively; g - graphite.

CENTER FOR FIRE RESEARCH
NATIONAL BUREAU OF STANDARDS
FY 83

Institution: University of Notre Dame

Contract No.: NBS Grant NB81 NADA 2000

Contract Title: Computer Modeling of Aircraft Cabin Fire Phenomena

Principal Investigators: Professor K. T. Yang
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Other Professional Personnel: H. S. Kou, Ph.D. Candidate
R. L. McClain, Research Specialist
B. P. De Souza, Ph.D. Candidate

NBS Scientific Officer: Dr. Walter Jones

Technical Abstract

This study of aircraft cabin fire phenomena addresses both the internal cabin fire problem and the external fuel spill fire-fuselage interaction problem. The goal of the study is to develop experimentally verified computer field modeling technology to study the spread of fire and smoke inside of and external to aircraft cabins which are important to the description of hazzards to passengers involved in survivable aircraft fires. The major objectives during the current year are to develop both experimental and computer based studies of fire fuselage interactions for externally burning fuel spills and the effects of distributed ceiling and floor vents on the spread of fire and smoke inside aircraft cabins. Progress is concentrated in the experimental studies for the eternal fuselage problem and in calculations of the effects of blowing from ceiling vents on the fire and smoke spread inside the cabin. The following is a brief description of the specific tasks which have been performed.

1. External Pool Fire - Fuselage Interaction Problem

The basic UNDSAFE program has successfully been modified to accommodate the cylindrical geometry in the neighborhood of the fuselage of circular cross-section. The calculation mesh is in cylindrical coordinates close to the fuselage and becomes cartesian far away from the fuselage. Initial calculations established that the second order conduction terms were programmed correctly through analysis of the transient conduction heat up around the fuselage. The debugging process has been completed for the complete conduction problem by comparing the finite difference calculation, through the cylindrical and cartesian mesh region, with the exact analytical solution. Of current interest is the starting up of a pool fire located on the ground beneath the fuselage. The interactions between the plume and the fuselage are of current concern.

The companion experimental study is being conducted in the specially designed wind tunnel. In the experiments air is blown across a circular cylinder model of the fuselage, of diamter D, which can be positioned at any height, H, above the floor of the tunnel. Flow visualization is accomplished through the use of a smoke wire. Figure 1 shows a typical photo with the cylinder located at a dimensionless height, H/D, of 1.1 and a Reynolds number of 5200 based on the cylinder diameter. The flow around the cylinder as well as the turbulent boundary layer flow along the wall are visible. Even at this height relative to the floor there is indication that there is some interaction between the cylinder and the floor. The cylinder was instrumented with a single pressure tap and the cylinder was made so that it could be rotated. The pressure on the cylinder as a function of angle around the cylinder is currently being measured as a function of Reynolds number and H/D ratio. Shown in Figure 2 are two sets of data for H/D = 0.58 and 0.75. The pressures on the top and bottom surfaces are noted. In the middle of the tunnel the dimensionless pressure distribution (not shown) is identical for the top and bottom surfaces. As the cylinder moves closer to the surface the effect of the wall is to increase the pressures on the lower surface. The point of the minimum also moves back around the cylinder in the presence of the wall. These data will be used for code verification when the corresponding cases are calculated.

2. Internal Cabin Fire Control by Venting

Calculations have been made of the internal cabin geometry with a fire initiated in the central region of the cabin. Fresh air is injected through the ceiling vents at a velocity of 0.09 m/sec which is equivalent to a complete air change every 20 minutes. Figure 3 shows an isotherm (a) and a velocity field (b) plot of the cabin environment. The presence of unsteady behavior is clearly noted in both figures. Seats are now being added to the flow geometry and radiation effects on the cabin environment are being examined.

Fire hazard is an inherent scenario in survivable accidents for aircraft, and it is generally recognized that loss of life can be reduced when fire and smoke spread phenomena are better understood through careful, systemmatic research.

Reports and Papers

Satoh, K., Lloyd, J. R., Yang, K. T., Kanury, A. M., "A Numerical Finite-Difference Study of the Oscillatory Behavior of Vertically Vented Compartments," Proceedings Second National Symposium on Numerical Methods in Heat Transfer, 1983, pp. 517-528.

Figure 1. Smoke wire flow visualization of flow around cylinder located 1.1 diameters above the floor. Re_D = 5200

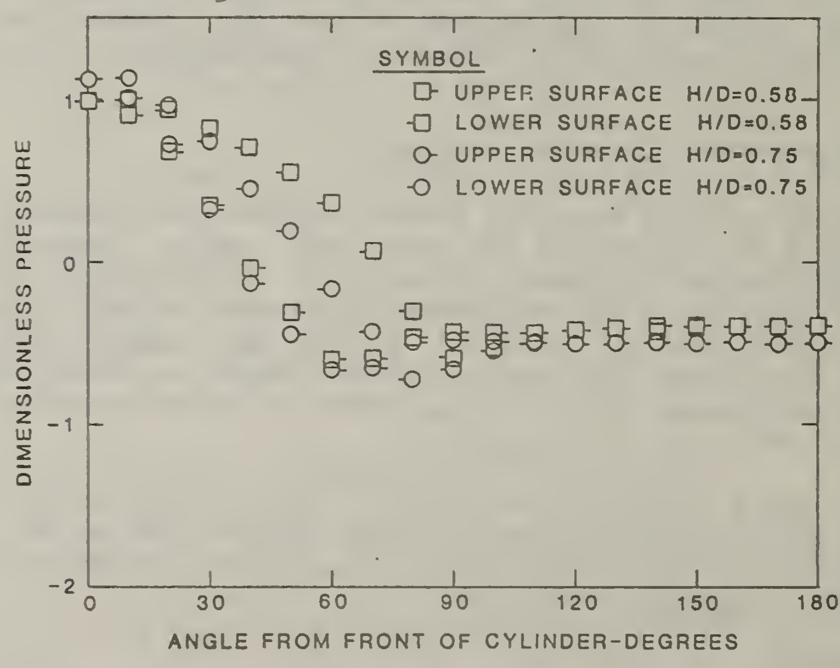
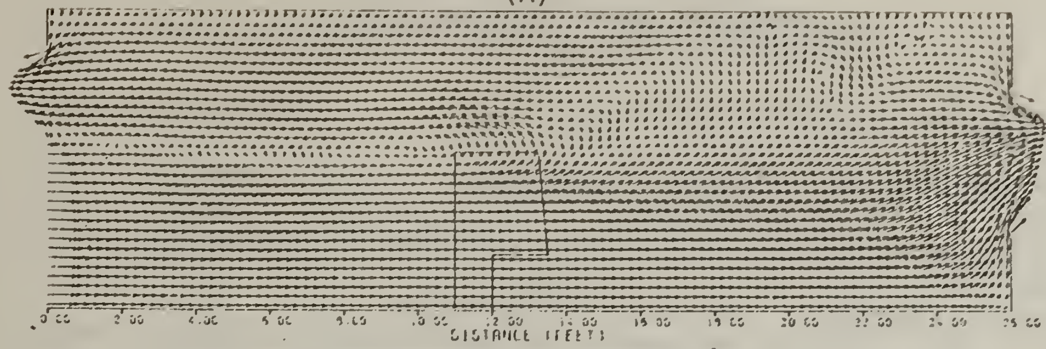


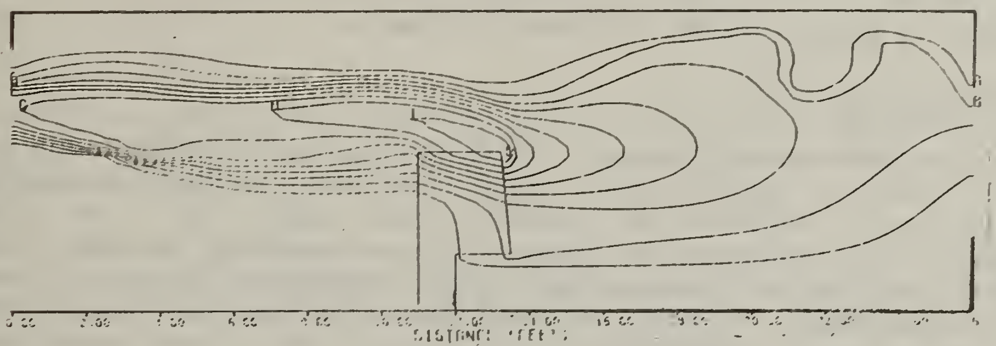
Figure 2. Measured pressure distributions around a cylinder near the floor. Re_D = 5200

(A)



At Time = 118.38 Seconds (Heat = 280 KW)

(B)



A , T=1.049
B , T=1.099
C , T=1.148
D , T=1.197
E , T=1.247
F , T=1.296
G , T=1.345
H , T=1.394
I , T=1.444
Q , T=1.493

At Time = 118.38 Seconds (Heat = 280 KW)

Figure 3. Calculated velocity and temperature distributions with air injection at ceiling.

CENTER FOR FIRE RESEARCH
NATIONAL BUREAU OF STANDARDS
FY 83

Institution: University of Notre Dame

Contract Number: NBS Grant NB 81 NADA 2021

Contract Title: Scaling Correlations of Flashover Experiments

Principal Investigator: Professor A. M. Kanury
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Notre Dame, IN 46556

Other Professional Personnel: Mr. M. S. Riepenhoff
Graduate Research Assistant

NBS Scientific Officer: Mr. William J. Parker

Technical Abstract

The objective of this project is to develop scaling rules for the room fire flashover problem and to apply these rules to the experimental data obtained at NBS with the quarter scale model room. The hope underlying this objective is to discover a correspondence between rooms of different scales and geometries in their flashover behavior. With such a correspondence in hand, it might become possible to assess from a set of well-planned experiments if and when flashover would occur in a real room.

Special consideration is given in the present scaling rule development to the role played by the room dimensions, the lintel height, wall-linings, the window or door opening geometry and the nature of the fire source.

Based on mass, momentum, and energy conservation for the fire room, the following dimensionless parameters are deduced.

Initial fire parameter $\phi_o \equiv \dot{m}_v/kW_oH_o^{3/2}$

Wall lining parameter $\beta \equiv \bar{h}(T_f-T_w)f\ \overline{q/I}$

Window geometry parameter $\psi \equiv W_o/H_o$

Lintel depth parameter $\gamma \equiv \bar{A}/W_oH_o$

Ceiling heat transfer parameter $\Omega = \bar{h}/kC_{pg} H_0^{1/2}$

[Time to flashover $\tau^* \equiv \bar{h}^2 t^*/(K\rho C)$]

$\dot{m}_v$ is the fuel input to the initial fire source. k is a constant equal to 1.6 $kg/sm^{5/2}$ whose origin lies in the mechanics of flow through the window. W_0 and H_0 are respectively the window width and height. $\bar{A}$ is the area of the ceiling plus the upper part of the walls lying above the soffit skirt. $\bar{h}$ is the convective plus radiative heat transfer coefficient between the hot fire gases and the ceiling. C_{pg} is gas specific heat, t* is flashover time. K, ρ, and C are respectively the lining thermal conductivity, density and specific heat. $\bar{h}(T_f-T_w)$ is the heating rate of the wall linings by the growing flames. f is a constant equal to 0.02 m^2/kW,the area of walls covered by an initial fire of one kW strength. q is heat release rate (W/m^2) of the wall lining material exposed to an external flux of I (W/m^2) so that $\overline{q/I}$ is the measured average of heat release rate per unit exposure rate.

When the NBS-CFR mobile home flashover fire test data are plotted with flashover time τ* as a function of the initial fire strength φ and wall lining combustibility β for given Ω, γ and ψ, the following conclusions are apparent.

(a) Data of all the tests for which the flashover time is finite follow a pattern of decreased τ* with increased $\phi(1+\beta)$. This pattern is expectable, for situations involving large initial fires and highly combustible walls culminate in an early flashover.

(b) There appears to be indication that no flashover would occur if the initial fire is so small and the wall lining is so noncombustible as to result in the quantity $\phi(1+\beta)$ less than about 2.

(c) The range of variation in the soffit parameter γ, window aspect ratio ψ, and the ceiling heat transfer parameter Ω, between the two sets of full-scale tests and one set of quarter-scale tests, is quite wide although not systematic. The scatter in the correlation does not now permit a clear-cut delineation of these parametric effects. The scatter could be partly due to the incompleteness of the correlation scheme, partly due to the method of interpretation of the flashover phenomenon as embodied in the time to flashover recorded in the source reports, partly due to uncontrolled variances between tests which are otherwise deemed identical, partly due to departures in geometric (and, sometimes, dynamic) similarity between test groups, and lastly due to possible property variations. Recall that: (i) the wall lining moisture content is ignored; (ii) the heat release rate of the lining materials is averaged over the expectable incident radiant fluxes; (iii) the convective and radiant heat transfer coefficients are merely estimated and taken to be the same for the flame to wall lining heat transfer as well as hot gas layer to the ceiling; and (iv) the wall combustibility parameter β as well as the functional form in which it enters into our correlation are based on heuristic arguments rather than on a reasoned hypothesis. Further study is required of these and other relevant issues of the room fire scaling problem. Consideration of further systematically conducted experiments with an improved hypothesis and with better property values appears to be in order.

(d) Ambiguities related to moisture exist for further scrutiny. For example, how does the moisture affect the conductivity, density and specific heat in addition to the heats of combustion and pyrolysis?

(e) The ambient air relative humidity is purported to have an influence on the fire development process. We do not now know how to account for this influence.

(f) The role of furnishings in the flashover process is another issue not clear from the present correlation.

(g) Not withstanding these difficulties, it is indeed encouraging that there exists a reasonable trend of dependency of flashover time on the initial fire and the wall combustibility.

Reports and Papers:

A. M. Kanury, "Scaling Correlations of Flashover Experiments," Final Report Submitted to NBS-CFR for Grant NB 81 NADA 2021, 1983.

CENTER FOR FIRE RESEARCH
NATIONAL BUREAU OF STANDARDS
FY 83

Institution: University of Pittsburgh

Contract Number: NB79NADA0009

Contract Title: Toxicity of Plastic Combustion Products

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NBS Scientific Officer: Barbara C. Levin, Ph.D.

Technical Abstract

The objective of this project is to develop methods for investigating the toxicity of thermal decomposition products from synthetic or natural polymers.

Two major projects were completed this year. The first one consisted of correlating the data obtained for the toxicity of thermal decomposition products from polyurethane foam, cotton batting and polyester fibers obtained in the small scale decomposition system with the results obtained on chair smoldering tests using the same materials used for the chair construction. Polyurethane was found to produce the most toxic smoke in the small scale system as well as during the chair smoldering tests. Cotton and polyester were found to have similar toxic potencies when decomposed in the small scale tests and in the chair smoldering tests.

The second project was conducted to evaluate delayed pulmonary toxicity in guinea pigs following exposure to sub-lethal levels of thermal decomposition products from polyvinylchloride (PVC). Also, following the acute pulmonary effects, the animals were evaluated for a period of up to 60 days to measure recovery, if any, from the injury. We found PVC to be more acutely toxic to guinea pigs than to mice. For this reason a slower decomposition rate (11^{o}C/min) was used instead of 20^{o}C/min used in our previous work with mice. A very severe pulmonary function decrement occurred following exposures to the thermal decomposition products of PVC and this effect persisted for 5 days for all exposure groups. Recovery was noted during the following 14 days but complete recovery was not achieved in the group exposed at the highest concentration when evaluated 57 days following exposure. We are now completing a similar series of experiments using Douglas fir in order to compare these two materials. Two Special Reports were prepared. The first one is a discussion on how

to express toxicity data and their limitations. The second one is on animal models that can be used in studying the toxicity of thermal decomposition products from polymeric materials.

<u>Reports and Papers</u>

Alarie, Y. Special Report to the National Bureau of Standards under Research Grant NB79NADA0009: Toxicity of Plastic Combustion Products. How to express "toxicity" for smoke obtained from decomposing polymers under thermal stress and the limitations of the data obtained in such tests. Reprinted by: Subcommittee on Human Services of the Select Committee on Aging, House of Representatives. Committee Publication No. 97-368, U.S. Government Printing Office, Washington, 1983.

Alarie, Y. Special Report to the National Bureau of Standards under Research Grant NB79NADA0009: Toxicity of Plastic Combustion Products. On animal models for evaluation of the toxicity of thermal decomposition products from polymeric materials.

Matijak-Schaper, M. and Alarie, Y. Toxicity of carbon monoxide, hydrogen cyanide and low oxygen. J. Combustion Toxicol. <u>9</u>, 21-61, 1982.

Alarie, Y., Stock, M.F., Matijak-Schaper, M. and Birky, M.M. Toxicity of smoke during chair smoldering tests and small scale tests using the same materials. Fundam. Appl. Toxicol., in press.

Wong, K.L., Stock, M.F. and Alarie, Y. Evaluation of the pulmonary toxicity of plasticized polyvinylchloride thermal decomposition products in guinea pigs by repeated CO_2 challenges. Toxicol. Appl. Pharmacol., in press.

Matijak-Schaper, M., Stock, M.F. and Alarie, Y. Toxicity of thermal decomposition products from commonly used polymers. Fire Science and Technology, Vol.1, No. 1, 1982, ISSN0733-6721. Available from Comtex Scientific, 850 3rd Ave., New York, NY 10022. Microfiche only.

APPENDIX A

AGENDA

1983 ANNUAL CONFERENCE ON FIRE RESEARCH HONORING PROFESSOR HOWARD EMMONS

CENTER FOR FIRE RESEARCH
NATIONAL ENGINEERING LABORATORY
NATIONAL BUREAU OF STANDARDS
August 23, 24, 25, 1983

Tuesday, August 23

8:15 a.m.	Registration, Green Auditorium, Lobby
9:00 a.m.	Introduction - J.E. Snell, Director, CFR/NBS
9:20 a.m.	Remarks - F. Villella, Director, National Emergency Training Center

Session 1. Modeling Fire Growth in Compartments

Chairman: W. Berl, Applied Physics Lab, Johns Hopkins University

9:35 a.m.	Historical Overview of Fire Research - H. Hottel, Massachusetts Institute of Technology
9:50 a.m.	Keynote: "A Perspective on Modeling Fire Growth in Compartments" - J. Quintiere, CFR/NBS
10:35 a.m.	Coffee Break, Employee Lounge
11:00 a.m.	"Characteristics of Fire in a Forced Ventilation Enclosure" - N.J. Alvares, K.L. Foote, and P.J. Pagni
11:30 a.m.	"Zone Modeling of Forced Ventilation Fires" - H. Mitler, CFR/NBS (formerly Harvard)
12:00 noon	"Modeling of Turbulent Buoyant Flows in Aircraft Cabins" - K.T. Yang, J.R. Lloyd, A.M. Kanury, K. Satoh, University of Notre Dame
12:30 p.m.	"Zone Modeling of Aircraft Cargo Compartment Fires" - C. McArthur, University of Dayton Research Institute
1:00 p.m.	Lunch, NBS Cafeteria

Session 2. Flame Phenomena and Spread

Chairman: R. Fristrom, Applied Physics Lab, Johns Hopkins University

2:00 p.m.	Keynote: "Flamespread Modeling" - C. Fernandez-Pello, University of California, Berkeley
2:45 p.m.	"Numerical Modeling of Wall Burning" - F. Tamanini, Factory Mutual Research Corp.
3:15 p.m.	"Wind Aided Flame Spread Along a Horizontal Fuel Slab: Ceiling and Floor Geometries" - F. Fendell, TRW, Inc.
3:45 p.m.	Coffee Break, Employee Lounge

4:15 p.m.	"Transient Fire Spread on Horizontal Surfaces of Wood" - A. Atreya, Michigan State University (formerly Harvard)
4:45 p.m.	"Flame Heights in Turbulent Wall Fires" - M.A. Delichatsios, Factory Mutual Research Corp.
5:15 p.m.	Adjourn
6:30 p.m.	Barbeque at Smokey Glen

Wednesday, August 24

Session 3. Structure of Diffusion Flames and Radiation

Chairman: C. Tien, University of California, Berkeley

9:00 a.m.	Keynote: "Radiation from Diffusion Flames" - J. de Ris, Factory Mutual Research Corp.
9:45 a.m.	"Measurements on Gaseous-Fuel Pool Fires with a Fiber-Optic Absorption Probe" - G.M. Markstein, Factory Mutual Research Corp.
10:15 a.m.	"Soot and Radiation in Combusting Boundary Layers" - R.A. Beier, P.J. Pagni, and C.I. Okoh, University of California, Berkeley
10:45 a.m.	Coffee Break, Employee Lounge
11:15 a.m.	"Sooting Counterflow Diffusion Flames with Varying Oxygen Index" - U. Vandsburger, I. Kennedy, and I. Glassman, Princeton, University
11:45 a.m.	"Several Numerical Schemes Potentially Capable of Examining Elliptic-Type Flows" - T.M. Shih, University of Maryland
12:15 p.m.	"The Prediction of the Onset of Layer Burning in Compartment Fires" - C. Beyler, Harvard University
12:45 p.m.	Lunch, NBS Cafeteria

Session 4. Fire Plumes

Chairman: J. Prahl, Case Western Reserve University

2:00 p.m.	Keynote: "Buoyant Plumes: Entrainment Rates and Interactions with Boundaries" - E. Zukoski, California Institute of Technology
2:45 p.m.	"Some Experimental Aspects of Turbulent Diffusion Flames and Fire Plumes Along a Wall and in a Corner of Walls" - Y. Hasemi, Japan Building Research Institute

Session 4. Fire Plumes (Continued)

3:15 p.m.	"On the Signficance of a Wall Effect in Enclosures with Growing Fires" - L.Y. Cooper, CFR/NBS
3:45 p.m.	Coffee Break, Employee Lounge
4:15 p.m.	"Nonluminous Flame Radiation in Turbulent Buoyant Axisymmetric Flames" - S-M. Jeng, M-C. Lai and G.M. Faeth, Pennsylvania State University
4:45 p.m.	"Calculations of Three Dimensional Buoyant Plumes in Enclosures" - H.R. Baum, CFR/NBS and R.G. Rehm, CAM/NBS
5:15 p.m.	Adjourn
6:30 p.m.	Banquet - Gaithersburg Marriott Hotel G. Carrier - Master of Ceremonies Speakers - R. Gross, Dean, Columbia University R. Friedman, Vice President, Factory Mutual Research Corp. J. Lyons, Acting Deputy Director, National Bureau of Standards

Thursday, August 25

Session 5. Extinction and Suppression

Chairman: R. Gann, CFR/NBS

9:15 a.m.	Keynote: "Actuation of Extinguishing Systems" - D. Evans, CFR/NBS
9:45 a.m.	"Numerical Modeling of the Interaction Between a Droplet Spray and a Buoyant Plume" - R.L. Alpert, Factory Mutual Research Corp.
10:15 a.m.	"Investigation of Completeness of Combustion in a Wall Fire" - M. Sibulkin and S.F. Malary, Brown University
10:45 a.m.	Coffee Break, Employee Lounge
11:30 a.m.	"Extinction of Large Jets" - B.J. McCaffrey, CFR/NBS

Session 6. Data for Models

Chairman: A. Fowell, CFR/NBS

12:00 noon	Keynote: "Data for Room Fire Models" - J. Rockett, CFR/NBS
12:45 p.m.	Lunch, NBS Cafeteria

1:45 p.m.	"Recent Developments in Fire Testing for Fire Growth in Buildings" - P.H. Thomas, British Fire Research Station
2:30 p.m.	"The ASTM Room Fire Test and Model" - R.B. Williamson, F.L. Fisher, and F. Mowrer, University of California, Berkeley
3:00 p.m.	"Heat Release Rate Measurements with the Cone Calorimeter" - V. Babrauskas, CFR/NBS
3:30 p.m.	Remarks - H. Emmons Introduction by J. Lyons, NBS
4:00 p.m.	Remarks - J. Snell, CFR/NBS
4:15 p.m.	Adjourn

APPENDIX B

CONFERENCE ON FIRE RESEARCH

Center for Fire Research
National Engineering Laboratory
National Bureau of Standards
August 23, 24, 25, 1983

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