NISTIR 4449

ELEVENTH JOINT PANEL MEETING OF THE UJNR PANEL ON FIRE RESEARCH AND SAFETY

Nora H. Jason
Deborah M. Cramer
Editors

U.S. DEPARTMENT OF COMMERCE
National Institute of Standards and Technology
National Engineering Laboratory
Center for Fire Research
Gaithersburg, MD 20899

U.S. DEPARTMENT OF COMMERCE
Robert A. Mosbacher, Secretary
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
John W. Lyons, Director

NIST

NISTIR 4449

ELEVENTH JOINT PANEL MEETING OF THE UJNR PANEL ON FIRE RESEARCH AND SAFETY

Nora H. Jason
Deborah M. Cramer
Editors

U.S. DEPARTMENT OF COMMERCE
National Institute of Standards and Technology
National Engineering Laboratory
Center for Fire Research
Gaithersburg, MD 20899

October 1990

U.S. DEPARTMENT OF COMMERCE
Robert A. Mosbacher, Secretary
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
John W. Lyons, Director

CONTENTS

Page

INTRODUCTION

The 11th Joint Meeting of the United States-Japan Panel on Fire Research and Safety was held on the campus of the University of California, Berkeley, October 19-24, 1989. This meeting had a unique setting. On October 17 at 5:04 pm, Pacific Daylight Time, there was a major earthquake measuring 7.1 on the Richter Scale. The epicenter was about 60 miles southeast of San Francisco, in the Loma Prieta mountains near Santa Cruz. The San Francisco Bay area in general and the San Francisco International Airport in particular suffered significant damage. Part of the Japanese delegation was already in Berkeley; the remainder was airborne. The United States members were in various stages of transit to the meeting. Access to the area was reduced, and transportation from the airports to the campus was not as direct as usual. A number of the delegates and interpreters did not attend, prompting constant changes in the meeting agenda. When possible, qualified colleagues presented these papers. Some were not presented, but are included in this volume.

The earthquake and its aftermath presented us with some rare opportunities. James McMullen, Fire Marshal of the State of California and director of the recovery effort, spent several hours with us, presenting a description of how the State responds to such emergencies. We then were able to spend an afternoon viewing the Marina District of San Francisco, the area within the City that was hardest hit. Dr. Tsukagoshi became the eyes and ears of the Japanese media. Mr. Nelson participated in a Federal investigation team and accompanied a Congressional delegation inspecting the damage.

And yet, with all this excitement, an excellent technical program was held, much in the tradition of the past ten UJNR Panel Meetings. Progress reports and supporting papers were presented in 3 areas: Risk, Hazard, and Evacuation; Fire and Toxicity Chemistry; and Fire and Smoke Physics. All members visited the University's Fire Test Station in Richmond.

At the closing of the meeting, recognition was paid to those who had been affected by the earthquake. The next Panel Meeting will be held in Japan in the autumn of 1992.

Agenda
Eleventh Meeting of the
U.S.-Japan Panel on Fire Research and Safety

October 19-24, 1989
University of California
Sibley Auditorium
Berkeley, California

Wednesday, October 18, 1989

6:00	Chairmen's Meeting
6:30	Tour of Claremont Hotel and Spa

Thursday, October 19, 1989

9:00	Opening Ceremonies
10:00	Group Photograph and Break

Risk, Hazard and Evacuation

10:30	J. Hall (NFPA) - "Progress Report on U.S. Research in Fire Risk, Hazard and Evacuation" (presenter - R. Gann)
10:45	I. Tsukagoshi (BRI) - "Progress Report on Risk, Hazard and Evacuation in Japan"
11:00	A. Sekizawa (FRI) - "Analysis on Fatalities' Characteristics of Residential Fires"
11:30	I. Hagiwara, I. Tsukagoshi (BRI) - "Simulation of Fire Propagation in a Wood Frame House" (presenter - I. Hagiwara)
12:00	Lunch
1:30	T. Tanaka (BRI) - "The Concept of a Performance Based Design Method for Building Fire Safety"

Open Technical Session

2:00	W. Pitts (NIST) - "Carbon Monoxide Production and Prediction" (presenter - R. Gann)
2:45	H. Suzuki, T. Goto (BRI) - "Expected Fire Resisting Performance and Evaluation Methods for Building Materials" (presenter - H. Suzuki)
3:15	Break

3:30 R. Gann (NIST) - "Replacement for the Halogenated Fire Suppressants: A Research Strategy and Plan"

4:15 T. Kashiwagi (NIST) and A. Omori (NRIPR, Japan) - "Effects of Polymer Characteristics on Flammability Properties" (presenter - T. Kashiwagi)

5:00 Adjourn - Evening Free

Friday, October 20, 1989

Fire and Toxicity Chemistry Session

8:30 B. Levin (NIST) - "Progress Report on Fire Toxicity and Chemistry Research in the United States" (presenter - R. Gann)

8:45 H. Suzuki (BRI) - "Progress Report on Fire and Toxicity Chemistry in Japan"

9:00 T. Hirata, Y. Fukui, S. Kawamoto and M. Inoue (FFPRI) - "Combustion Toxicity of Woods Treated with Retardants and CCA Preservatives" (presenter - T. Hirata)

9:30 V. Babrauskas (NIST) - "Large-Scale Toxicity Correlations" (presenter - R. Gann)

10:15 Break (Room 120A)

10:30 K. Satoh and D. Kozeki (FRI) - "Numerical Calculations and Computer Graphic Analysis of Window-to-Window Propagation of Building Fires" (presenter - D. Kozeki)

11:00 H. Koseki (FRI), G. Mulholland (NIST), and T. Jin (FRI) - "Study on Combustion Property of Crude Oil - A Joint Study Between NIST/CFR and FRI" (presenter - T. Jin)

11:30 Lunch

12:15 Depart for Tour of Earthquake Damage in San Francisco

6:00 Dinner House Party - P. Pagni

Saturday, October 21, 1989

Optional Activities

Sunday, October 22, 1989

8:45	Leave Claremont Hotel
10:00	Palace of the Legion of Honor in San Francisco
10:30	Golden Gate Bridge Vista Point
11:30	Sebastiani Public Tour & Tasting/Sonoma Plaza Walkabout
12:00	Sonoma Plaza Walkabout/Sebastiani Public Tour & Tasting
12:30	Lunch at Buena Vista
1:30	Leave for Napa
2:30	Clos Pegase Private Tour and Tasting with Souvenir Glass
3:30	Christian Brothers Private Tour and Tasting
4:30	St. Helena Town Walkabout
5:30	Inglenook Private Tour and Tasting
6:30	Dinner by André in the Inglenook Cask Hall
8:45	Leave for Claremont Hotel
10:00	Arrive Hotel

Monday, October 23, 1989

Fire and Smoke Physics

8:45	E. Zukoski, (Cal. Tech.) - "Review of Progress in the Fire and Smoke Physics Area"
9:00	Y. Hasemi, (BRI) - "Progress Report on Fire and Smoke Physics in Japan"
9:15	Y. Hasemi, M. Yoshida (BRI), A. Nohara (Science Univ. of Tokyo) - "Unsteady-State Upward Flame Spreading Velocity Along a Vertical Combustible Solid and Influence of External Radiation on the Flame Spreading Velocity" (presenter - Y. Hasemi)
9:45	L. Zhou and C. Fernandez-Pello (Univ. of CA) - "Concurrent Turbulent Flame Spread" (presenter - C. Fernandez-Pello)
10:15	Break (Room 120A)
10:30	Y. Hasemi, (BRI) - "Collaborative Experiment of Interior Lining Materials"
11:00	J. Shaw (Weyerhaeuser) - "The North American Wood Industry Room Fire Test and Predictive Modeling Program"
11:30	A. Sekizawa (FRI) and J. Hall (NFPA) - "Fire Risk Analysis: General Conceptual Framework for Describing Models" (presenter - A. Sekizawa)
12:00	R. Alpert (FM) - "Radiation from Turbulent Jet Flames and Wall Fires" (presenter - R. Friedman)
12:30	Lunch
1:00	J. McMullen - "Discussion of Earthquake Damage and Response of Fire Fighters"
2:00	Laboratory Tours I - Richmond Field Station, R.B. Williamson - "Evaluation of the Fire Hazard of Wall Covering Materials"
4:00	Return from Richmond Field Station
4:30	Adjourn - Evening Free

Tuesday, October 24, 1989

Fire and Smoke Physics (cont.)

8:30	G. Heskestad and R. Spaulding (FM) - "Inflow of Air Required at Wall and Ceiling Apertures to Prevent Escape of Fire Smoke" (presenter G. Heskestad)
9:00	H. Hayasaka (Hokkaido Univ.) and H. Koseki (FRI) - "Estimation of Thermal Radiation from Large Pool Fires" (presenter - H. Hayasaka)

9:30	O. Sugawa, K. Kawagoe, Y. Oka (Science Univ. of Tokyo) - "Burning Behavior in a Poorly-ventilated Compartment Fire--Ghosting Fire" (presenter - O. Sugawa)
10:00	Break (Room 120A)
10:15	J. Klote (NIST) - "Smoke Control Tests at the Plaza Hotel in Washington, DC" (presenter - J. Quintiere)
10:45	M. Tsujimoto, T. Takenouchi (Nagoya Univ.), S. Uehara (Takenaka Corp.) - "A Scaling Law of Smoke Movement in an Atrium" (presenter - M. Tsujimoto)
11:15	T. Matsushita (BRI) - "A Smoke Control Calculation for a Pressurized Elevator Shaft"
11:45	T. Yamada (FRI) - "Method for Estimating Smoke Leakage through Small Openings Using Tracer Gas"
12:15	Lunch
1:15	R. Levine and H. Nelson (NIST) - "Full Scale Simulation of a Fatal Fire and Comparison of Results with Two Multiroom Models" (presenter - H. Nelson)
1:45	D. Evans and W. Walton (NIST) - "Burning of Oil Spills" (presenter - T. Kashiwagi)
2:15	O. Sugawa, K. Kawagoe, Y. Oka, T. Mizuno, (Science Univ. of Tokyo) - "Experimental Study on Gasoline Pool Fire Using a Full Scale Service Station Model and a 1/15 Reduced Scale Model" (presenter -O. Sugawa)
2:45	P. Pagni, A. Joshi, (Univ. of CA) - "Thermal Analysis of Effect of a Compartment Fire on Window Glass" (presenter - P. Pagni)
3:15	Break (Room 120A)
3:30	Closing Ceremonies
4:30	Adjourn - Cocktail Party

Wednesday, October 25, 1989

9:00	Laboratory Tours II - P. Pagni, C. Pello and E. Zukoski

Support Papers

H. Ohtani (Yokohama National Univ.), H. Koseki (FRI), T. Hirano (Univ. of Tokyo) - "Heat Transfer Mechanisms in Materials on Fire Retardation"

T. Hirano (Univ. of Tokyo) - "Effectiveness Evaluation of Expense for Loss Prevention"

T. Tanaka (BRI) - "A Performance Based Design Method for Fire Safety of Buildings"

LIST OF MEMBERS (JAPAN)

Panel Members

Dr. Isao Tsukagoshi
Associate Director for Fire Research
Enviornment, Design and Fire Department
Building Research Institute

Dr. Hiroaki Suzuki
Head, Smoke Control Division
Environment, Design and Fire Department
Building Research Institute

Dr. Takeyoshi Tanaka
Head, Building Design Division
Environment, Design and Fire Department
Building Research Institute

Dr. Yuji Hasemi
Head, Fire Safety Division
Environment, Design and Fire Department
Building Research Institute

Dr. Tadahisa Jin
Head, The Second Research Division
Fire Research Institute

Dr. Ai Sekizawa
Chief, Earthquake Disaster Section
The Third Research Division
Fire Research Institute

Dr. Toshimi Hirata
Senior Scientist
Wood Chemistry Division
Fire Retarding Laboratory
Forestry and Forest Products Research Institute

Associate Members

Dr. Makoto Tsujimoto
Associate Professor
Department of Architecture
Faculty of Engineering
University of Nagoya

Mr. Takayuki Matsushita
Chief Research Member
Testing and Evaluation Department
Building Research Institute

Associate Members (continued)

Mr. Ichirou Hagiwara
Research Member
Fire Safety Division
Environment, Design and Fire Department
Building Research Institute

Mr. Daisuke Kozeki
Researcher
Alarm and Communication Section
The Third Research Division
Fire Research Institute

Dr. Osami Sugawa
Lecturer
Center for Fire Science and Technology
Science University of Tokyo

Dr. Hiroshi Hayasaka
Associate Professor
Graphic Science
Department of General Education
Faculty of Engineering
University of Hokkaido

Mr. Shigeo Uehara
Building Design Department
Takenaka Corporation

Current NIST Visiting Scientist

Dr. Tokiyoshi Yamada
Researcher Life Safety Section
The Third Research Division
Fire Research Institute

Observer

Mr. Tetsuji Takenouchi
Department of Architecture
Faculty of Engineering
University of Nagoya

LIST OF MEMBERS (U.S.)

Panel Members

Dr. Jack E. Snell (U.S. Chairman)
Director, Center for Fire Research
National Institute of Standards and Technology

Dr. Richard G. Gann (CFR Coordinator)
Chief, Fire Measurement and Research Division
Center for Fire Research
National Institute of Standards and Technology

Dr. Takashi Kashiwagi (Secretary)
Combustion and Flammability
Center for Fire Research
National Institute of Standards and Technology

Dr. Raymond Friedman (retired)
Factory Mutual Research Corporation

Dr. John R. Hall, Jr. (Did Not Attend)
Director, Fire Analysis Division
National Fire Protection Association

Mr. Harold E. Nelson
Center for Fire Research
National Institute of Standards and Technology

Prof. Patrick J. Pagni
Vice Chairman, Department of Mechanical Engineering
University of California-Berkeley

Dr. James G. Quintiere
Chief, Fire Science and Engineering Division
Center for Fire Research
National Institute of Standards and Technology

Prof. Edward E. Zukoski
Division of Engineering and Applied Sciences
California Institute of Technology

Honorary Member

Prof. Howard W. Emmons (retired) (Did Not Attend)
Harvard University

Associate Members

Mr. Gordon H. Damant
Chief, Bureau of Home Furnishings
State of California
Department of Consumer Affairs

Associate Members (continued)

Prof. A. Carlos Fernandez-Pello
Dept. of Mechanical Engineering
University of California-Berkeley

Dr. Gunnar Heskestad
Factory Mutual Research Corporation

Prof. Frederick W. Mowrer
Department of Fire Protection
University of Maryland

Mr. James R. Quiter
Rolf Jensen and Associates, Inc.

Dr. James Shaw
Fire Technology Unit
Weyerhaeuser Company

Prof. R. Brady Williamson
Professor of Engineering Science
Dept. of Civil Engineering
University of California-Berkeley

Observers

Mr. Nicholas Dembsey
Civil Engineering Department
University of California-Berkeley

Dr. Yuh-Chyurn Ding
Division of Building Administration
Construction and Planning Administration
Ministry of Interior, Taiwan

Mr. Charles Fleischmann
Civil Engineering and Mechanical Engineering Department
University of California-Berkeley

Mr. William Gale
Civil Engineering Department
University of California-Berkeley

Mr. Aruna Joshi
Department of Mechanical Engineering
University of California-Berkeley

Prof. Michio Kitano
Department of Mechanical Engineering
Faculty of Engineering
Tohoku University

Observers (continued)

Prof. Philip S. Marcus
Department of Mechanical Engineering
University of California-Berkeley

Prof. Robert Martin
Department of Forestry and Natural Resources
University of California-Berkeley

Prof. Malcolm J. McPherson
Department of Materials Science and Mineral Engineering
University of California-Berkeley

Mr. Charles Perry
Civil Engineering Department
University of California-Berkeley

Prof. Robert F. Sawyer
Department of Mechanical Engineering
University of California-Berkeley

Mr. Jose Torero
Department of Mechanical Engineering
University of California-Berkeley

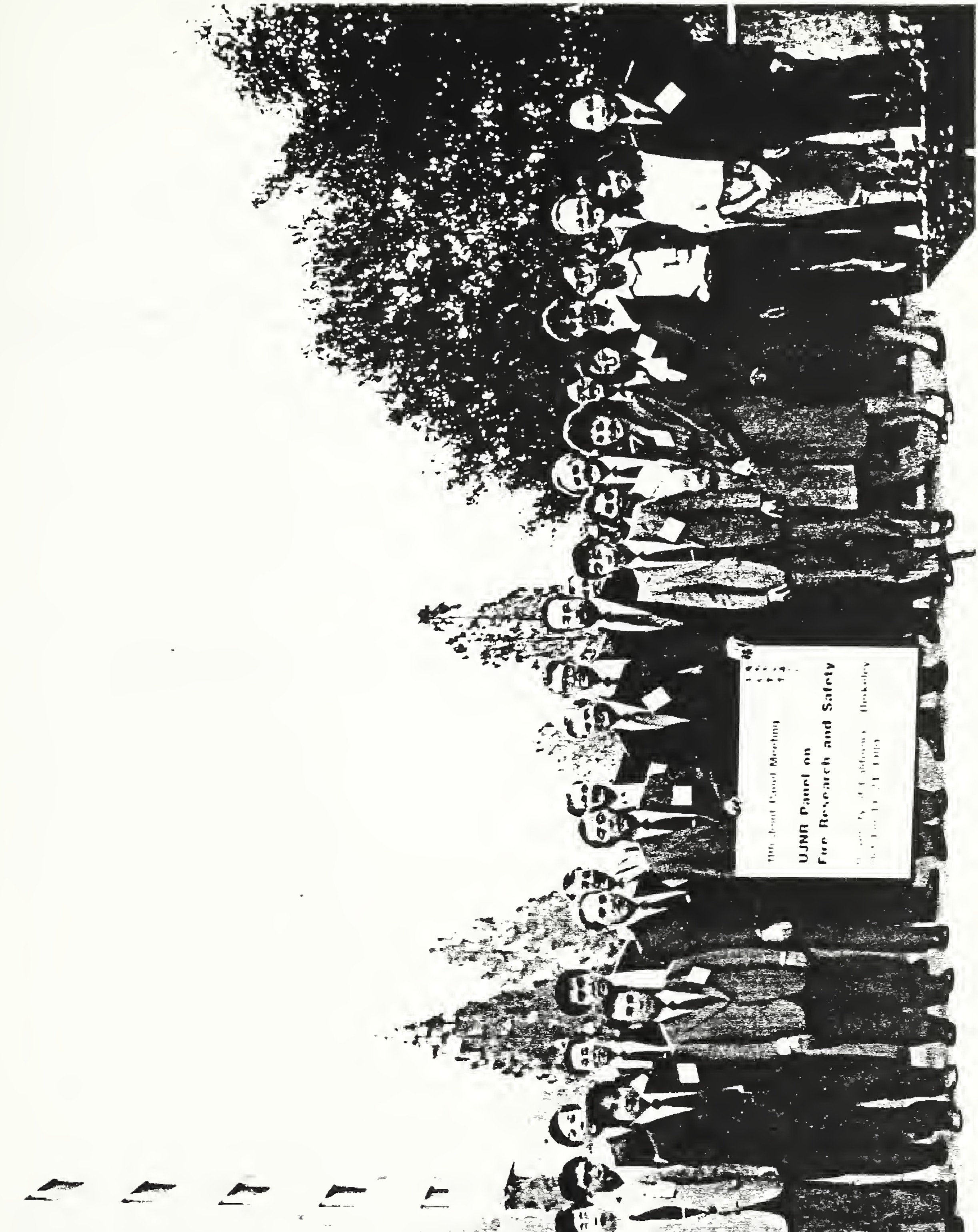
Mr. Javier Trelles
Department of Mechanical Engineering
University of California-Berkeley

Mr. Li-Ming Zhou
Department of Mechanical Engineering
University of California-Berkeley

Meeting Coordinators

Mrs. Deborah M. Cramer
Secretary, Center for Fire Research
National Institute of Standards and Technology

Mrs. Cecile Grant
Department of Civil Engineering
University of California-Berkeley


UJNR Panel on
Fire Research and Safety

RISK, HAZARD AND EVACUATION SESSION

Progress Report on U.S. Research in Fire Risk, Hazard, and Evacuation

JOHN R. HALL, JR.
National Fire Protection Association
Quincy, Massachusetts 02269 U.S.A.

Since the last UJNR meeting in mid-1988, considerable progress has been made in the U.S. in the areas of fire risk, hazard, and evacuation.

1. PROGRESS

In August 1989, the National Institute of Standards and Technology's Center for Fire Research (CFR) officially released its Hazard I computer model and analysis method for fire hazard analysis. Following several years of development and a year-long, formal beta test, Hazard I is now considered ready for application to real decisions in specified areas. CFR recommends that Hazard I be used only in analyses of single-family dwellings or other properties having similar sizes and layouts.

The elements of Hazard I were described to the UJNR in previous meetings. It includes four principal models: (1) a model of the growth and spread of fire effects, given a user-specified fire, (2) a model of the activation of detectors, (3) a deterministic model of the evacuation behavior of occupants, and (4) a model of the cumulative impact of fire effects on occupants, based on their exposure.

Two simpler fire hazard models were used by Harold E. Nelson to assist in the investigation and reconstruction of the 1988 fire at the First Interstate Bank Building in Los Angeles, California.(1) Mr. Nelson used the Available Safe Egress Time (or ASET) model of fire development and the Detector Activation (or DETACT-QS) model of detector activation. This analysis was the latest in a still small but growing number of real applications of computer fire models published in wide-circulation magazines to reach a larger audience than fire researchers.

Hazard I also serves as the central core of a fire risk assessment model developed by researchers at CFR, Benjamin/Clarke Associates, and the National Fire Protection Association (NFPA), under the sponsorship of the National Fire Protection Research Foundation (NFPRF). The second phase of this four-year, three-phase project was completed this month, and the prototype version of the general model is now complete. The next and last phase will address the preparation of a user's manual. Dr. Frederic Clarke will describe the model later in this session.

Hazard I and the new fire risk assessment model also served as the occasion for a new evacuation model developed by Rita Fahy of NFPA in 1989. EXIT89 is designed to combine the essential deterministic behavioral elements of Hazard I's EXITT model with modeling of the queueing and delays that occur in common exit paths of larger buildings. A presentation on EXIT89 also will be given later in this session.

In a joint U.S./Japan collaboration in the fire risk area, Dr. Ai Sekizawa of the Fire Research Institute and Dr. John Hall of NFPA developed a general conceptual framework to describe the growing number of fire risk models in Japan and the U.S. This paper will be presented later in this session.

Under a grant from CFR, Mark Brandyberry and Professor George Apostolakis of the University of California at Los Angeles developed a set of concepts and models to use in translating laboratory tests and other physical measurements of the properties and relationships of potential heat and fuel sources into probabilities of fire ignition for fire risk analysis.(2) The example scenario used by the authors involves ignition of upholstered furniture by a portable or space heating device. Bayesian statistical techniques are used to allow experimental evidence to adjust a user-specified estimated distribution for the probability of ignition.

Dr. G. Ramachandran of the United Kingdom published in a U.S. fire research journal an overview of probabilistic models that can be applied to fire risk evaluation.(3) These models include (a) a model of ignition probability as proportional to a power of floor area, (b) a similar model of total area damaged by fire, (c) a model of area damaged by fire as an exponential function of burning time, (d) a model of financial loss as a log normal distribution, (e) logit-based models of the probability that loss in a particular fire will exceed a specified large value, and (f) Markov process models for state-transition models of fire development.

Three authors from Washington University in St. Louis, Missouri published an analysis using the event-tree format called decision analysis to assess the impact of laws requiring smoke detectors.(4) This topic had earlier been the subject of an analysis by Offensend and others through CFR.(5)

It should be clear from this review that most of the progress of the past year and a half has revolved around the CFR Hazard I project. This includes the fire risk assessment model built on Hazard I as a base, the Brandyberry and Apostolakis work to support Hazard I, and the Fahy model to extend Hazard I. Other work involves either application or synthesis of older, less comprehensive models. The latter work represents progress in the use of fire risk, hazard, and evacuation models, while the Hazard I-related work remains the principal force behind development of new models and methods for fire risk, hazard, and evacuation in the U.S.

2. REFERENCES

1. Harold E. Nelson, "Science in Action", Fire Journal, Volume 83, Number 4, July/August 1989, pp. 28-34.

2. Mark D. Brandyberry and George E. Apostolakis, "Fire Risk Analysis Methodology: Initiating Events", NIST-GCR-89-562, prepared for the National Institute of Standards and Technology under NIST Grant No. 60NANB6D0649, Gaithersburg, Maryland: NIST-CFR, March 1989.

3. G. Ramachandran, "Probabilistic Approach to Fire Risk Evaluation", Fire Technology, Volume 24, Number 3, August 1988, pp. 204-226.

4. David D. Jensen, Alice E. Tome, and William P. Darby, "Applying Decision Analysis to Determine the Effect of Smoke Detector Laws on Fire Loss in the United States", Risk Analysis, Volume 9, Number 1, March 1989, pp. 79-89.

5. Susan Godby Helzer, Benjamin Buchbinder, and Fred L. Offensend, Decision Analysis of Strategies for Reducing Upholstered Furniture Fire Loss, NBS Technical Note 1101, Gaithersburg, Maryland: National Bureau of Standards, June 1979.

PROGRESS REPORT ON RISK, HAZARD AND EVACUATION IN JAPAN

Isao TSUKAGOSHI

Building Research Institute
Ministry of Construction
Tsukuba-shi, Ibaraki-ken, 305 JAPAN

INTRODUCTION

Progress in the field of risk analysis, hazard evaluation and evacuation modeling since the 10th UJNR panel is reviewed. There seems to be little development of new research program comparable to Fire Safety Design Method or Fire Risk Evaluation Method which were presented in the ninth panel. After the 10th panel meeting, the annual meeting o f Architectural Institute of Japan 1988 and the annual conference of Japanese Association of Fire Science and Engineering 1989 took place and several papers on this field were reported.

1. ANNUAL MEETING OF A.I.J. 1988

The group of Tokyo Science University reported on human behavior in residential fire.(1.1) This is an analysis of the investigation data by the fire service department of a local authority and refers to the relation between the human behavior in fire and the conditions of fire when it is perceived.

Ref.(1.2) which was partly introduced in the progress report for the 10th panel, is a study based on the memories of subjects who have passed through a route like a maze.

Mr. Takahashi and others compared human behavioral data observed in a real theater with the BRI evacuation model for fire safety design and reported the good agreement of the model.(1.3)

Dr. Sekizawa related residential fires in Japan with those in the U.S. using Fire Investigation Report by the Fire Defense Agency in Japan and the Fire in the United States, edit.2, 1982.7 by USFA (1.4)

Dr. Tsujimoto studied on the concept of risk analysis such as the problem of uncertainty and randomness, the difference of relative and absolute criteria of the degree of risk, and the relation between risk and risk perception.(1.5) Comparing building fire risk with other sorts of risk such as aircraft/ automobile accidents and home casualties in staircases, he and his colleagues also reported that the acceptable level of risk for public facilities becomes lower as time goes, while that for private house stays always constant.(1.6)

Kobe University group headed by Dr. Murosaki proposed a calculation model of fire awareness time which is assumed to be the required time for a night watcher to reach each door of bed room.(1.7) The distribution of calculated times was validated with the result of human behavioral tests in a real building.

2. ANNUAL CONFERENCE OF J.A.F.S.E. 1989

Dr. Tsujimoto and his group estimated fire risk of building fire on the basis of fire statistic data by Tokyo Fire Department and Housing Survey of Japan by the Management and Coordination Agency.(2.1) Fire outbreak rate(number of fire buildings per year/total number of existing buildings) and burned floor area by size of building, by construction method and by completion year are calculated. A part of this result is quoted in Mr. Hagiwara's presentation in this session.(3.1)

Dr. Sekizawa analyzed residential fires with fatalities and clarified that around 70% of the dead are weak people like aged or handicapped.(2.2) This research will be explained by himself in this session.

3. OTHERS

Some papers on this topic were submitted also to the 1989 annual meeting of A.I.J. but most of them were the continuation of the above mentioned works. Among them, Mr. I. Hagiwara and Dr. I. Tsukagoshi reported a part of the Ministry of Construction's five year project entitled "Development of New Technology for Wood Frame Building"(3.1). It proposes a method for evaluating fire loss by the expected value of burned floor area calculated as a function of the fire outbreak rate of each room, the distribution of starting time of fire fighting and the frequency of the use of building materials. Details are to be presented by the author in this session.

Prof. T. Hirano of the University of Tokyo proposed an attractive approach for analyzing loss prevention. He developed a concept to evaluate the effectiveness of different types of disaster preparedness by means of cost-effectiveness theory. He applied the proposed procedure to the evaluation of expense for loss prevention against oil reservoir tank fire. It seems that the general nature of his concept enables us to apply it to other different cases including building fire.

4. OVERVIEW

Looking through all of these papers, the general tendency can be summarized as follows:

(1) In the researches 1.1, 1.4, 1.6, 2.1, 2.2 and 3.1, fire statistic data are analyzed to utilize as the data source for risk evaluation model or to compare the characteristics of fires in various categories. As the progress of international exchange of information in the field of fire science, it will become more and more important to standardize methods of survey and indices of statistics or to have a way of data conversion.

(2) As seen in 1.1, 1.4, 2.1, 2.2 and 3.1, number of researchers are focusing their attention on the analysis of residential fire. In the background of this tendency, we can find two great problems namely the evacuation problem of aged or handicapped and the problem of mass fire in wood house built up areas. For the former, it is required to study more carefully human behaviors in fire and for the latter, to have an adequate method for evaluating risk of combustible constructions.

(3) Concept of building design method and risk assessment are pursued in the papers 1.5, 1.6, 3.2 3.4 and 3.5, among which the joint project by Drs. J. Hall and A. Sekizawa gives us useful informations for our future works.(3.4) They compared related works in the U.S. and Japan in the common format and clarified the concepts for fire risk analysis model. This will be discussed in this meeting together with Dr. T. Tanaka's report which describes the concept of fire safety design system.(3.5)

REFERENCE

1. Summary of Technical Papers of Annual Meetings, Architectural Institute of Japan 1988:

   1.1 M. Baba, S. Sugawa, S. Tanaka & K. Kawagoe "Investigation of Human Behavior in Residential Fire"
   1.2 M. Minagawa, K. Kishitani, S. Sugawara & M. Yoon "A Study on Human Behavior on a Highly Complicated Evacuation Route: Ⅱ. Perceptional Disturbances Dued from Corner Angles: Ⅲ. Perceptional Impact Evaluation Dued from Directional Axis Distortion of Guidance Map"
   1.3 K. Takahashi, T. Tanaka & S. Wataya "A Method of Predicting Evacuation in Theater"
   1.4 A. Sekizawa "Comparative Analysis on the Characteristics of Residential Fires between the United States and Japan"
   1.5 M. Tsujimoto "A Methodology of Risk Assessment Method for Building Fire"
   1.6 T. Ishikawa, M. Tsujimoto & H. Kakegawa "A Research on Fluctuation of Risk with Time: Part 1. Definition and Calculation of Risk: Part 2. Fluctuation with Time and Consideration of Risk"
   1.7 M.Murosaki, K.Ohnishi and Terasawa "A Study on Computation Model for Time of Fire Awareness"

2. Annual conference of the Japanese Association of Fire Science and Engineering 1989

   2.1 H. Kakegawa, T. Nagaoka & M. Tsujimoto "Estimation of Fire Risk Utilizing buildings and fires Data Base: Part 2. Fire Risk of Residential Building in Tokyo Metropolis"
   2.2 A.Sekizawa "An Analysis on Fatalities' Characteristics of Residential Fire"

3 Papers for the 11th UJNR panel

   3.1 I. Hagiwara & I. Tsukagoshi "Simulation of Fire Propagation in a Wood Frame House"
   3.2 T. Hirano "Effectiveness Evaluation of Expense for Loss Prevention" to be presented at the International Conference on Safety and Loss Prevention in the Chemical and Oil Processing Industries; Oct. 23-27, 1989; Singapore
   3.3 S. Sekizawa "Analysis on Fatalities' Characteristics of Residential Fires"
   3.4 J. Hall & A. Sekizawa "Fire Risk Analysis: General Conceptual Framework for Describing Models"
   3.5 T. Tanaka "Concept of Performance Design System for Building Fire Safety"

Analysis on Fatalities' Characteristics of Residential Fires

Ai Sekizawa
Fire Research Institute
Ministry of Home Affairs
Mitaka-shi, Tokyo, 181 JAPAN

1. INTRODUCTION

Every Year, a half of structure fires occur in residential buildings, and three fourths of fire deaths caused by structure fires are due to residential fires in Japan. Moreover, Japan is facing the problem of the rapid aging of society which is expected to continue to a stage where one fourth of total population will be 65 or older at the beginning of the 21st century. Since almost a half of the total fire deaths are 65 or older, the rapid aging of Japanese society would cause increasing number of fire deaths in the coming near future. Considering these facts, much more concern than ever has addressed the residential fire problem in this decade from the viewpoint of fire deaths reduction in Japan.

The purpose of this study is to analyze the characteristics of fatalities due to residential fires for examining appropriate residential fire protection measures in terms of life safety especially for the people with disabilities like aged people.

2. SOURCE OF FIRE DEATHS DATA BASE USED IN THIS STUDY

Every fire death as well as every fire incident is reported systematically in an unified format from municipal fire departments to Fire Defense Agency. The data base of fire deaths used here contains the information of the fire deaths that occur in single-family dwellings, and multiple-family dwellings for five years from 1983 to 1987. However, the fire deaths caused by such fires as incendiary fires and suicide fires are excluded from analysis here, because this kind of problem should be treated with from other viewpoints such as a crime or a social problem. The total number of residential fire deaths analyzed here is 3,629.

The information in a fire death report includes the building features of an origin house or an apartment, the data of a fire profile such as a cause, the first item ignited, extent of fire spread etc., and the fatality's characteristics such as age, sex, physical and mental conditions at a fire including incapacitation due to alcohol.

3. RESULTS OF ANALYSIS

3.1 Life Loss Risk by Structure Type

Table 1 shows the comparison of life loss risk by structure type of residential buildings. Six structure types here are determined by combining three construction types such as fire resistive construction, fire proof wooden construction, and ordinary wooden construction, and two housing types such as a single-family dwelling and a multiple-family dwelling.

As can be seen in Table 1, the number of fire deaths per year per million units of a corresponding structure type changes mainly according to the change of construction type rather than that of housing type. Therefore, if characteristics of a fatality himself (or herself) is omitted from consideration in analysis, fire severity such as an extent and/or rapidity of fire spread is naturally considered to be a dominant factor that affects life loss risk in a residential fire.

3.2 Life Loss Risk by Fatality's Characteristics

The items concerning fatality's physical functions obtained from a fire death report are age, whether one suffers from sickness or not, whether one is handicapped or not, and whether one is bedridden or not. Likewise, the items concerning a level of one's consciousness awakening in terms of fire detection are whether one is sober or not, and whether one is awake or asleep. Using these items, the relation between life loss risk and fatality's characteristics is analyzed hereafter.

(1) Age

Figure 1 shows a histogram of the proportion of fire deaths by three age groups as 65 or older, 5 or younger, and 6 to 64. As shown in Figure 1, almost a half (47.8 %) of the total fatalities are 65 or older.
By the way, Table 2 gives us another aspect of life loss risk among four groups as 65 or older, 75 or older, handicapped, and bedridden. In terms of the death rate (the number of fire deaths per year per 100,000 persons), the aged who are 65 or older have 4.5 times as high risk as average, and the aged who are 75 or older have 8 times higher risk than average. Handicapped persons, who are given a certificate by government, have almost as same risk as the aged who are 65 or older. However, the most noticeable fact is that bedridden persons, 82 % of whom are 65 or older, have indeed 41 times as high risk as average.

From this fact, the most difficult condition is considered to be the case of a bedridden person among the groups categorized as the people with disabilities. Although such two characteristics of fatalities as aged and bedridden overlap each other, a substantial feature of physical functions like bedridden should be given priority to categorize high risk groups.

(2) Physical Functions

The conditions of physical functions can be sorted out into such seven categories as shown in Figure 2 based on the items in a fire death report. Figure 2 shows a histogram of the proportion of fire deaths by these seven category groups. In order to think of a strategy of fire deaths reduction program, it is a considerably important fact that the total percentages of the six groups that have some handicap at any rate in terms of escaping ability reach almost 70 %. This fact tells us that occurrence of fire death depends not only on severity of a fire itself but also largely on conditions of occupants' physical functions.
Therefore, besides fire control measures, we should notice improvement of environmental conditions of disabled persons and the elderly as well as emergency assistance by their family or neighbors for reducing fire deaths.

(3) The Level Of Consciousness Awakening

With combination of two items of drinking status and awakening status, the levels of consciousness awakening of fatalities can be sorted out into such five category groups as shown in Figure 3. From the histogram of the proportion of fire deaths by these five groups, about a half (53.1 %) of the total number of fatalities come under such status as drunk or asleep. Figure 4 shows the breakdown by three age groups as described in Figure 1 for each level group of consciousness awakening. In the cases of drunk status to some extent, the proportion of the age group "6 to 64" is over 65 %. On the other hand, the proportion of elderly group "65 or older" exceeds that of "6 to 64" in the cases of sober status.

(4) Presence of Others at a Fire

Presence of others, i.e. whether one is staying alone or not at a fire, is also a very important item as an environmental condition of fatalities especially for the people who need help to move. The status of staying alone here includes being left alone temporarily and living separately from one's family in the same site as well as living alone.

Figure 5 shows a histogram of the proportion of fire deaths by presence of others at a fire. A half (50.8 %) of the total fire deaths correspond to the status of staying alone at a fire in any case. Although the living alone case has the most proportion (24.8 %) among the cases of staying alone at a fire, the case of being left alone temporarily has a quite large proportion (20.9%). The number of fire deaths in this case could increase in the future, because there is an increasing tendency for elderly persons to be left alone during daytime, since more and more women go out to work in recent Japan.
In either case of staying alone at a fire, emergency help by neighbors and emergency communication system for that are needed for disabled persons to be rescued.

3.3 Fire Deaths Incidence by Time of Day

For each of three items such as age grouping, whether one is bedridden or not, and presence of others at a fire, fire deaths incidence by every two hours in a day is illustrated respectively in Figure 6 through Figure 8. The distribution pattern of each category in these figures can be clearly identified as "more in daytime" type and "more in night-time" type. Namely, as to the categories of the aged, infants, bedridden persons, and being left alone temporarily, fire deaths tend to occur much more during daytime than during night-time. In contrast to above categories, as to "6 to 64" year age group, persons who are not bedridden, and living alone, fire deaths incidence during night-time is considerably higher than that during daytime.

4. Concluding Remarks

Considering fire deaths incidence by time of day described above, residential fire deaths can be grouped as "the Disaster-Vulnerable people & Daytime Fire" pattern and "Non Disaster-Vulnerable people & Night-time Fire" pattern. Table 3 gives a summary of the distinctive features of these two typical fire death patterns.
The former pattern can be described typically as the case that a person, who needs help to move, encountered a fire alone and resulted in a fire death while other family member(s) went out for work or shopping.
On the other hand, the latter pattern could be the probable case that a person, who has normal physical functions, died in a fire mainly due to delay of detection while he was drunk or asleep at night.

Towards the goal of the reduction of fire deaths, "the Disaster-Vulnerable people & Daytime Fire" pattern is more important than "Non Disaster-Vulnerable people & Night-time Fire" pattern, because the death rate as well as the number of deaths in the former pattern is quite high and further the population of such a high risk group corresponding to this pattern is increasing rapidly in Japan.

This kind of pattern classification of fire deaths makes it easy to understand how fire protection measures, such as a smoke detector, home sprinkler system, and emergency communication system, would be appropriate for a specified target group like the aged, the handicapped, or the persons who tend to be left alone during daytime.
In addition, based on statistics on the proportion of fire death patterns and the population of corresponding target high risk groups, estimation of effect of a specified fire protection measure would be possible.

Table 1 The Number of Residential Fire Deaths by Structure Type

Structure type (Housing type / Construction type)	The number of fire deaths per year per million units of house by structure type
Single-family / wooden	35.1
Single-family / fire proof wooden	10.2
Single-family / fire rated reinforced concrete	5.1
Multiple-family / wooden	33.4
Multiple-family / fire proof wooden	17.1
Multiple-family / fire rated reinforced concrete	6.0
Total of above	21.3

Table 2 Comparison of Residential Fire Death Rate among High Risk Group

Category of high risk group	The number of residential fire deaths per year per 100,000 persons	Ratio of fire death rate to the average (1.0) of total population
The Bedridden (65 ≦)	24.6	41.0
The handicapped*	3.0	5.0
The Aged (a) (65 ≦)	2.7	4.5
The Aged (b) (75 ≦)	4.8	8.0
Total Population	0.6	1.0

* Handicapped : The people who are given a certificate by government

Table 3 Two Typical Fire Death Patterns Derived from Study of Fire Deaths Incidence by Time of Day

Fire Death Pattern	Distinctive Features of Fires
Disaster-Vulnerable* people & Daytime Fire	* Victims are people who are disabled, elderly, or infant. * There are relatively few victims who are drunk or asleep. * There are many such cases that victims are left alone at a fire during other family members' absence. * For this pattern, home sprinkler system and/or neighbor's assistance is needed.
Non Disaster-Vulnerable people & Night-time Fire	* Most of victims are people who are 6 to 64 years old and with normal physical functions. * There are many victims who are drunk or asleep. * Many cases of living alone as well as staying with other family members at a fire come under this pattern * For this pattern, efficient fire detection system would save many lives.

* Disaster-Vulnerable : The people who are vulnerable to disaster

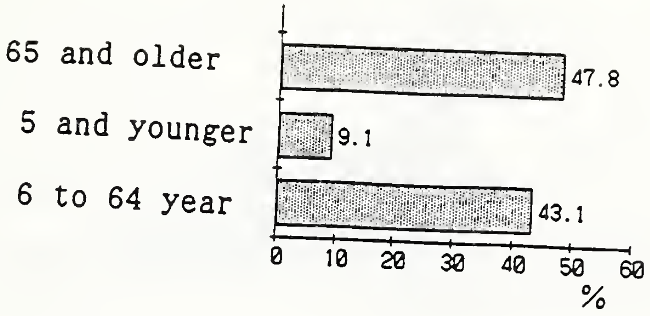


Figure 1 Proportion of Residential Fire Deaths by Age Classification

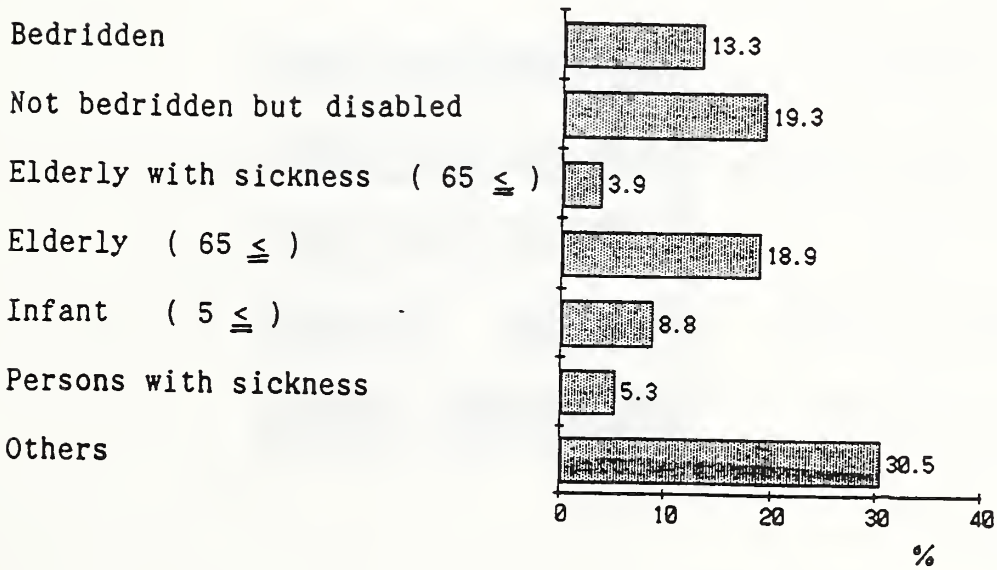


Figure 2 Proportion of Residential Fire Deaths by Conditions of Physical Functions

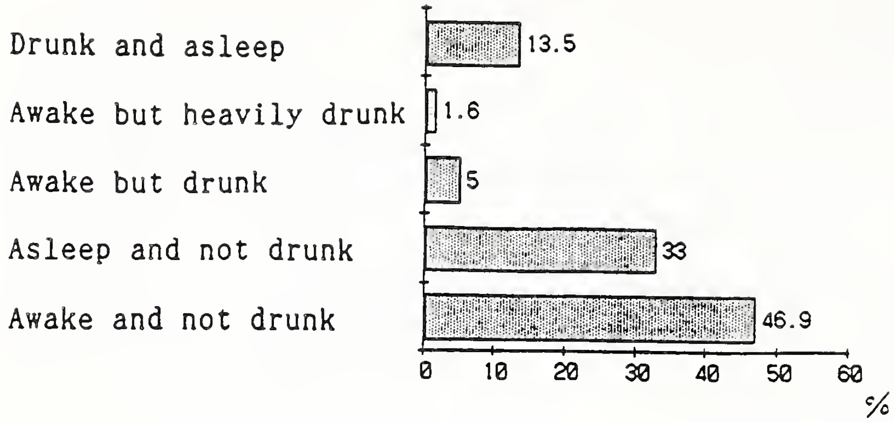


Figure 3 Proportion of Residential Fire Deaths by Levels of Consciousness Awakening at a Fire

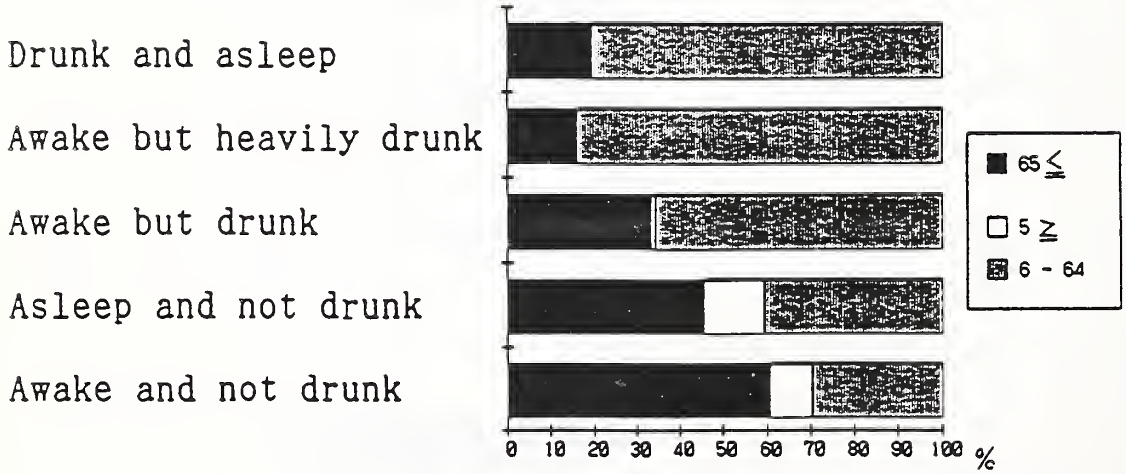


Figure 4 Breakdown by Age Classifications in Each Category of Levels of Consciousness Awakening at a Fire

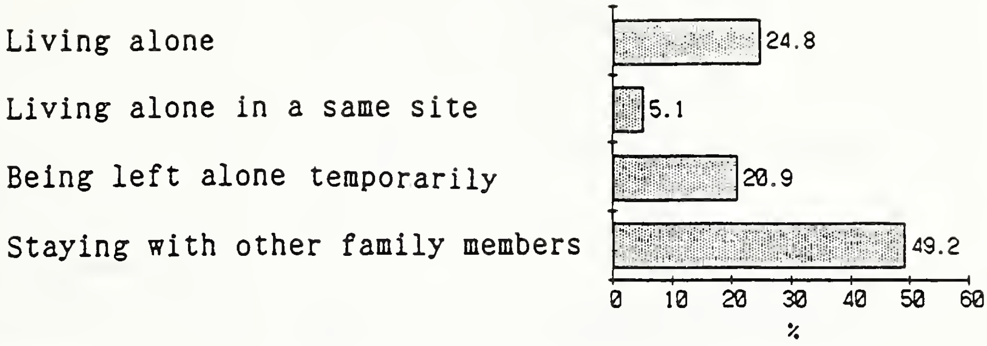


Figure 5 Proportion of Residential Fire Deaths by Presence of Others at a Fire

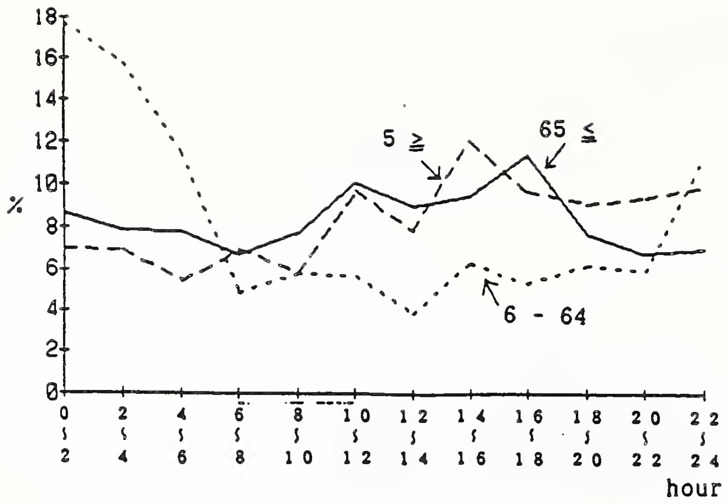


Figure 6 Fire Deaths Incidence by Time of Day
for Each Category of Age Classification

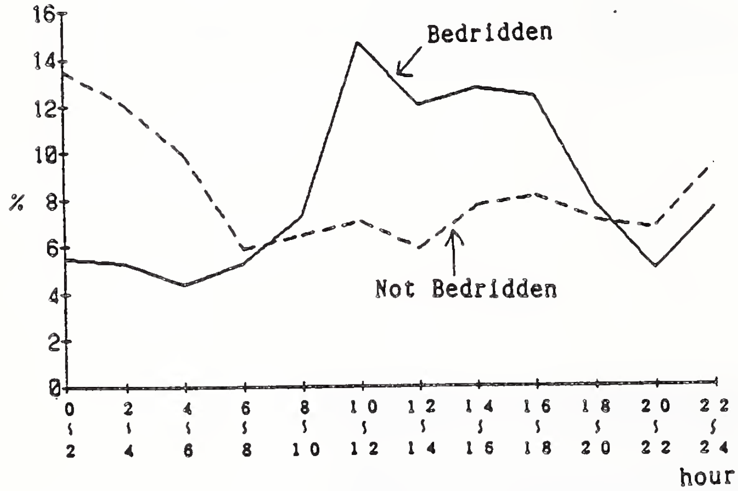


Figure 7 Fire Deaths Incidence by Time of Day
for Each Category of the Bedridden and
the Not Bedridden

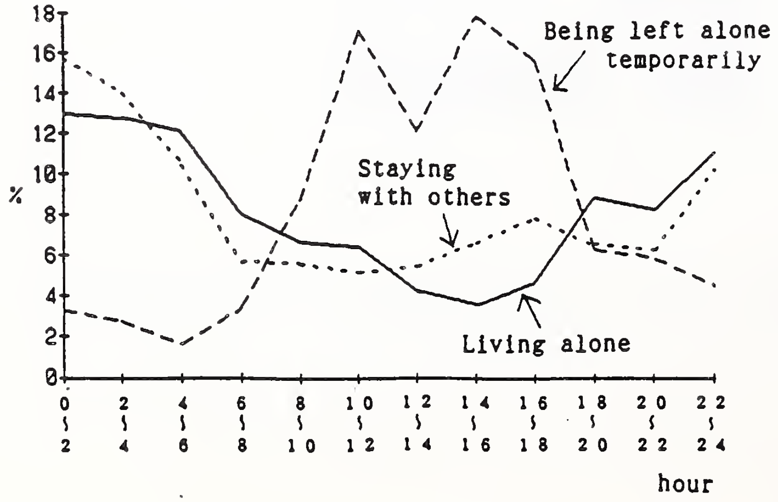


Figure 8 Fire Deaths Incidence by Time of Day
for Each Category of Presence of Others
at a Fire

SIMULATION OF FIRE PROPAGATION IN A WOOD FRAME HOUSE

by
Ichirou HAGIWARA
and
Isao TSUKAGOSHI

Building Research Institute
Ministry of Construction
1 Tatehara, Tsukuba-city, Ibaraki-ken, 305 JAPAN

ABSTRACT

Fire safety of residential wood buildings were discussed on the basis of fire incident statistics. Finishing and lining materials used in newly built houses are surveyed. Using these data, a computer simulation was tried for predicting the average burned area in a standard wood frame house.

1. INTRODUCTION

As Japan has frequently encountered city fires of extremely large scale, it has become a common sense that wood frame building is the most hazardous construction type. Recently large scale city fire scarcely happens and the combustibility of major structure does not seem to be related to the problem of casualties in fire. So it is considerable that the worse reputation for wood frame house is due to its inferiority in preventing property loss.

It is a fact that the average burned floor area for wood construction is larger than that for other constructions as shown in Fig.1.[*1] Attention should be paid to that the statistic data includes the fire loss for old houses constructed 20 or 30 years ago and the proportion of such old houses in wood construction category is greater than in other categories. Fig.2 shows the average burned floor area by completion year of houses and by construction method.[*2] The loss for newly built house of wood or fire protected wood construction is apparently small, while fire resistant construction does not make much difference.

According to the analysis of statistic data, it can be assumed that the recent construction method of wood frame house is different from the old one and has the better fire protective characteristics. However, this should be validated or enforced by other methods because statistics give us very little information on the causes of facts.

The purpose of this paper is to look over the fire risk of wood frame buildings for dwelling occupancy in view of the property loss. The present state of construction method was surveyed by an inquiry to house builders and using the results of the survey, a computer simulation of fire propagation was done in order to know the average property loss.

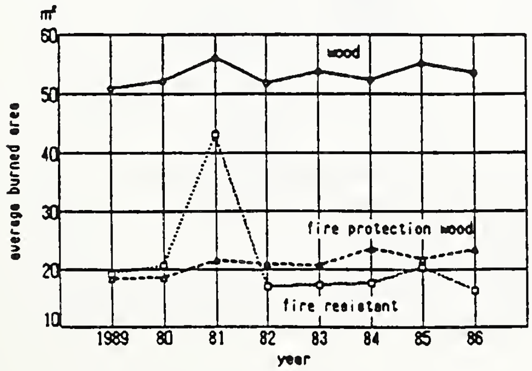


Fig.1 Average burned area
by construction category

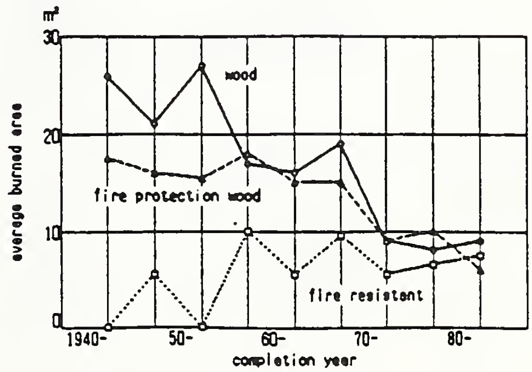


Fig.2 Average burned area
by completion year

2. SURVEY FOR CONSTRUCTION METHOD

The objective of this survey is limited to wooden detached houses constructed in 1987 FY by the subsidy of the Housing Loan Corporation(HLC); this is the most popular type of housing in Japan. In addition to the information on finishing materials which were already surveyed by HLC, the information on lining or underlayer materials are indispensable to determine the fire resistance of separations such as ceiling, wall and floor. Therefore, we decided to conduct the secondary survey.

Inquiry format was sent to about 100 house builders through the Wooden Home Builders Association of Japan and have got 31 answers which cover 15358 houses constructed in 1987 FY. By means of this survey and the HLC survey, we can know how frequently what materials are used for the assemblies of ceiling, wall and floor in four types of room such as living room, bedroom, kitchen and japanese room.

It was found that similar materials are selected for the types other than Japanese room and the most popular assemblies are wall paper on 9mm gypsum board for ceiling, wall paper on 12mm gypsum board for wall and flooring plywood or plank with no underlayer for floor. The frequencies in use of these representative assemblies are 55-80%, different by element and type of room. In Japanese room, the tendency of material selection is different from in other rooms: 94.6% of ceiling is covered by 3-4mm finished plywood with no underlayer: 59.6% of wall finish is "Sen-i-kabe"(daubed pulp) on 7mm plaster board: 87.1% of floor is "Tatami-mat" made of straw and others made of foamed plastic, with underlayer of 12-15mm plywood or plank.

Every combination of finishing material and underlayer material was evaluated in respect of fire resistance on the basis of existing test data and finally classified into four grades. The frequencies of these grades are shown on Tab.1 by three kinds of element and four types of room.

Tab.1 Frequency of interior assemblies by fire resistance (%)

grade fire resistance (min.)		1 (15)	2 (10)	3 (5)	4 (2.5)
ceiling	living room	14.00	73.96	5.04	6.98
	bedroom	13.65	75.82	3.88	6.66
	kitchen	9.60	80.04	9.41	0.96
	Japanese room	1.25	3.69	0.44	94.62
wall	living room	60.96	29.14	9.86	--
	bedroom	58.64	34.26	7.08	--
	kitchen	65.83	33.86	0.30	--
	Japanese room	39.86	59.60	0.55	--
grade fire resistance (min.)		1 (15)	2 (10)	3 (7)	4 (5)
floor	living room	9.83	20.51	69.65	--
	bedroom	18.81	20.53	60.65	--
	kitchen	1.39	42.00	56.59	--
	Japanese room	39.89	53.17	6.94	--

3.SIMULATION OF FIRE PROPAGATION

1) CONCEPT

It is not easy to describe the transition of burning area among multi-rooms by means of complete physical model. But, generally speaking, as every room in a wooden house has relatively large windows and they are not fire protected, an initiated fire would grow up in short time into an active fire and it is considerable that the early state of fire is not so important for the prediction of burned area in a whole house. In addition to this, there is another problem that numerous repetitions of calculation are required according to the combination of initial conditions and building materials for each element of each room. And therefore, we have finally chosen a very simplified model which is only based on fire resistance of building assemblies between rooms.

The house in Fig.3 was presented by the HLC as the japanese standard detached house whose characteristics such as the total floor area, the number of story, the number and the sorts of room, etc. are the average of surveyed data. We have decided to apply our simulation model of fire loss prediction to this specific house.

This house can be simplified to a network model with nodes and links; it is possible to assign: a node to a room, a space behind ceiling or an exterior space, a link to a fire spread route with a fire resistance.

Providing that all the separations between rooms are made of the ideal fire resistant construction (we call this type of house as fire resistant house), we need not consider a fire spread route through floor and ceiling, wall, ceiling spaces nor exterior space. Fire would spread only by way of interior doors. In this case the network model is very simplified as shown in Fig.4 and the fire spread time for each room could be given by hand calculation.

On the other hand, if a house is a wood construction, there are many fire spread routes between two rooms. The fastest fire spread time is determined by comparing the fire resistance of the routes.

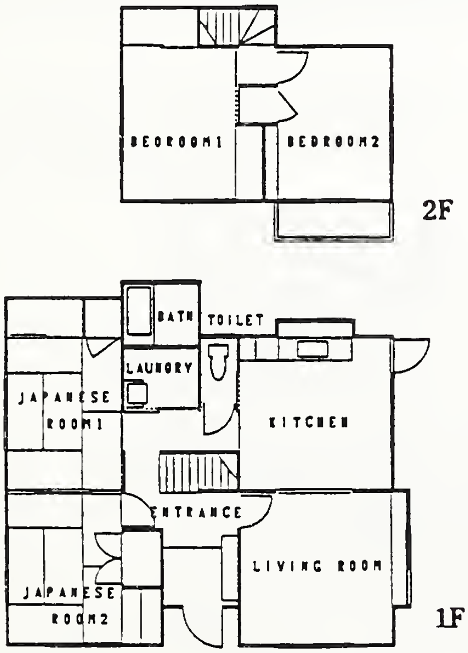


Fig.3 Model house

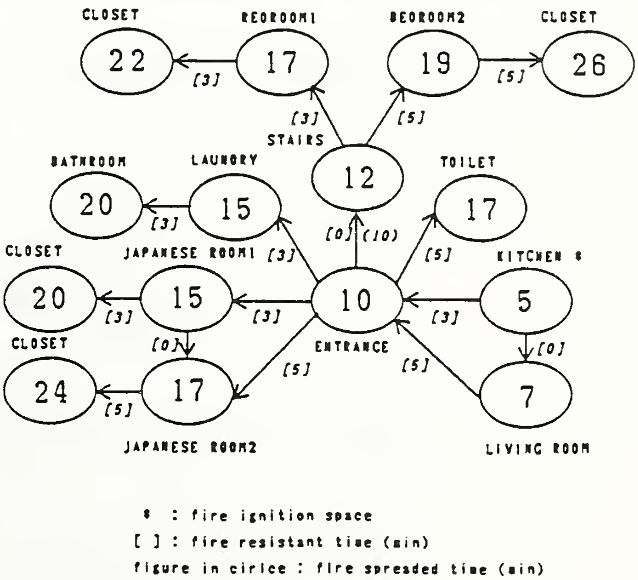


Fig.4 Example of network space model (a fire resistant house)

2) ASSUMPTION IN SIMULATION

This simulation is based on the following assumptions :

(1) A fire breaks out in one of the 9 rooms in the model house with the probability corresponding to fire statistics.

(2) A fire ignition room needs 5 min. to be burned out, other spaces 2 min.

(3) The fire resistant time and the frequency in use for each fire grade of building element are given by Tab.1. The fire resistant time of openings (doors, windows) is

a door (3mm plywood flush door) : 5 min.

a sliding door (Japanese "Fusuma", or glass door): 3 min.

(4) The test data of horizontal separation with the upper surface exposed could not be obtained and the fire fire resistance for such case is assumed to be one half times of the normal case.

All the openings are also assumed to be closed, because the comparison of fire loss between wood frame construction and fire resistant one is one of the objectives of our work and this assumption would expands the difference of them.

3) ALGORITHM OF PROPAGATION

To determine the fire spread time of each room the following algorithm is adopted. If there is any fire spread route between the node i and j on the network space model, the fastest spread time Lij can be determined as multiple value of time unit(dt) which is sufficiently small to be accepted as the allowance of calculation. On Fig.5, if the node j starts to burn at time t, the fire has had to come from one of the adjacent nodes which was already in fire at time t-dt. Thus the node j is burned by the fire from i or n, not from k, because k is not in fire at time t-dt.

Which node is the spread source depends on fire resistant time of link and fire spread time of adjacent node. There are 3 possible cases.

i) if $t = Ti + Lij$ & $t < Tn + Lnj$ then from node i

ii) if $t < Ti + Lij$ & $t = Tn + Lnj$ then from node n

iii) if $t = Ti + Lij$ & $t = Tn + Lnj$ then from both

if t does not fit to any of these cases, the node j has not get been in fire at t. As this procedure is repeated at every dt and for every node not get in fire, fire spread times of all the nodes can be determined.

4) CALCULATE BURNED AREA

One case of simulation, corresponding to a location of initial fire and a combination of all the related materials, makes one burned area-time curve. This

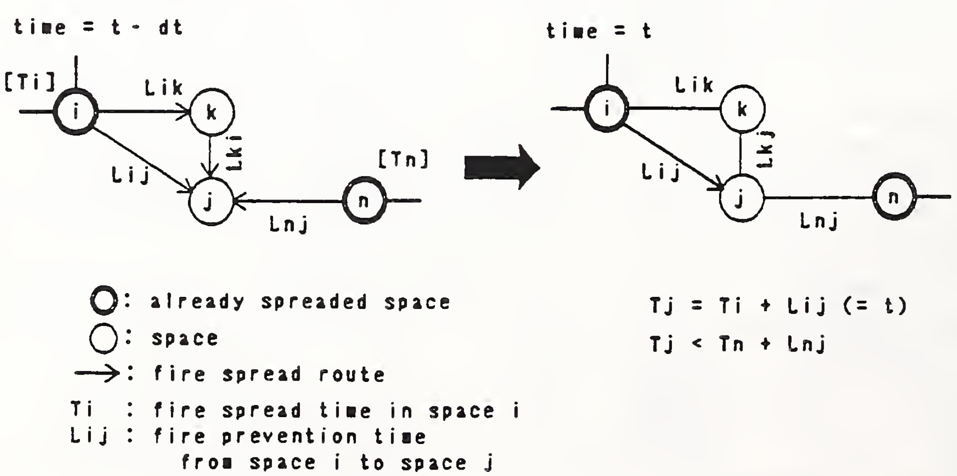


Fig.5 How to determine the fire spread time

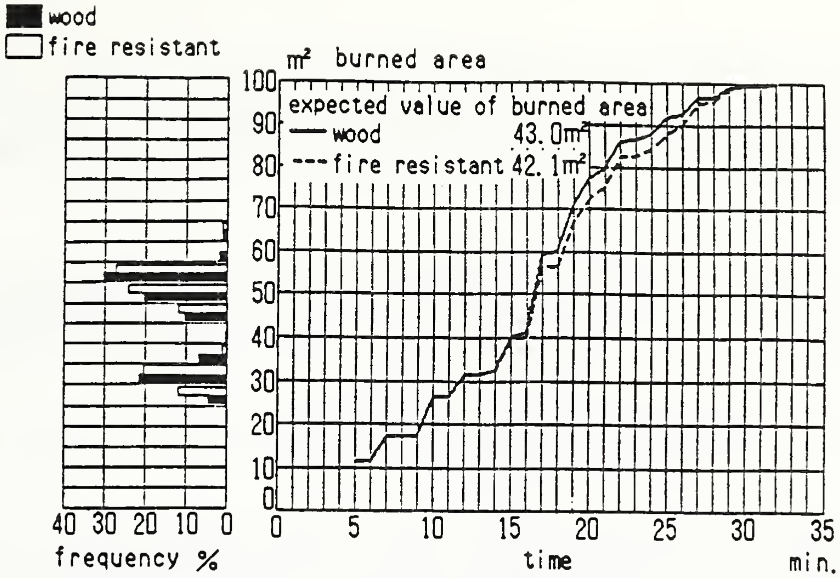


Fig.6 Burned area-time curve
and frequency of expected burned area

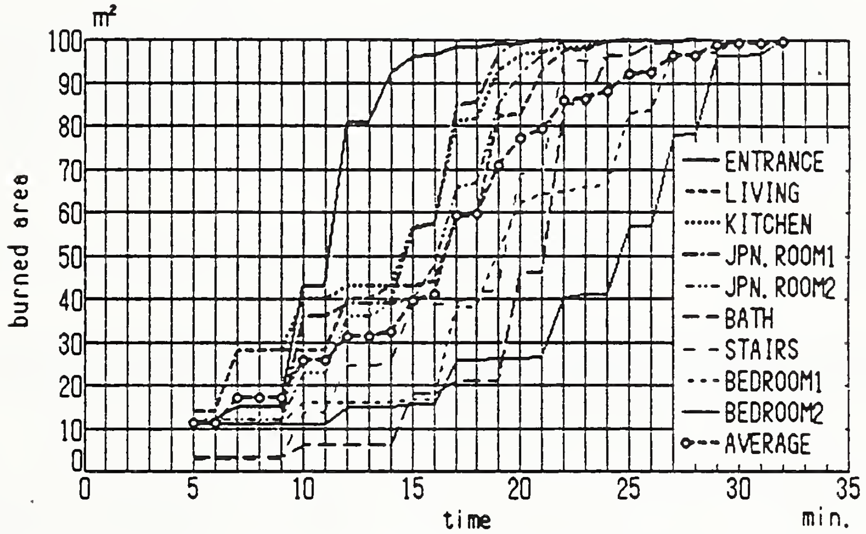


Fig.7 Burned area-time curve by fire ignition room

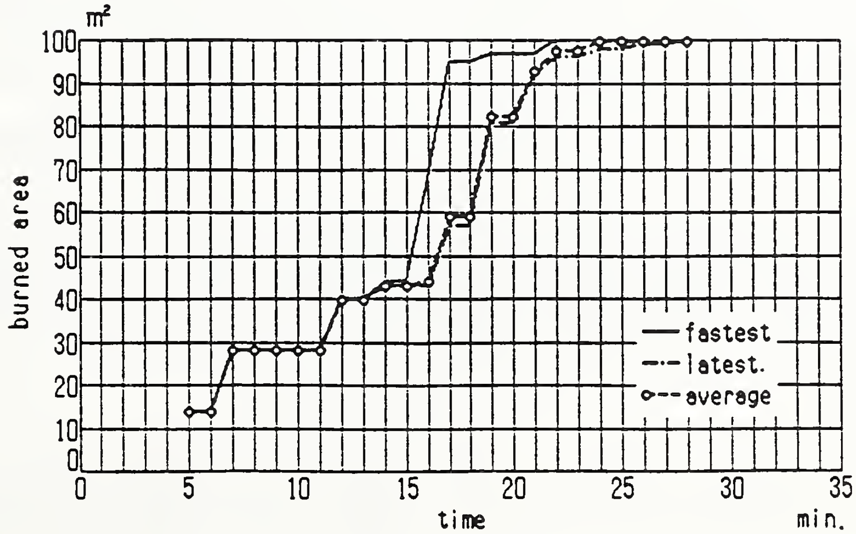


Fig.8 A case of living room fire

curve shows the burned area at each time under the condition without fire fighting. So, to calculate the expected value of burned area, the curve should be multiplied by the probability of fire extinguishment at each time and summed up for all the cases. After all, the plan in Fig.3 needed about 15 millions cases of simulation.

5) RESULT

As shown in Fig.7, a burned area-time curve mainly depends on the location of fire ignition. A fire starting in the entrance hall(1F) spreads out fastest of all the ignition. The latest case is for a fire from the bedroom2(2F).

Fig.8 shows the burned area-time curve for the living room fire, indicating the difference by assembly materials. In the fastest case, all the separations are made of the 4th or 3rd fire resistant grade.

The latest case referring to the first grade separations is corresponding to the case of a fire resistant case, because a fire does not penetrate through the first grade separations and spread out only by way of openings. And the average curve for a wood frame house is almost same as the curve for a fire resistant house.

The solid line curves in Fig.6 is the average of all the curves in Fig.7 and represents the fire growth curve for japanese newly built wood frame house and the dotted line is the result of the summation of the cases corresponding to a fire resistant house. The two curves have almost no difference. The expected value of burned floor area for a wood frame house is 43.0 m^2 and for a fire resistant house 42.1 m^2.

4. CONCLUDING REMARKS

The analysis of fire statistics and the result of simulation study indicate following remarks:

1) In a recent wood frame house in Japan, noncombustible materials like gypsum board are used in large quantities as linings or underlayers. They are replaced to plywoods or planks in conventional construction.

2) This has improved the fire resistance of assemblies of ceiling, wall and floor and it serves to keep a fire in a room relatively long time. Consequently, the burned area growth curve given by the computer simulation is resembles to that for a fire resistant house.

3) It is important in the background of the simulation that doors separating two rooms have only 3-5min. of fire resistance and make the major route of fire propagation. The situation for a fire resistant house is all the same as that for a wood frame house. Therefore, the improvement of quality of doors would provide a better result of property loss but, at the same time, a greater difference between wood frame construction and fire resistant construction.

4) For future studies with a more plausible model, we need a sub-model which gives fire spread time in a room with the specific conditions of combustibles and openings. After an adequate improvement of the model, combined with smoke development model and human behavior model, we believe that it can be evolved to a comprehensive model to evaluate the fire risk in a small house.

REFERENCE

*1 Fire statistics data by the Fire Defense Agency, Ministry of Home Affair
*2 H.Kakegawa, T.Nagaoka, M.Tsujimoto "Estimation of Fire Risk Using Data Base, No.2 Fire Risk in Residential Buildings in Tokyo" Proceedings of 1989 Annual Meeting of the Japanese Association of Fire Science and Engineering, 1989.5.17

THE CONCEPT OF A PERFORMANCE BASED DESIGN METHOD FOR BUILDING FIRE SAFETY

Takeyoshi TANAKA
Building Research Institute
Ministry of Construction

1. INTRODUCTION

Traditionally, fire safety measures of buildings have been determined based on the prescriptive specifications in building and fire codes, but the multiplication of the rules in many years has caused several problems, such as illegibility of the codes, excessive cost for fire protection and inflexibility in accepting new design or technology of buildings. Considering such situation and the significant progress recently achieved in the area of fire science and engineering, BRI launched a 5 years project called "Development of Fire safety Design Method of Buildings" in 1982. The final report was just published and a new scheme for fire safety design of buildings based on the results of this project is expected to be operated in three years, after some work for the perfection of the design method. In this paper, the concepts undermined in this design method are briefly outlined.

2. STRUCTURE OF THE FIRE SAFETY DESIGN METHOD

The "Fire Safety Design Method" was planned to provide minimum standards for fire safety in the form of performance standards on the assumption that it operates through the same administration system as that of the Building Standard Law. The structure of the fire safety design method is illustrated in Figure 1 in comparison with that of fire safety provisions in the Building Standard Law of Japan. The main difference of fire safety design method from the Building Standard Law are as follows:

a) The fundamental requirements are redefined more explicitly,
b) Technical standards are expressed in terms of performance standards as long as possible and beneficial,
c) Calculation methods and computer codes for the prediction of fire related behavior are provided.

3. FUNDAMENTAL REQUIREMENTS FOR FIRE SAFETY

As for the fundamental requirements for fire safety of buildings, the Building Standard Law states in Art 35 that buildings shall be so constructed and maintained that any hindrance against evacuation safety, fire prevention and fire fighting is avoided. Obviously, this statement is too inclusive and abstract to derive directly technical standards from, so considering the implicit purposes of the prescriptions, the fundamental requirements of the Fire Safety Design Method are redefined more explicitly as follows:

(1) Requirements for Fire safety as an Individual Building
  (1.1) Precaution against outbreak and rapid spread of fire
  (1.2) Assurance of life safety
    (a) Control of building materials which may cause serious hindrance to evacuation in the event of fire
    (b) Proper evacuation plan
    (c) Assurance of safe refuge
    (d) Assurance of safe egress routes
  (1.3) Prevention of serious nuisance to the third parties
    (a) Prevention of fire spread to buildings or a part of a building owned by the third parties
    (b) Prevention of collapse of buildings
    (c) Assurance of reusability of buildings of multi-ownership
  (1.4) Assurance of activities of fire brigades
    (a) Assurance of activities for search and rescue of occupants
    (b) Assurance of fire fighting activities

(2) Requirements for Prevention of Urban Fire

Functional definitions are given to each of the requirements.

4. TECHNICAL STANDARDS FOR THE CONFORMITY TO THE REQUIREMENTS

It is necessary to provide technical standards to each of the fundamental requirements so that designers, building officials, inspector or whoever can check if a designed building satisfies the requirement.

The procedure for examining the conformity of a building to the requirements are illustrated in Figure 2 taking the example of the design of evacuation routes. In this process, the technical standards are given in terms of the standard fire conditions(or design fire) and the standard safety criteria, and the former is inputted to the relevant means to predict evacuation of occupants and smoke behavior, which play very important roles in this system, and the predicted results are compared with the latter to see if the designed building is at acceptable safety level. In concept, the standard fire condition, standard safety criteria and the prediction means respectively correspond to design load, allowable stress(or deformation) and structural calculation in a structural design of buildings.

<Character of the prediction methods>

In general, it is very difficult to develop accurate prediction methods for complex objects as a building, whether the method is for structural behavior or for fire behavior. Inevitably, such prediction methods are considerably simplified in the course of modeling, and in addition to this, from the nature of buildings, conducting experiments for the validation of the predicted results for actual buildings is not easy. These make it very difficult to evaluate the discrepancy between what is predicted to be necessary and what is in reality needed.

Fortunately, however, construction of buildings has long been almost an every day practice of men, so we have a considerable amount of empirical knowledge about what are needed for fire safety of ordinary buildings. This does not mean that theories are useless. Theories are indispensable when we try to adopt unconventional design or method of construction since empirical knowledges work well only where experiences exist.

<Harmonization of Theories and Experience>

In many engineering designs, since the theories and the conditions considered are significantly simplified, some adjustments are usually needed to compensate the discrepancy between theories and empirical knowledges, of which the safety factors in structural design may be a good example. This concept of the harmonization of theory and experience is illustrated in Figure 3. Once we have managed to find how to adjust them, we will be able to extend this technique to where we have no experience. In a strict sense, there remains a certain degree of risk since it is not guaranteed that this technique is still valid for inexperienced region, but this will be the risk we have to tolerate in conjunction with the benefit we can enjoy by introducing inventive designs or methods.

<Meaning of Technical Standards>

As mentioned in the above, the technical standards of the performance based design method consist of (a)standard fire conditions and (b)standard safety criteria. It is possible to harmonize theories and experiences by adjusting the values of the former and/or the latter so that a necessary level of fire safety can be attained in buildings. In this particular case of the Fire Safety Design Method, it will be more appropriate to get the standard fire conditions, which consist not only of the size but also of the scenario of fire, assume the principal role of the adjustment since the safety criteria for men or building elements can be determined in comparatively more accurate manners than the design fire conditions.

The connotation of the standard fire conditions is illustrated in Figure 4, in which fire condition is simplified as size of fire. The solid curve stands for the conceptual frequency(or probability) of the appearance of fire vs. size of fire. According to the general characteristics of accidents, the frequency of the appearance of fire is high when the size is small, but decreases dramatically as the size increases. Needless to say, the larger the size of a fire, potentially it is more dangerous, but the level of real danger depends on the fire safety measures provided, in other words, a building space having better safety measures can cope with severer fire conditions. The essential significance of the standard fire condition is to demand to provide fire safety measures necessary to clear the danger represented by the standard fire conditions so that the probability of the appearance of hazardous fire can be kept below an acceptable level.

If a higher level of safety is desired, it can be achieved by raising the standard. It should be kept in mind, however, that this is often accompanied by raising building cost, so the standard fire conditions must be so determined that fire safety measures can be provided for the cost which the society is prepared to pay and yet the society is not seriously disturbed by the fire accidents due to the remaining risk.

5. EXAMPLE OF TECHNICAL STANDARDS

The technical standards for a performance based method need to be given by calculable or measurable values so that the conformity to the standards can be examined without ambiguity. Here, the technical standards for assurance of safe evacuation from the room of origin are given for an example.

The standard fire conditions for the assurance of safe evacuation from the room of origin are summarized in Table 1. Any space must be considered as a potential room of origin unless exempted by the conditions shown in this table. The standard fire which is illustrated also in Table 1 is generated taking account of the burning propensity of building contents in fire tests and the current fire safety measures legally required. In sprinklered rooms, the heat release rate of the fire is limited to the maximum rate at which the sprinkler heads are not actuated. In case of ceiling mounted sprinklers, this rate is determined as a function of ceiling height and the spacing and the actuation temperature of the sprinkler heads.

While the existing regulations directly give prescriptive solutions for evacuation safety, it is necessary for the establishment of performance standards to analyze the potential causes and mechanism of dangers due to fire to the occupants in the course of evacuation. As can be seen in Figure 5, while the direct hazards for the evacuees are smoke, heat, collapse and breakage, the factors causing hindrance on the egress routes play an important role to induce or accelerate the direct dangers.

The standard safety criteria are summarized in Table 2. These are the conditions at which the room of origin has to be maintained during the period of evacuation from the room of origin for the safety of the occupants against the potential dangers due to fire.

REFERENCE

Tanaka, T.: "A Performance Based Design Method for Fire Safety of Buildings" Fire Safety and Engineering, International Symposium Papers, The Warren Centre for Advanced Engineering, The University of Sydney, 1989

	BLDG. STANDS. LAW	FIRE SAFETY DESIGN METHOD
Ultimate Goals	a) Life Safety b) Property Protection c) Public Welfare	a) Life Safety b) Property Protection c) Public Welfare
Level of Requirements	Minimum	Minimum
Principle for Fire Safety	Article 35 etc.	Fundamental Requirements for Fire Safety
Technical Standards	- Bldg. Stands. Law - Enforcement Orders - Minist. of Const. Orders (Specification Stands.)	(Performance Stands.) - Stand. Fire Condition - Stand. Safety Criteria (Specification Stands.)
Support Technologies	Fire Tests	- Fire Tests - Means of Fire Prediction - Computer Codes

Figure 1. The Structure of The Fire Safety Design Method in Comparison with the Building Standard Law of Japan

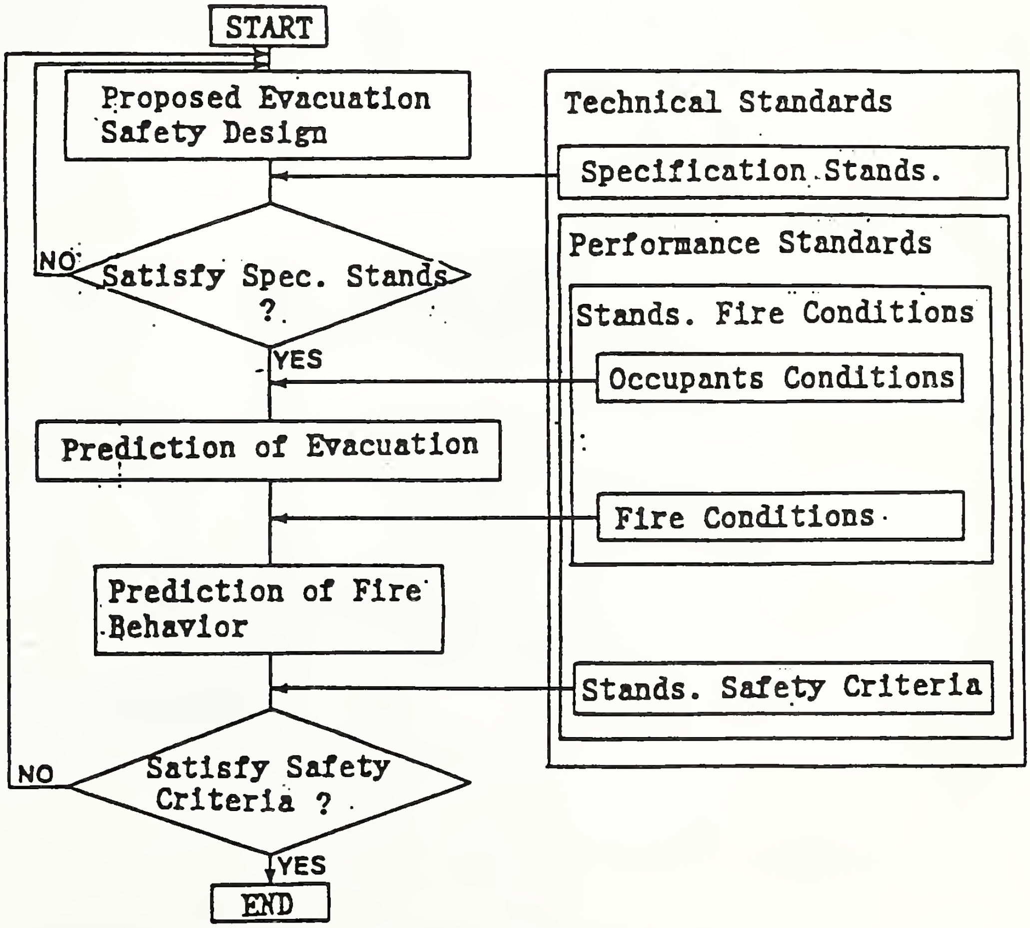


Figure 2. The Procedure of The Evacuation Safety Design

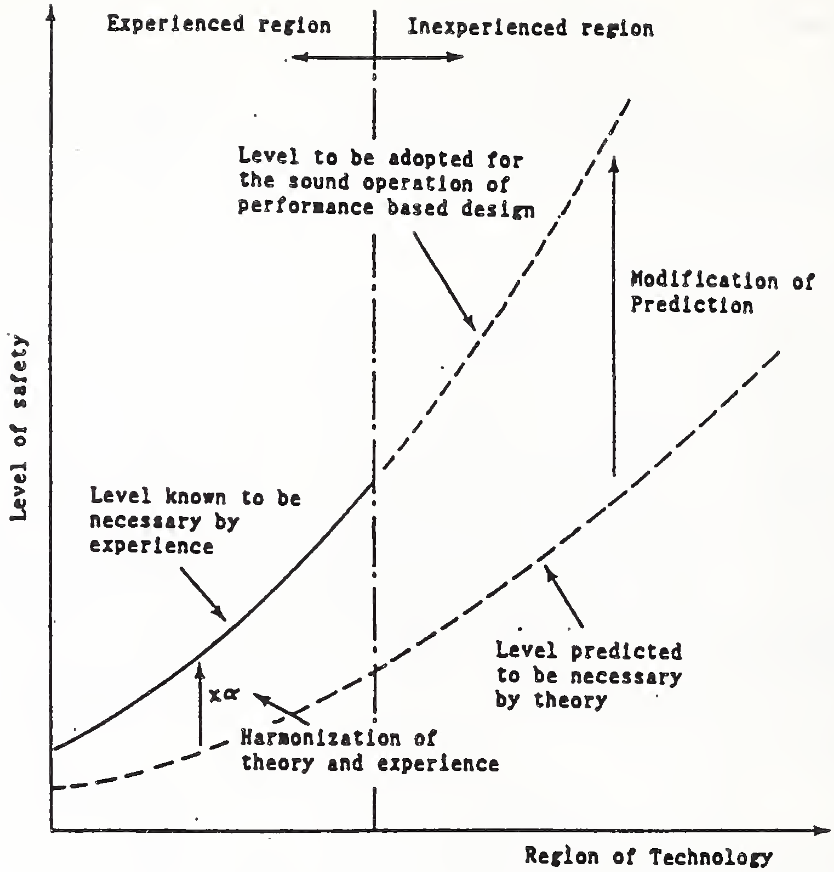


Figure 3. Concept of harmonization of theories and experiences

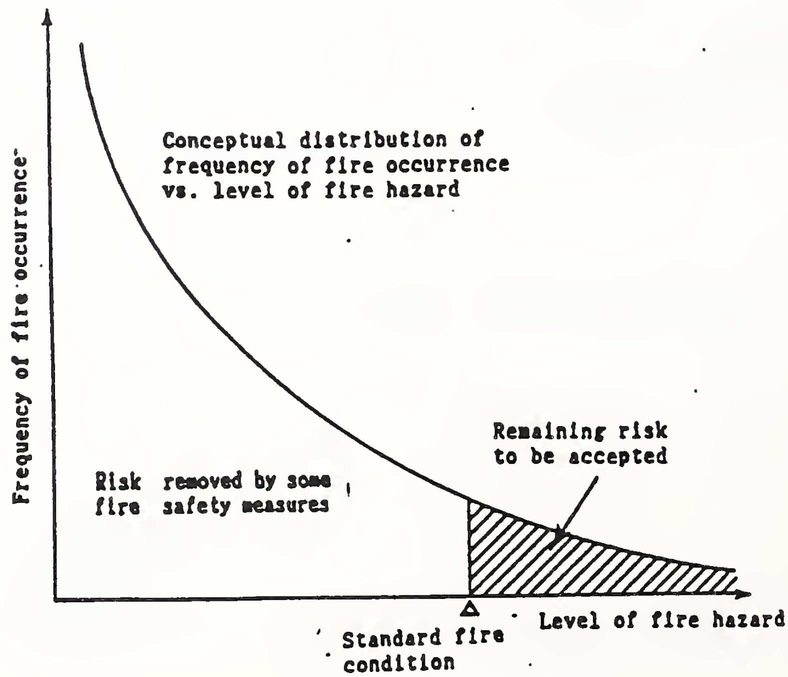


Figure 4. Meaning of standard fire condition

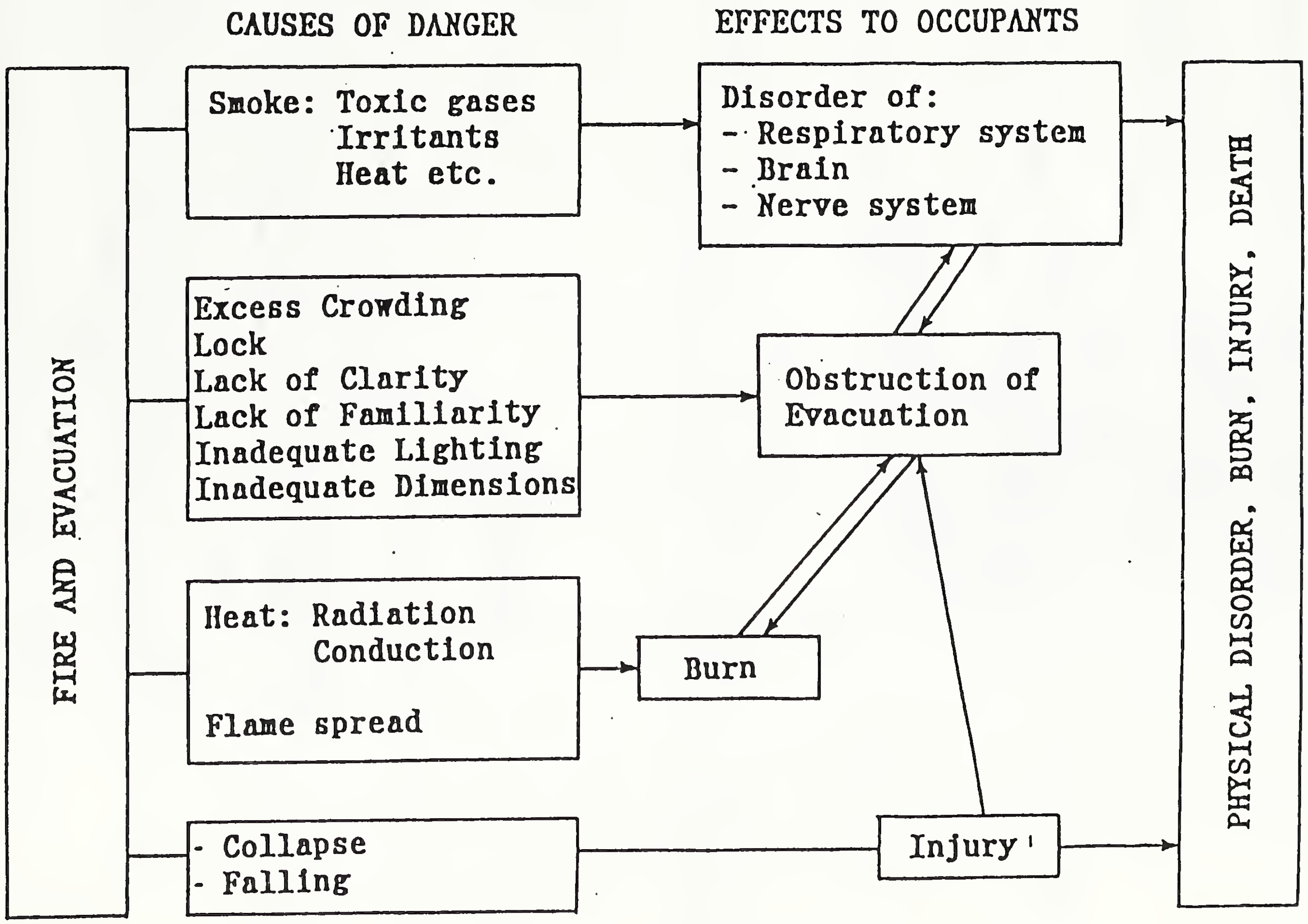
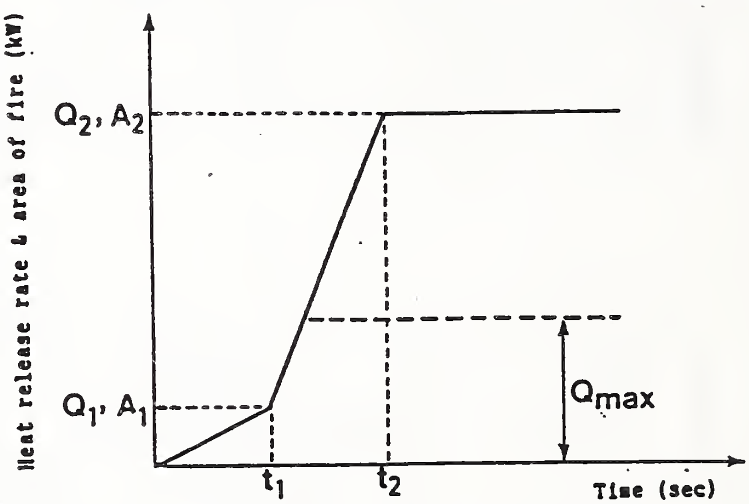


Figure 5 FIRE HAZARDS IN EVACUATION ROUTES

Table 1 Standard fire conditions for safe egress from the room of origin

Space of origin	: All the spaces which do not fall into the followings; a) No occupant exists in normal use b) Safer than a space which satisfies safety standards
Occupants	: 1) Number of evacuees; Specified in terms of occupants' density or some other ways according to the type of space 2) Evacuation ability; Specified according to the type of space and occupants 3) Evacuation start time; The smallest of the times at which occupants recognize the danger due to fire by means of a) Cue by fire, smoke b) Cue by other occupants c) Through the fire detection and alarm system
Scale of fire	: 1) Unsprinklered space; Specified as follows according to type of space 2) Sprinklered space; The smaller of the followings a) fire source specified by 1) b) maximum fire which cannot actuate the sprinkler head



Occupants' condition	Quantity of Contents	Time (sec)		Heat release (kW)		Area (m^2)	
		t_1	t_2	Q_1	Q_2	A_1	A_2
Wake	Large	120	240	300	3,000	1.7	1.7
	Small	120	320	750	25,000	0.5	17.0
Sleeping		480	720	200	1,000	2.5	2.5

note: For spaces in which ceiling mounted sprinklers are installed, the maximum heat release rate Q_{max} is given by

$$Q_{max} = 0.08\ r\ \{(T_c - T_o)H\}^{3/2}$$

where H : ceiling height (m)
r : maximum horizontal distance between a sprinkler and the axis of fire plume (m)
T_c : critical temperature of sprinkler actuation (K)
T_o : ambient temperature (K)

Table 2 Standard safety criteria for safe egress from the room of origin

Items to be Checked	Safety criteria
1. Smoke	Either of the followings: (1) Smoke layer bottom is kept at height s (m) which satisfy $s > 1.6 + 0.1(H - h)$ where H : ceiling height (m) h : height of the floor of evacuation route (m) (2) The smoke to which evacuees are exposed satisfy $\int_0^{t_e} (\Delta T)^2 dt < 4.0\times10^3$ where ΔT : temperature rise (K) t_e : time during which evacuees are exposed to smoke (s)
2. Heat	Incident radiation heat flux r (kW/m^2) to evacuees satisfy $\int_0^{t_e} (r - 2)^2 dt < 10$ (if $(r - 2)<0$, $(r - 2)^2=0$) where t_e : evacuation time (s)
3. Flame spread	The interior lining materials do not induce the combustion which violates the safety criteria of 1. Safety from smoke and 2. Safety from heat during the time of evacuation.
4. Collapse of building	N/A
5. Falling objects	Functional standard
6. Excessive crowding	Unless in space specially protected, crowding at any opening on evacuation routes satisfy $n < 120$ where n : number of evacuees in crowding per unit width (person/m)

OPEN TECHNICAL SESSION

CARBON MONOXIDE PRODUCTION AND PREDICTION

WILLIAM M. PITTS
Center for Fire Research
National Institute of Standards and Technology
Gaithersburg, MD 20899, USA

ABSTRACT

A long-term research plan has been formulated which is designed to improve the understanding of and predictive capability for the formation of carbon monoxide in enclosure fires. The current understanding of the problem is briefly discussed. Goals (milestones) for the project are listed and the research plan is discussed in terms of eighteen individual research components.

1. INTRODUCTION

One of the mandates of the Center for Fire Research (CFR) is a reduction in the number of fire deaths and injuries. To achieve this goal, CFR has led the effort to characterize and model fire behavior. The development of realistic fire models allows strategies to be developed for ameliorating its effects.

Investigations have shown that a large percentage of fire deaths and injuries can be attributed to products of incomplete combustion. Even in cases where burn injuries and death occur, incapacitation of victims by fire gases often plays a pivotal role since escape from flames is hindered or rendered impossible. Careful studies (e.g., [1,2]) have shown that more than one half of all fire victims have fatal levels of carboxyhemoglobin in their bloodstreams.

Even if a complete understanding of the physiological effects of CO (in combination with effects due to other fire products, e.g., reduced oxygen and increased respiration resulting from elevated carbon dioxide concentrations) is available, accurate predictions of fire toxicity require reliable estimates for the concentrations of toxic gases generated by a fire.

Systematic investigations of CO formation in fires date from at least the 1960s. However, despite nearly three decades of research the current understanding of CO formation in enclosure fires must be characterized as poor. For any given fire scenario it is impossible to predict accurately the concentrations of CO which will be produced and transported from the room of fire origin. As a result, models for fire toxicology are dependent on crude estimates for the CO concentrations generated.

CFR has embarked on a long-term effort to develop an improved understanding of the chemistry and physics responsible for the generation of high levels of CO and the development of reliable algorithms for predicting the CO levels generated by fires. During the past year a research plan has been drafted [3] which is designed to provide the understanding necessary for the prediction of CO levels generated by enclosure fires. This presentation briefly describes the current understanding concerning CO formation in fires and the research approach which has been adopted. Goals for the project are discussed. The project plan consists of a number of research components which are included in tabular form.

The research plan has been developed following an extensive review of the existing literature and relevant intramural and extramural CFR research programs. An important component of this review is the findings of a <u>Workshop on Developing a Predictive Capability for CO Formation in Fires</u> which was held in Clearwater, Florida on December 3-4, 1988. Leading experts in the field have provided recommendations and justifications for the principal areas in which research is required in order to achieve the ultimate project goal. An executive summary of this workshop is available [4].

2. CURRENT UNDERSTANDING

Numerous large-scale enclosure fire tests have been reported in which CO concentrations have been measured (e.g., [5,6]). These tests show unequivocally that CO concentrations high enough to be life-threatening often occur in this type of fire. On the other hand, no systematic investigations of CO formation in full-scale tests have been identified in the literature, and the conditions necessary for the generation of high levels of CO are not well characterized. The uncertainties are compounded by variations in experimental protocols (e.g., probe placement) and the utilization of inadequate experimental instrumentation.

In general, high CO concentrations are associated with either smoldering or underventilated fires. Smoldering fires will not be considered here. Some crude correlations of CO formation and the ventilation parameter for an enclosure ($Ah^{1/2}$) have been attempted [7]. However, the fire behaviors in these studies have not been adequately assessed, and the utility of these correlations for actual fires is limited.

For locations removed from the room of origin, CO concentrations may depend critically on whether or not additional combustion of product gases occurs after exiting the enclosure. The understanding of this process is very poorly characterized, and the controlling parameters have not been identified.

Dr. George Mulholland has developed a zeroth-order model for CO formation in room fires [8] which assumes very low concentrations of CO for preflashover conditions and significant CO concentrations for postflashover fires. CO concentrations following flashover are estimated to be 0.5 times the carbon dioxide concentration. This model is based on measurements recorded in three series of full-scale fire tests performed at CFR.

In recent years some carefully performed experiments have been carried out which offer the promise of an improved understanding of CO formation in terms of engineering correlations. Workers at Harvard [9] and Cal Tech [10] have generated controlled two-layer combustion systems which closely mimic the simple two-layer model often used to represent enclosure fires. Note that, in general, these experiments are steady state while actual fires are highly dynamic. A remarkable finding of these experiments has been that the major products of combustion (including CO) for a given fuel can be correlated in terms of the global equivalence ratio in the upper layer containing the combustion products. The correlations do depend on fuel type. Experiments [10] have shown that the same correlations hold even for the cases where additional air is injected into the upper layer.

Very recently, the Cal Tech workers have extended their studies to an experimental configuration where the entire flame is located within the upper layer [11]. For this case, burning occurs entirely within a vitiated atmosphere. The rather surprising observation (based on earlier speculation in the literature) is made that very low concentrations of CO are measured for increasing fuel equivalence ratios up to the point where oxygen concentration in the vitiated environment (≈ 13%) is insufficient to support combustion. Similar observations have been made at CFR for preliminary measurements in a cone calorimeter modified to allow partial vitiation of the air supply. These studies indicate that vitiation of the air supply is not responsible for high levels of CO as long as sufficient oxygen is available for complete, fully-involved combustion.

3. PROJECT GOALS

The general project goal for the CO Production and Prediction project "is to improve the understanding of and predictive capability for the formation of carbon monoxide (CO) in fires" [3]. Clearly this overall goal is far too general to serve as a legitimate means for project planning. More specific goals (milestones) have been formulated. The following milestones represent realistic goals for a five-year research program. A five-year period has been chosen only for planning purposes. The actual project length will be dependent on resources and personnel available for the project.

1. By the end of the third year of the project an engineering correlation for CO concentrations in terms of the global equivalence ratio will be available for incorporation into fire computer models. Further work during the final two years of the project will be required to fine tune this correlation and determine the appropriate conditions for which its use is valid. By the end of the five-year period it will be possible to incorporate the effects of the combustion behavior of products exiting an enclosure on CO formation.

2. By the end of the five-year period the fundamental portion of the project will have identified the important parameters controlling CO formation in fires. A general understanding of the reasons for the success of the global equivalence ratio concept in terms of the combustion behavior within the fire plume will have been attained. Modelling of CO formation for very simple systems (e.g., a single gas burner located in an enclosure) will be possible.

4. PROJECT PLAN

A project plan has been formulated to meet the milestones listed in the last section. The plan incorporates the findings of the workshop [4] as well as the analysis of the project manager. The plan is summarized in terms of the eighteen research components listed in Table 1. The full research plan [3] describes the assumptions which went into the choice of these components in more detail.

Research component 4 deals specifically with the first milestone listed in the last section. A number of the other research components are designed to feed information into this effort. Most important are numbers 2, 9, 10, 14, 15 and 16. For planning purposes it has been assumed that a suitable engineering correlation will become available during the third year of the project, and component number 17 is included for the incorporation of the correlation into whichever fire model(s) is deemed appropriate.

In developing project goal 1 it was recognized that even though it should be possible to formulate an engineering correlation for CO concentration in terms of the global equivalence ratio within the first three years of the project, certain aspects of the problem can not be completed within this time frame. The burning behavior of gases exiting the enclosure is sure to be one of the remaining uncertainties. Components 11 and 12 are to address this problem. It is anticipated that a sufficient understanding of the controlling parameters will be available to allow crude estimates of the effects of such burning on the CO concentration correlation.

The second goal of the priority project deals with fundamental aspects of the problem. As was true for the first goal discussed above, several of the research components address this goal.

Research components 1, 2, 6, 7, 8, 9, 10, and 13 are required to generate the research findings to meet the fundamental project goal. Components 1, 2, 7, 8, 9, and 10 will aid in the identification of the important physical processes responsible for the formation of high levels of CO during ventilation-limited burning. Note that 2, 9, and 10 are also necessary to validate the engineering correlation developed to meet the first goal of the project.

In order to have confidence in the engineering correlation which is generated, it is necessary to have some understanding of the physical basis for the success of the correlation. The fundamental studies mentioned in the last paragraph will provide the insights required to develop this understanding. At the same time, component 13 deals specifically with the question of whether or not the high levels of CO formed during vitiated burning can be understood simply in terms of turbulent combustion processes. Turbulent combustion modeling is to be employed for this purpose. Note that the experimental results of component 1 are required as input for this research.

The final goal of the fundamental studies is to develop a model capable of predicting the time development and concentrations of CO for a simple prototypical fire in an enclosure. Research component 5 deals specifically with this topic.

5. FINAL COMMENTS

The complexity associated with CO formation and prediction in fires precludes an effective project by one or even a few individuals. As mentioned in Section 2, the current understanding of CO formation is very poor despite the availability of many uncoordinated investigations. The amount of expertise required to make meaningful progress and the complexity of the problem requires that a large number of research problems be addressed and that investigators have a wide range of capabilities. This is reflected in the range of research components included in Table 1.

One of the most difficult aspects of the proposed research effort will be the coordination and direction of the various components. A great deal of effort will be required on the part of the project manager to stay apprised of progress on the various efforts. The importance of project management is emphasized by including it as one the components in the research plan (Component 18, Table 1).

The research plan which has been formulated builds on existing research efforts within CFR. By utilizing these existing research components (with some redirection) along with selected new research efforts, it has been possible to formulate a research plan which brings significant resources to bear on the problem of CO prediction without requiring unreasonable levels of new funding. It seems likely that significant progress will be made if this research plan is implemented.

6. REFERENCES

[1] Harland, W. A.; Anderson, R. A. Causes of death in fires. Proceedings, Smoke and Toxic Gases from Burning Plastics; 15/1-15/19; Jan. 6-7, 1982; London, England.

[2] Harwood, B.; Hall, J. R. What kills in fires: smoke inhalation or burns? Fire J. 83: 29-34; 1989 May/June.

[3] Pitts, W. M.; Long-range plan for a research project on carbon monoxide production and prediction, to appear as a National Institute of Standards and Technology Internal Report, 1989.

[4] Pitts, W. M.; Executive summary for the workshop on developing a predictive capability for CO formation in fires. National Institute of Standards and Technology NISTIR 89-4094; 1989 May. 68 p.

[5] Wilson, W. J. Large scale fire tests. J. Fire Flam. 7: 112-124; 1976.

[6] Levine, R. S.; Nelson, H. E. Full-scale simulation of Sharon, PA fatal fire: data and analysis. To appear as a National Institute of Standards and Technology Internal Report.

[7] Rasbash, D. J.; Stark, G. W. V. The generation of carbon monoxide by fires in compartments. Fire Research Station F.R. Note No. 614; 1966 Feb. 38 p.

[8] Mulholland, G. W. Position paper regarding CO yield. Letter report to Richard G. Gann, Chief, Fire Measurement and Research Division, Center for Fire Research; 1988, June 16; 8 p.

[9] Beyler, C. L. Major species production by diffusion flames in a two-layer compartment fire environment. Fire Safety J. 10: 47-56; 1986.

[10] Zukoski, E. E.; Toner, S. J.; Morehart, J. H.; Kubota, T. Combustion processes in two-layered configurations. Fire Safety Science. Proceedings of the Second International Symposium. New York, NY: Hemisphere; 1989. 295-304.

[11] Morehart, J. H.; Zukoski, E. E. Chemical species produced by natural gas fires near the extinction limit. Part of Final Report for National Institute of Standards and Technology Grant No. 60NANB600638; 1988 October.

TABLE 1

#	RESEARCH COMPONENT	FUNDAMENTAL OR ENGINEERING	GOALS AND/OR PURPOSE	EXISTING RESEARCH OR NEW START	DURATION AND PROJECT TIMING
1	Study of underventilated laminar flames	Fundamental	To characterize the structure of underventilated laminar flames and to correlate chemical species in terms of the local equivalence ratio	New start	Years 1-4
2	Laboratory studies of turbulent underventilated flames	Engineering	To characterize structures of underventilated turbulent fires and to test the validity of the global equivalence ratio concept for correlating major gas species in upper layers	Existing	Years 1-3 Years 1-4
3	Development of experimental flame diagnostics	Both	To develop and test techniques for accurate flame gas (particularly CO) measurements within sooting flames	New start	Years 1-2
4	Develop and test global equivalence ratio concept for predicting CO in fires	Engineering	To develop the global equivalence ratio concept to allow prediction of CO in actual fires and incorporation into CFR fire models	New start	Years 1-5
5	Prediction of CO for simple configuration of burning in enclosure	Both	To develop fundamental modeling capability for fires in enclosures	New start	Years 3-5
6	Experimental and theoretical investigations of turbulent combustion	Fundamental	To develop an understanding of turbulent combustion sufficient to allow calculation of chemical source terms for simple flow configurations	Existing	Years 1-5
7	Vitiated burning in cone calorimeter	Fundamental	To investigate the effects of air vitiation on levels of CO produced in laminar burning	Existing	Years 1-2
8	Vitiated burning of buoyancy-driven turbulent flames	Both	To investigate the effects of air vitiation on turbulent flames, to test the global equivalence ratio concept for this type of burning	Existing	Years 1-2
9	Kinetic calculations for the investigation of upper-layer stability	Fundamental	To investigate the chemical stability of upper layers for appropriate ranges of gas concentrations and temperatures	New start	Years 1-3

#	RESEARCH COMPONENT	FUNDAMENTAL OR ENGINEERING	GOALS AND/OR PURPOSE	EXISTING RESEARCH OR NEW START	DURATION AND PROJECT TIMING
10	Experimental Investigation of the effects of heterogeneous chemiatry on CO concentrations	Both	To characterize the effecta of heterogeneous chemistry on soot particles on the stability of gas compositions in a heated upper layer	New start	Years 1-3
11	Burning behavior of upper-layer gaaes outside of small-scale enclosure	Engineering	To characterize conditions where burning of upper-layer gasea occurs outside of enclosure fires and the effectiveness of such burning in removing CO	Existing	Years 2-4
12	Burning behavior of upper-layer gasea outaide of full-scale encloaure	Engineering	To characterize conditions where burning of upper-layer gases occura outside of enclosure firea and the effectiveneas of auch burning in removing CO	New start	Years 3-4
13	Turbulence modeling of CO formation in enclosure firea	Both	Evaluate effectiveness of the laminar flamelet concept with k- turbulence modeling for predicting CO in enclosure fires	New start	Years 2-4
14	Development of data base for CO formation in full-scale fire teats	Engineering	To include appropriate reporting of CO meaaurements in large-scale fire teat data base and access levels of CO which are observed	Existing	Yeara 1-2
15	Large-scale fire teats	Engineering	Perform accurate measurements of CO and other flame gaaes both within the enclosure and downstream for full-scale fires	Both	Years 1-5
16	Scaling studiea	Engineering	Test effectiveness of scaling from small to full-scale tests, focus on the global equivalence ratio concept and correlations for burning of upper layer gases on exiting enclosure	New start	Years 3-5
17	Incorporation of CO formation in fire models	Engineering	Incorporate findings of CO priority project into CFR fire modela	New start	Years 3-5
18	Project management	-	Effective project coordination	Existing	Years 1-5

EXPECTED FIRE RESISTING PERFORMANCE AND EVALUATION METHODS FOR BUILDING MATERIALS

Hiroaki Suzuki
and
Tatsuhiro Goto
Building Research Institute
Ministry of Construction
Tatehara, Tsukuba-shi
Ibaraki-ken, 305
JAPAN

ABSTRUCTS

The living way has become more and more universal over the world. Modernized buildings and houses have been built in the similar ways according to the purpose of use of them except some traditional fanctions. Many efforts on establishment of international testing and evaluation methods have been made, but not so many of international standards have actually been established. What grade of fire performance is expected to building materials ? What are essential problems for establishing common standard testing and evaluation methods ? Discussion on probability of cooperative work on assessment of common standards will be made for a future work.

INTRODUCTION

Different culture has introduced different test methods for evaluation of building materials in fire. There exist so many test methods which classify materials in some fire rated grades in each country. However buildings and houses have been changing due to the improvement of living conditions. This causes a trend of uniform way of life through the world. The difference of test methods among countries have caused barriers for trades in these decades.

On the other hand, many test methods have been tried to develop and studied at the ISO/TC 92 in these decades. A few of them have already been adopted as International Standards. Most of them, however,seem to have been piled up as technical reports in the members countries. This may basically lack of consensus among administrative officers and researchers. An analytical study of estimating fire risk have been made.[1] It is expected to continue. Further study for development of new common test methods, therefore, will be expected to propose for classifying building materials and predicting fire growth with survey of social requirements.

PRACTICAL EVALUATION AND CHEMICAL/PHYSICAL PROPERTIMES

Many countries have their own requirement for fire performance of building materials in their fire codes.[2][3] The idea in each country involves the same purpose based on the following items;

1. Not to catch fire easily
2. Not to spread fire easily
3. Not to release heat and toxic gases

The purpose for fire safety is clear and simple, but complicated in practice. The Japanese requirements for fire rated building materials are provided in the Details of Regulations of the Building Standard Law as "Restriction of Use of Interior Building Materials if they are used in "Specially Regulated Buildings in the Details of Regulation". Materials which may belong to furniture like curtains, carpets and thin matèrials for decoration etc., are not included in building materials. These are provided in the Fire Service Law in Japan.

Classification, for instance, in Japan is as follows:

① Non-combustible
② Semi-non-combustible
③ Fire retardant
④ Semi-fire retardant (for plastics)

by results of five test methods which are Non-combustible test, Surface test, Surface test with 3 holes through specimens, Box test and Toxicity test depending on the grades. These test methods are convenient for empirical classification, but may not give suitable data for prediction of fire growth for engineering treatment.
For fire safety in modernized buildings, a systematic evaluation methods which is based on engineering calculation is being introduced. But some kinds of current methods for evaluation of fire performance of building materials may still be required as specified test methods, because they are empirically easy to understand. Some materials, PVC sheet for instance, as shown in fig.1, give a small difference in ignitability with Polyethyren, but the former is commonly estimated as a material which is higher fire resisting than the latter. Ignitability does not always correspond to the propagation of flame. Some materials which are classified in a higher grade of fire rated materials by fire tests may be expected to be safer against fire. But, polycarbonate, for instance, which is classified into semi-fire-retardant may catch fire in some time and may release more heat from a unit weight than that of PMMA which is classified as "Combustible".

Further, non-combustibe and semi-non-combustible materials do not always stop fires as everybody knows. There is a tragic fire incident which caused 24 fatalites at an aged nursing home outskirt of Tokyo in 1987.[4)] The building didn't break the fire regulations from the point of literature document. But the fire broke windows of non-wired glass which was estimated as parts of walls to be made of non-combustibles and got inside of rooms. The fire spread a room to another in succession. This is a bad example warning designers and building inspectors. That is "Catch not at the shadow and lose the substance". There may be so many examples like this. A big fire sometimes plays a trigger of revision of the current codes. But once it become regulation, then it may be difficult to remove in a rather short period, eventhough it does not meet practical way of life. A revision of a code may widely and seriously effect to the society.

ALTERENATING APRLICATION OF SPECIFIED CLASSIFICATION AND ENGINEERING METHODS

Many efforts have also been made for analyses of test data from the point of chemical and physical properties, but some materials, composit materials combined with plastics, may be difficult to be suitablly classified in current test methods(Table 2). Some materials, may not easily conduct a simplified test method. Because some of them which become swell, shrunk, melted etc, at elevated temperatures give different data between at real fire and at fires tests.
Rigid polyurethane and/or polystyrene with aluminium foil over the surface may have a

sort of fire rated grade, eventhough the latter is melt inside, but they are only fire resisting for a short period at an early stage of a fire. This kind of materials also have some trouble at tunnel test.

The difference of thickness of a material may give different fire resisting performance in practice, even though the composition is same.
More problems are implied in thiner materials like wallpaper which is widely used in the world. A simplified test method does not cover all materials to be suitablly classified in practical application. Some test results from heat release and surface test may give a contrary data which is shown in table 3.

Wallpaper do not show a rapid flame spread at a test, but if a room is involved in a fire, then wallpaper sometimes show a sudden combustion which leads flashover. This due to the chemical composition of wallpaper itself, lining materials and the glue in use. Contribution of furniture to fire must not be neglected, but restriction of more furniture to put in buildings may be difficult. Building materials will only be responsible in building fire.

Building materials may be too complicated to classify into some expected performance, but for a smoother trade and for a wider use of materials, essential discussion for development of common testing and evaluation methods may be needed. More and more materials which will be developed will change fire patterns for ever, but we must charange to improve testing and evaluation methods studying the following items.
- Survey of present problems for testing and evaluation methods.
- Survey and analyses of spreading fire in actual incidents.
- Essential study in practical use of materials.
- Development of test methods.
- Development of calculation methods.
- Social consensus to up-to-date target.

Reference

1) J. R. Hall: A Method for Estimating Fire Risk of Products in Buildings, 10th UJNR Panel on Fire Research and Safety, Tsukuba, 1988

2) R E H Read: International fire tests on structures, BRE information, IP 20/80, October 1980

3) R E H Read: International fire tests on building materials, BRE information, IP 21/80 October 1980

4) Tokyo Fire Department : Report of Shojuen Fire — An Asylum for the Aged, Japanese Association of Fire Science and Engineering, Vol.37 No.5 P 1 1987

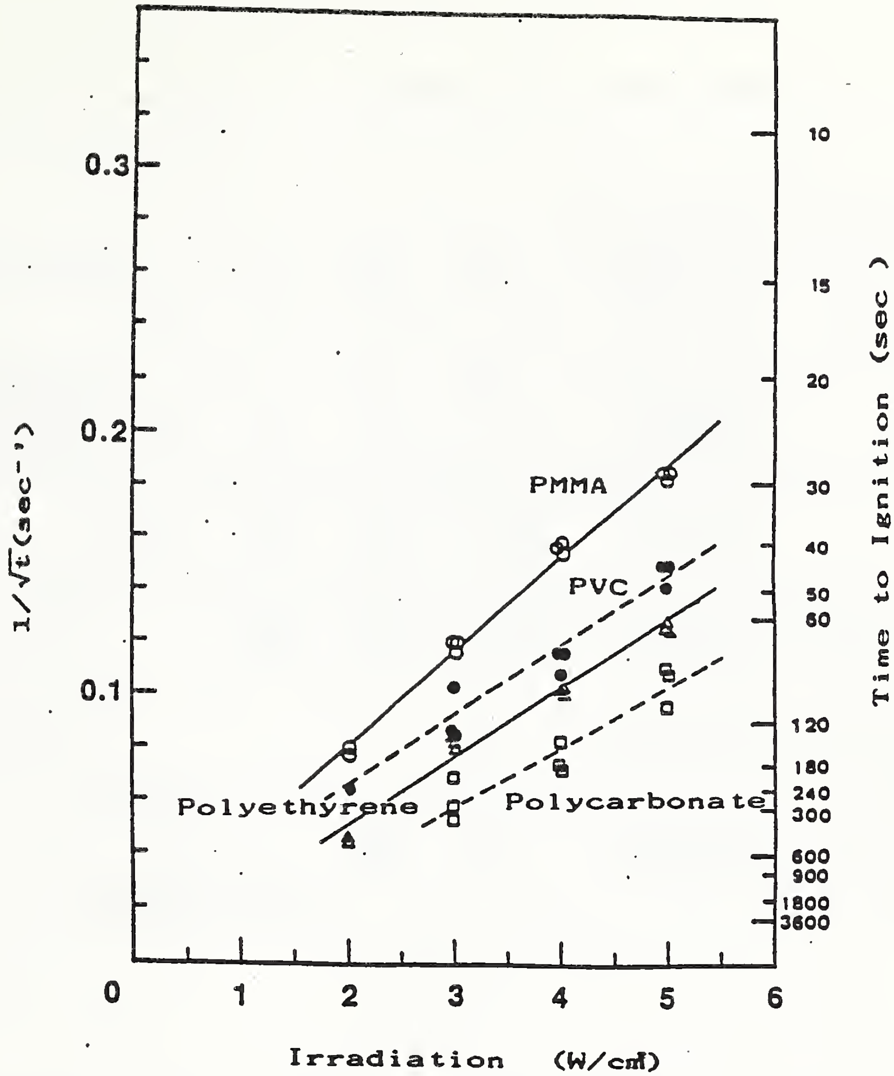


Fig.1 Relationship between Irradiation and Time to Ignition

Table 1 Typical Pattern of Burning Behavior at Real Fire and at Tests

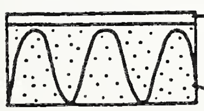
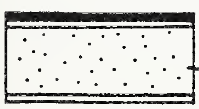
Composition Materials	Characteristics in real Fire	Phenomena at surface test and box test
	Maltilayers by painting over painting in use burn and spread fire fast, but not large fire load	Fresh specimen do not release large amount of heat and smoke because of their thin layers at surface test, but sharp peeks of them arise at box test becouse of flashover
	Does not release severe heat at initial stage of fire but has potential of releasing more heat at elevated temperatures.	Heat and smoke are surpressed by the surface materials at tests.
	Combustion behavior changes due to the way of spreading glue for adhesson.	Flash over occurs at box test
	To burn forming char due to incident energy. To reach flashover, if there are other fire load.	To burn giving proper amount of heat and smoke due to the mass and treated chemicals

Table 2 ISO Round Robin Test Result on Spread of Flame At BRI

No	Materials(Thickness)	Phenomena \ No.	1	2	3	4	Remarks
1	Birch-faced plywood (9 mm)	Ignition(sec) Extinction(sec) Distance(mm)	29" 13'40" 610	29" continued 765	27" 14'00" 765	30" 21'42" 710	Burnt steadily
2	FR plywood (4 mm)	Ignition(sec) Extinction(sec) Distance(mm)	23" 4'32" 420	18" 4'47" 450	24" 2'20" 420	32" 21'42" 710	Front flames of 2 ~ 3cm width were succeeded by the secondary flame 10~15cm apart
3	PMMA (3 mm)	Ignition(sec) Extinction(sec) Distance(mm)	20" continued 765	21" continued 765	26" continued 765	18" continued 765	Steadily burnt
4	Polystyrene cemented to non-combustible board (38 + 6mm)	Ignition(sec) Extinction(sec) Distance(mm)	2'43" 8'41" 430	2'51" 8'28" 410	3'22" 8'56" 450		Melted suddenly, then flame spread gradually
5	Isocyanurate foam faced with Aluminium foil (28 mm)	Ignition(sec) Extinction(sec) Distance(mm)	53" – 0	10" – 0	26" – 0	3" – 0 Impinging	Flame didn't spread, but existed at the pilot burner
6	PVC faced plasterboard (10 mm)	Ignition(sec) Extinction(sec) Distance(mm)	18" 1'26" 270	1'06" 2'20" 350	Non flaming 350 (Smoldering)	Non flaming 400 (Smoldering)	Flame spread by smoldering

Table 3. Material properties and classified grade

		Heat Released cal/g	O.I.	Saface Test
1	Acrylic Resin	6,265	18.8	Combustible
2	Polyethyrene	10,965	19.3	Combustible
3	PVC	4,315	26.5	Semi-fire-retardant
4	Polycarbonate	7,294	32	Semi-fire-retardant

Replacement for the Halogenated Fire Suppressants:
A Research Strategy and Plan

RICHARD G. GANN
Center for Fire Research
National Institute of Standards and Technology
Gaithersburg, MD 20899

ABSTRACT

A consortium of industrial firms and Federal agencies has developed a plan to identify candidate fire suppressants to replace halons 1211 and 1301. The strategy is to conduct a program of closely-coordinated research, empirical testing, and analysis. The paper contains an outline of the 27-element plan.

I. BACKGROUND

Because of their role in depleting stratospheric ozone, production of the current halogenated fire suppressants will likely be greatly reduced or phased out by the turn of the century. A consortium of concerned industrial firms has formed with Federal agencies to support a program to identify candidate replacement chemicals for halons 1201 and 1301.

The search for new fire suppressant chemicals is not likely to be brief or easy. Successful candidates must perform appropriately in tests for a wide variety of properties:

- fire suppression efficiency,
- ozone depletion potential,
- greenhouse warming potential,
- suppressant residue level,
- electrical conductivity,
- metals corrosion,
- materials compatibility,
- stability under long-term storage, and
- toxicity (inhalation and contact) of the chemical and its combustion products.

In addition, there is a practical benefit to identifying chemicals that are "drop-in" replacements for the current suppressants. This requires similar state and fluid mechanical properties. Satisfying this combination of demands will be distinctly more difficult than identifying, for instance, a new refrigerant, de-greaser, or aerosol propellant.

This program will identify acceptable candidate chemicals. To the extent that we only find choices of partially-desirable chemicals, the trade-offs will be clearly presented so that policy officials may make informed decisions. All information on chemicals and their test results will be in the public domain.

II. RESEARCH STRATEGY

Our strategy is to conduct a program of closely-coordinated research, empirical testing, and analysis.

The principal output of the first four years of the program will be appropriate test methods and criteria, compilation of information, and knowledge for designing or selecting potential replacement chemicals.

A key intermediate accomplishment that will facilitate the development of alternative suppressants is a reliable predictive model for the effectiveness of fire suppression at full-scale. This will be supported by accurate input data and tested on the current halons. The predictive capability will then be tested on other candidate chemicals.

This concept is assumed necessary because: (a) a number of the more obvious chemicals have already been tested and found wanting, and (b) the environmental demands on the agents will likely change during the course of the program.

By the end of the seventh year, the possible alternative chemicals will be few and of high quality. At the end of the eleventh year, the success of a small number of chemicals will have been fully documented.

III. RESEARCH PLAN

This plan is meant to be a "living" document. Breakthroughs will allow us to find more direct channels toward the conclusion; complications will necessitate further analysis and research.

The research plan begins with:

- A selection of trial chemicals and quick, relatively inexpensive performance screening tests to be run on them;
- A survey to identify the fire types for which halons are currently deployed and the requirements of a "drop-in" replacement agent;
- Research to identify the chemical, physical, and fluid mechanical properties of chemicals that would be most effective, economical, and safe; and
- Establishment of a systematic database to aid analysis of all pertinent information in support of the above.

These efforts will lead to the establishment of a reliable predictive capability for the effectiveness of fire suppression at full-scale and experience with the behavior of various types of chemicals under tests for the other needed properties. These results will, in turn, guide improvement in both the successive selection of compounds and the tests for obtaining performance data. As the selected chemicals become better and fewer, the scale of testing increases, culminating in full-scale toxicity and fire suppression tests. A schematic of this approach is shown in Figure 1.

The plan consists of 27 elements. Figure 2 shows how these elements fit together and provide the basis for their successors. Figure 3 depicts the time line for these elements. The following is a brief description of each of the program elements.

1. Preliminary Screening Procedures and Criteria

   Determine the most appropriate, currently available screening methods for fire suppression efficiency, residue level and electrical conductivity, ozone depletion potential, greenhouse warming potential, metals corrosion, materials compatibility, stability under long-term storage, and toxicity (inhalation and contact); determine reasonable first approximations for ratings of acceptable performance for each screen.

2. Exploratory Candidate Set (Set A)

   (a) Identify and (b) screen ≈100 gases or liquids, covering a range of chemical and physical principles thought to affect flame suppression capability.

3. Analysis of Set A Data

Identify potential winners, if any; extract guidelines for selection of further candidates and for elimination of classes of compounds.

4. Candidate Agent Database

Create and maintain an accessible tabulation of all chemicals that have been or are being considered as fire suppressants; database to include physical and chemical properties and performance data from tests for parameters in element 1; all data to be referenced.

5. Fire Type Survey

Determine the generic types of fires for which current halon systems are designed.

6. Ozone Depletion Potential Analysis

Assess the capability of method(s) for determining ODP of current and potential alternatives to the current halons; determine best quick screen method and technical criterion for ODP.

7. Greenhouse Warming Potential Analysis

Assess the capability of method(s) for determining GWP of current and potential alternatives to the current halons; determine best quick screen method and technical criterion for GWP.

8. Rigorous Fire Suppression Screening Protocol

Develop a screening protocol for fire suppression effectiveness on liquid and solid fuels of gaseous and liquid agents that replicates larger scale results, but requires only a small quantity of agent.

9. Fire Suppression Modeling Assessment

Determine best computational approaches for "experiments" to optimize fire suppressant selection.

10. Upgrade of Preliminary Screening Methods

Review and upgrade, as needed, the previous screening protocols for assessing residue level, metals corrosion, materials compatibility, stability under long-term storage, electrical conductivity, and especially toxicity (inhalation and contact) of chemicals and combustion products; must use small quantities of chemical.

11. Chemical Kinetics of Suppression

Determine the chemical pathways and reaction rate data for flame extinction by potential halon replacements.

12. Thermal Effects of Suppressants

Determine the contribution of the heat capacity and thermal decomposition of molecules to suppression.

13. Agent Transport Physics

Develop numerical methods for calculating an agent's delivery characteristics as a function of its physical properties.

14. Thermodynamic and Transport Properties

Determine the data needed for the model in element 13.

15. Thermal Stability and Decomposition

Assess stability of replacement chemicals under long-term storage.

16. Modeling of Suppressants in Turbulent Fires

Develop computations of the injection into and distribution of extinguishing agents in a fire bed and adjacent fire plume.

17. Agent Entrainment in Turbulent Combustion

Determine experimentally the role of density and chemical heat release variations in flame suppression agents on their entrainment behavior in a turbulent fire plume and the effectiveness with which the agent is mixed molecularly with the plume gases.

18. Select and Procure Candidate Set B

Identify a set of ≈100 potentially successful candidate suppressants and obtain the quantities needed for screen testing as refined in elements 6-10.

19. Test Candidate Set B

Obtain performance data for Candidate Set B chemicals.

20. Analyze Data from Set B

Determine additional compounds for screen testing.

21. Test and Analyze Set C

Determine the performance of compounds in Candidate Set C.

22. Select Candidate Set D

Identify reduced list of compounds for further testing.

23. Medium Scale Test Protocols

Design more realistic, larger-scale, and potentially more costly fire suppression methods for testing.

24. Test Candidate Set D

More realistic data on Candidate Set D compounds.

25. Full-Scale Suppression Tests

Develop and perform realistic fire-suppression tests.

26. Full Toxicity Testing

Perform toxicity tests needed for acceptance of new agents.

27. Prepare Final Report

Effects of Polymer Characteristics on Flammability Properties

by

Takashi Kashiwagi and Atsumi Omori[1]

Center for Fire Research

National Institute of Standards and Technology, Gaithersburg, MD 20899

ABSTRACT

The effects of material characteristics on piloted ignition, horizontal flame spreading, and heat release rate were studied by using two different polystyrene, PS, samples and two different poly(methyl methacrylate), PMMA, samples. The difference between the two PS samples was melt viscosity due to two different initial molecular weights and that between the two PMMA samples was thermal stability and melt viscosity also due to two different initial molecular weights. The results indicate that thermal stability of the material has significant effects on piloted ignition delay time, flame spread rate and heat release rate. The effects of melt viscosity, the transport of indepth degradation products through the molten polymer layer inside the sample, are negligible on piloted ignition. However, they are significant on horizontal flame spreading behavior and reduce its rate by forming opposed slow fluid motion of molten polymer along the inclined vaporizing surface against the traveling flame front.

Introduction

There have been numerous studies to determine the effects of polymer characteristics on flammability properties. Most of these studies were based on the comparison of flammability properties of many different polymer samples. Since there were always many differences in thermal properties, degradation characteristics, and gas phase oxidation chemistry due to differences in degradation products among polymer samples, these studies could not clearly explain why the flammability properties of polymer A were different from those of polymer B. In order to avoid this uncertainty, the effect of one or two differences in material characteristics on flammability properties were studied.

Initial molecular weight, MW, and thermal stability of the sample were selected as the two material characteristics. Since melt viscosity of molten polymer depends strongly on its molecular weight, varying initial molecular weight shows which flammability properties are affected by the melting characteristics of the sample without significantly modifying other material characteristics. Two types of polymers, poly(methyl methacrylate) (PMMA) and polystyrene (PS), were selected because the thermal degradation of PMMA is controlled mainly via the depropagation reaction[**1**,**2**], and the thermal degradation of PS is controlled mainly via the intermolecular- and intramolecular-transfer reaction[**3**,**4**]. Thus, it is expected that the thermal stability of PMMA is sensitive to initial molecular weight due to a change in the number of weak linkages in the polymer chains[**1**,**2**], but the thermal

---

[1] Guest scientist from National Research Institute for Pollution and Resources, Tsukuba, Japan.

stability of PS is not sensitive to initial molecular weight. The difference in flammability properties between two PS samples with two different initial molecular weights should indicate only the effects of initial molecular weight (and thus melt viscosity) of the sample. The difference in flammability properties between two PMMA samples with two different initial molecular weights should indicate the combined effects of initial molecular weight and thermal stability of the sample.

A detailed discussion of each flammability measurement and the results were published elsewhere, for example, piloted ignition is presented in Ref. 6, flame spreading in Ref. 7, and non-flaming gasification in Ref.9. The objective of this paper is to combine these results to understand the effects of material characteristics on flammability properties.

EXPERIMENTAL

The two PMMA samples were ELVACITE 2009 (MW 47,000, low MW PMMA) and 2041 (MW 200,000, high MW PMMA) (E.I. Dupont de Nemours & Co.) and the two PS samples were STYRON 6065 (MW 64,000, low MW PS) and 6069 (MW 120,000, high MW PS) (Dow Chemical Co.). Since thermal properties of linear polymers do not change significantly with a change in molecular weight, as long as the number of monomer units in the polymer chain exceeds approximately one hundred, differences in thermal properties such as thermal conductivity and specific heat between the two PMMA samples and between the two PS samples are negligible. Furthermore, the initial molecular structures are almost the same between the two PMMA samples and the two PS samples. The difference is about 1 unit per 1000 units. During degradation this might become 1 unit per 100 units, but still effects on thermal properties and infrared absorption characteristics are negligible. However, this is not true for polymers which cross-link during degradation.

The sample specimens were cast to make a plate about 10 cm wide x 36 cm long x 1.3 cm thick for the flame spreading study, about 7.5 cm x 7.5 cm x 1.3 cm thick for the piloted ignition study, and about 10 cm x 10 cm x 1.3 cm thick for the burning experiment. The sample was mounted horizontally in this study; a more detailed description can be found in Ref.5 for flame spreading and in Ref.6 for piloted ignition. Heat release rate was measured by the Cone Calorimeter[**7**], which measures the consumption rate of oxygen during burning of the sample[**8**]. Although some of the non-flaming radiative gasification rate data[**9**] will be used for comparison of surface temperature, detailed results are not discussed in this paper.

RESULTS AND DISCUSSION

Thermal Stability: Derivative thermogravimetry(DTG), i.e., normalized weight loss rate of the four samples was measured at a heating rate of 5 °C/min. Results for the PS samples are shown in Fig.1 and those for the PMMA samples are shown in Fig.2. Since thermal oxidative degradation and thermal degradation might occur near the sample surface[**10**], degradation characteristics were determined both in nitrogen and in air. The important result obtained from these figures is that there are no significant differences in thermal stability between the two PS samples, as we expected.

For the two PMMA samples, there are three peaks for the high MW sample degrading in nitrogen. Since this sample was polymerized by a free radical method, it is expected that the first peak at around 170 °C is caused by scission at the weak linkage of the head-to-head structure[2,11], the second peak at around 280 °C is due to radical initiation at the unsaturated chain ends[1,2,11], and the third peak at around 370 °C is due to random scission at the main chain linkages. Higher stability for low MW PMMA sample (only one high temperature peak) indicates that the low MW sample was polymerized with a chain transfer agent to avoid the formation of the weak linkages in the polymer chains during its polymerization process[2]. Results of the samples degrading in air show an increase in thermal stability at the low temperature range (the disappearance of the first peak for the high MW sample) and significant reduction in thermal stability at the high temperature range. This is consistent with our previous study of oxygen effects on PMMA degradation[2].

Piloted Ignition: The relationship between ignition time and incident external radiant flux is a straight line in the logarithmic plot shown in Fig.3 for the four samples. The results show that ignition delay times of low MW PMMA samples are much longer than those of high MW PMMA samples. However, there are no significant differences between the two PS samples. Ignoring heat losses and assuming the sample to be inert and thermally thick (inert model), the slope of the above relationship is approximated to be -2.0[6]. However, the slopes shown in Fig. 3 are -2.8 for the high MW PMMA, -3.2 for the low MW PMMA, and -2.9 for the PS samples. There are many reasons in which the simple inert model cannot be applied to this study such as that the sample used in this study is not thermally thick, and there are additional complexities of indepth absorption of the incident radiation by the sample, of re-radiation loss from the sample, small sample weight loss by endothermic degradation prior to ignition, and changes in surface reflectance and absorption characteristics with radiant flux due to a change in source temperature. Measured surface temperatures at ignition for low MW PMMA samples gradually increase with external radiant flux from about 320°C to 340°C and those for high MW PMMA samples were nearly constant at about 260-270°C[6] as shown in Fig.4. They were nearly constant at about 350-370°C for both low and high MW PS samples in the range of external radiant flux used in this study. By referring to Figs. 1 and 2, these ignition surface temperatures indicate that thermal oxidative degradation might significantly contribute to the generation of combustible gases during the ignition process of these samples. These results indicate clearly that the thermal stability of the material strongly controls the piloted ignition process and thus surface temperature at ignition of the low MW PMMA samples are much higher than those of the high MW PMMA samples.

Flame Spreading: The relationship between the location of the flame front and time for the two PMMA samples in Fig.5 and for the two PS sample in Fig.6 shows significant differences in flame spread rate. The average flame spread rate was 2.3×10^{-3} cm/s for the low MW PMMA and 8.5×10^{-3} cm/s for the high MW sample. Similarly, it was 6.7×10^{-3} cm/s for the low MW PS sample and 8.5×10^{-3} cm/s for the high MW PS sample.

Flame spread behavior over the surface of the low MW samples was quite transient and different from the high MW samples. The sample with high MW did not form molten polymer near the flame front so the flame spread steadily. However, flame spread over the low MW PMMA sample was quite complex, similar to flame spread over the low MW PS sample. A schematic illustration of flame spread behavior over the two PMMA samples is described in Fig.7. Flame spread very slowly after reaching about 8 cm location. The energy feedback from the flame to the surface ahead of the vaporization front appeared to be insufficient to degrade the thermally stable low MW sample ahead of the vaporization front. Therefore, the regression rate normal to the surface was larger than the flame spread rate, and the wall described in Fig.7b was formed. Once the wall was formed, the blue flame front was absent and the flame almost stopped spreading. When a small particle was put on the top of the wall, a slow downward movement of the particle toward the bottom of the wall was observed, which indicates the existence of a slow fluid motion of the molten polymer against flame spread direction. When the flame front reached approximately the 10 cm location, burnout of the downstream part of the sample occurred and the center of the flame moved forward due to narrowing of the width of the flame by the burnout. Under this condition, air was entrained mainly from the downstream side of the flame instead of from both sides (upstream and downstream) of the flame. It appeared that the wall acted as an obstacle to air entrainment from the upstream side of the small flame. This caused the flame to lean forward and to move back and forth as described in Fig.7c. Although there was no visible blue flame front, energy feedback from the flame to the wall was temporally enhanced when the flame leaned forward. The wall was rapidly smoothed by the enhanced degradation due to temporally enhanced energy feedback and the flame climbed partially over the step. The flame continued to spread in this mode. The flame spread rate appeared to be sensitive to the aerodynamics of the air entrainment, which was also sensitive to the shape of the burning surface contour. Therefore, there was some scatter in the flame spread rate over the low MW PMMA sample. This effect of fluid motion of the molten polymer (low MW sample) on vertical downward and upward flame spreading is more severe than for horizontal flame spreading. The large difference in flame spread rate between the two PMMA samples indicates also that thermal stability of the material significantly affects flame spreading rate.

Heat Release Rate: The changes in heat release rate and also in heat of combustion per unit sample weight loss with time are shown in Fig. 8 for the two PMMA samples and in Fig. 9 for the two PS samples at an external radiant flux of 40 kW/m^2. The results show that the heat release rate of the high MW PMMA sample is as much as 30% larger than that of the low MW PMMA sample. However, the heat of combustion per unit sample weight loss is almost the same for the two PMMA samples. This indicates that gas phase flame processes are almost the same for the two PMMA samples but the gasification rate(burning rate) for the high MW PMMA sample is higher (as high as 30%) than that for the low MW PMMA sample. However, heat release rates and heats of combustion per unit sample weight loss of the two PS samples are practically the same at various external radiant fluxes regardless of the molecular weight differences.

It appears that the mass transfer process for indepth degradation products through the molten polymer layer to the sample surface might not be important for determining burning rate of the PS samples. Further studies are needed to make it more general because the degradation of the PS samples occurs within a relatively narrow temperature range as shown in Fig. 1. The indepth degradation tends to be quite close to the sample surface where sample temperature is high. On the other hand, the high MW PMMA sample degrades over a wide temperature range compared to the low MW PMMA sample, as shown in Fig.2. Therefore, the indepth degradation tends to occur more deeply for the high MW PMMA sample than for the low MW PMMA sample. However, since melt viscosity of the high MW sample is much higher than that for the low MW sample, the transfer rate of the degradation products through the highly viscous layer of the high MW sample would be much lower than that for the low MW sample. These opposing two factors for the high MW PMMA sample, thermally unstable and highly viscous molten polymer, might reduce the difference in heat release rate between the two PMMA samples. At present, it is not clear how much each of these two factors affected the difference in heat release rate of the two PMMA samples as shown in Fig.8.

Surface Temperature: Since the same four types of sample were used for the measurements of various flammability properties, the surface temperatures for piloted ignition, flame spread and non-flaming radiative gasification are compared to determine whether a unique vaporization surface temperature exists for each sample. The surface temperature of the two PS samples during non-flaming radiative gasification is in the range 380-420°C[**9**]. The surface temperature at piloted ignition is in the range 350-370°C[**6**] and the vaporization temperature during horizontal flame spreading is about 470-500°C. Since the exact location of the vaporization front for the flame spreading study could not be precisely determined, the surface temperature is approximately 400°C if the flame front is about 0.1 cm ahead of the vaporization front, as defined in Ref.5 (This possibility is reinforced by the fact that there were sharp breaks in temperature rise around this temperature in Fig.5 of Ref.5.). For the low MW PMMA sample, the piloted ignition surface temperature is about 320-340°C and the vaporization temperature during horizontal flame spreading is roughly 400°C. The vaporization surface temperature during non-flaming radiative gasification is in the range 370-420°C. For the high MW PMMA sample the piloted ignition temperature is about 260-270°C and vaporization during horizontal flame spreading occurs at about 420°C. The vaporization temperature during non-flaming radiative gasification is in the range 360-410°C.

These results indicate that the piloted ignition surface temperature is much lower than the vaporization temperatures occurring in horizontal flame spreading and in non-flaming radiative gasification. With samples having as many different chemical degradation paths as the high MW PMMA sample shown in Fig.2, the piloted ignition temperature tends to be much lower than the vaporization temperatures. It is curious that there is a large difference in surface temperature between piloted ignition and horizontal flame spreading. If flame spreading is considered to be a successive piloted ignition process, the surface temperature for both cases should be the same. The difference could be caused by the difference in heat flux to a sample; the maximum flux is about 7 W/cm^2 for horizontal flame spreading[**12**] and the radiant flux range was 1.0-2.7 W/cm^2 for piloted ignition. The difference in surface temperature between piloted ignition and non-flaming radiative gasification could be due to a large difference in mass flux between the two cases. The mass flux during non-flaming radiative gasification is about 20 times larger than for piloted ignition, which tends to be more influenced by degradation path particulary for a low external radiant flux. There are no significant differences in surface temperature for horizontal flame spreading and non-flaming radiative gasification among the four samples.

Conclusion

1. Thermal stability of polymeric materials has significant effects on piloted ignition delay time, flame spread rate and heat release rate. Surface temperature at piloted ignition is controlled by detailed chemical degradation path of the material and is not necessarily the same as the vaporization temperature at the flame front.
2. The transport process of indepth degradation products of PS and PMMA through the molten polymer layer inside the sample has a negligible effect on piloted ignition. However, the sample with low initial molecular weight forms a molten polymer and the opposed slow fluid motion of molten polymer along the inclined vaporizing surface against the traveling flame significantly affects flame spreading behavior and reduces its rate.

Acknowledgement This study was partially supported by B.F. Goodrich Co..

Reference

1. N. Grassie and H.W. Melville, Proc. Royal Soc. London Ser.A, 14, 199(1949).
2. T. Kashiwagi, A. Inaba, J.E. Brown, K. Hatada, T. Kitayama, and E. Masuda, Macromolecules, 19, 2160(1986).
3. L.A. Wall, S. Straus, J.H. Flynn, D. McIntyre, and R. Simha, J. Phy. Chem., 70, 53(1970).
4. A. Guyot, Polym. Degrad. Stability, 15, 219(1986).
5. T. Kashiwagi, A. Omori, and J.E. Brown, Fire Safety Science-Proceeding of the Second International Symposium, p.107 (1989).
6. T. Kashiwagi and A. Omori, Twenty-Second International Combustion Symposium, The Combustion Institute, 1329 (1988).
7. V. Babrauskas, Fire and Materials, 8, 81(1984).
8. C. Huggett, Fire and Materials, 4, 61(1980).
9. T. Kashiwagi, A. Omori, and H. Nambu, "Effects of Melt Viscosity and Thermal Stability on POlymer Gasification", submitted to Combust. Flame.
10. K.A. Jakes and M.J. Drews, J. Polymer Sci., Polymer Chemist Ed., 19, 1921(1981).
11. D.H. Solomon, J. Macromol. Sci. Chem., A17(2), 337(1982).
12. A. Ito and T. Kashiwagi, Combust. Flame, 71, 189(1988).

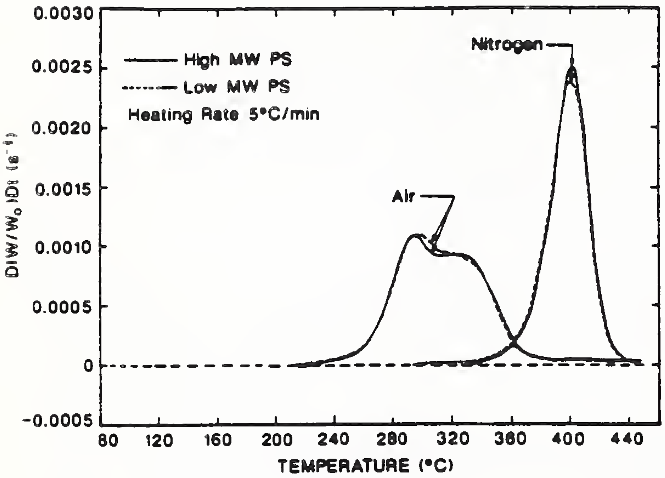


Fig. 1. Comparison of DTG curves of the two types of the PS samples degrading in nitrogen and in air.

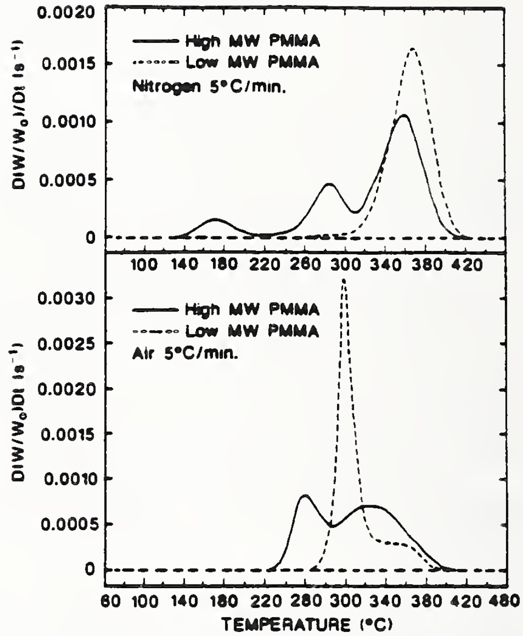


Fig. 2. Comparison of DTG curves of the two types of the PMMA samples degrading in nitrogen and in air.

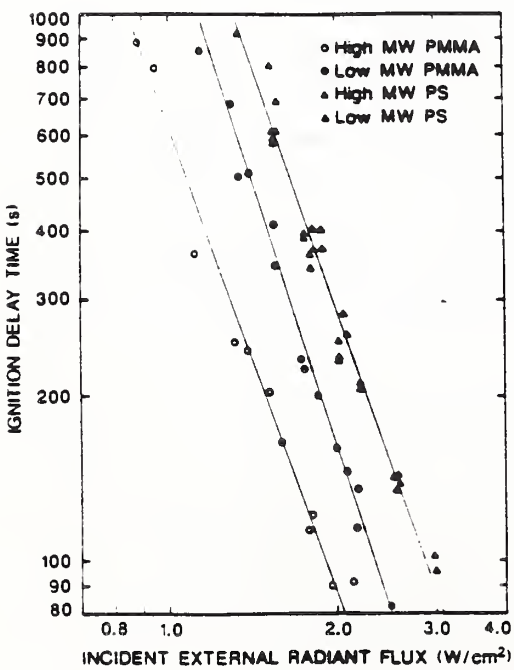


Fig. 3. The relationship between ignition delay time and incident external radiant flux for the four samples.

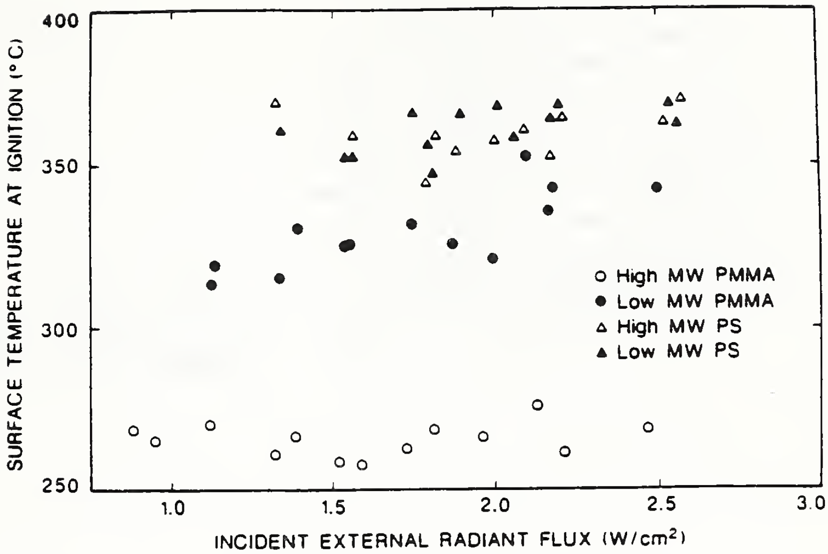


Fig. 4. The relationship between surface temperature at ignition and incident external radiant flux.

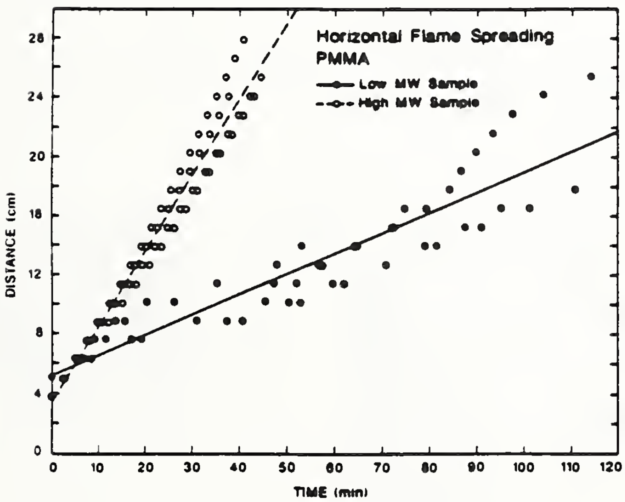


Fig. 5. Plot of flame front position with time for the PMMA samples.

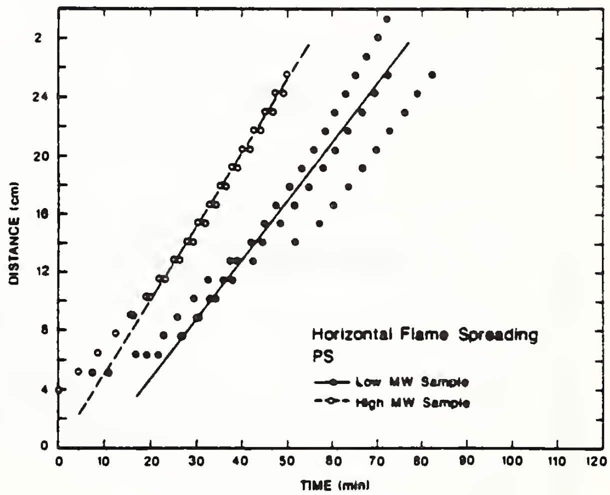
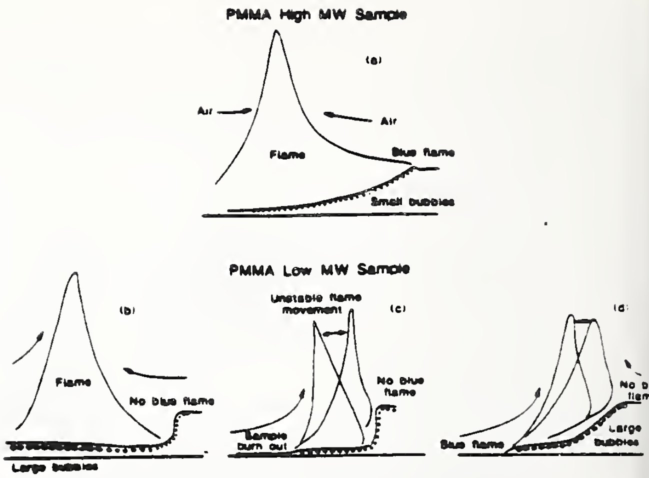


Fig. 6. Plot of flame front position with time for the PS samples.

Fig. 7. A schematic illustration of flame spread behavior over the PMMA samples. (a) over the high MW sample, (b) over the low MW sample with the wall, (c) over the low MW sample with unstable flame movement, and (d) over the low MW sample with air entrained mainly from the downstream side of the flame.



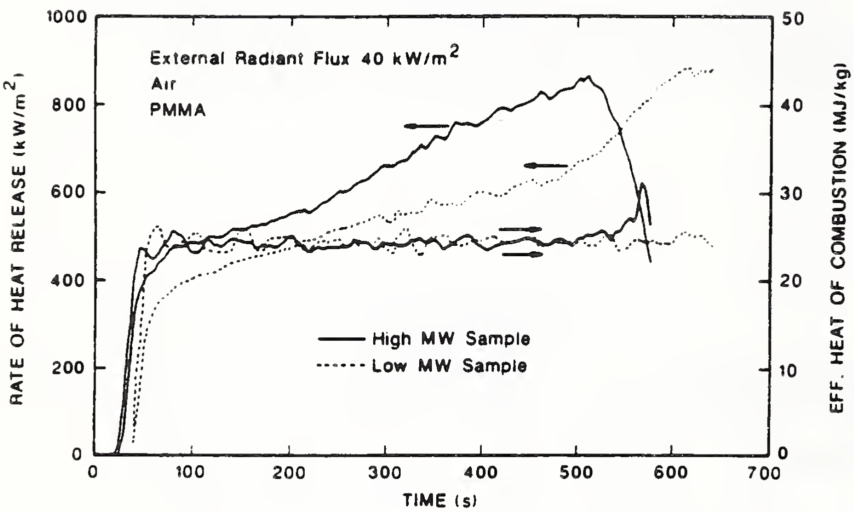


Fig. 8. Comparison of heat release rate and effective heat of combustion between the two PMMA samples at 40 kW/m^2.

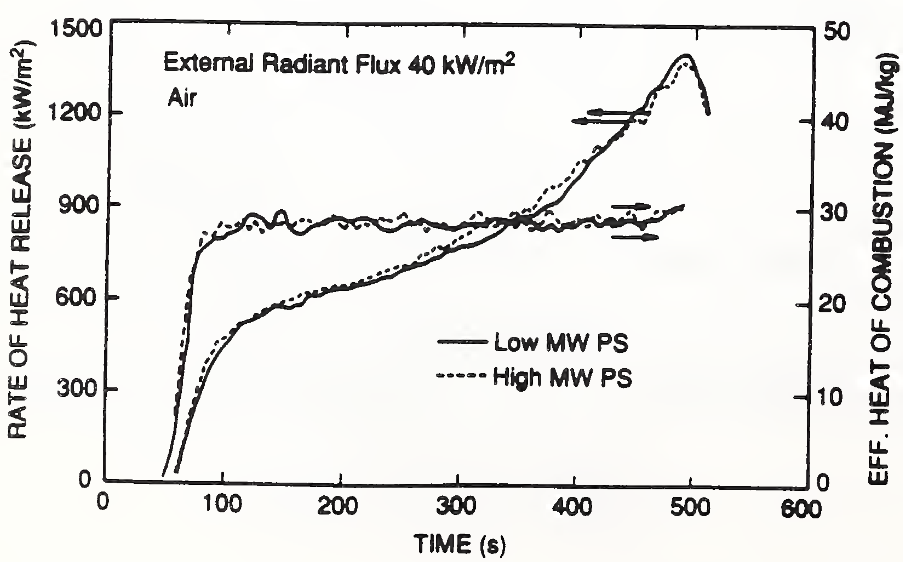


Fig. 9. Comparison of heat release rate and effective heat of combustion between the two PS samples at 40 kW/m^2.

FIRE AND TOXICITY CHEMISTRY SESSION

PROGRESS REPORT ON FIRE TOXICITY AND CHEMISTRY RESEARCH IN THE UNITED STATES

Barbara C. Levin
Center for Fire Research
National Institute of Standards and Technology
Gaithersburg, MD 20899 USA

Deaths, injuries, and losses due to fires continue to be major problems in the United States which still holds the dubious distinction of having the highest death rate per capita in the industrialized world. Interest in the fire problem was indicated by a major week-long symposium entitled "Fire and Polymers" which was sponsored by the American Chemical Society in Dallas, Texas in April, 1989. One day of that symposium was devoted to combustion product toxicity and the rest of the sessions were devoted to the chemistry. The proceedings of that meeting are in the process of being published.

The research efforts in toxicity and chemistry, which at one time were pursued individually, are now starting to meld into a common endeavor. There are a number of issues which continue to drive the direction of this research:

1. The development of a proper small-scale toxicity test apparatus which will qualitatively and quantitatively simulate the combustion atmospheres found in large-scale fire tests and provide data that can be used in the prediction of fire hazard and regulation of materials and products.

2. The implementation of state-of-the-art analytical tools for identification and quantitation of toxic agents in fire atmospheres.

3. The development of a simplified gas model which can be used to predict the toxic potency of complex gas mixtures found in fire atmospheres and to provide data for hazard assessment.

4. The development of a bioanalytical screening test to determine whether the combustion products from materials are extremely toxic or unusually toxic.

5. The development of an incapacitation model that can be used in a hazard assessment analysis to predict the escape potential of people in fires.

6. The characterization of the smoke components from smoldering combustion and increased understanding of smoldering phenomena.

7. The prediction of carbon monoxide generation from various fuels and under various fire conditions.

8. The chemistry of soot formation and destruction in diffusion flames.

There are at least three laboratories [National Institute of Standards and Technology (NIST), Southwest Research Institute (SwRI), and University of Pittsburgh (UPITT)] which are currently working individually and cooperatively on perfecting small-scale toxicity test apparatus. This work is continuing even though the State of New York has passed a regulation that electrical conduit and electrical wire insulation; pipe, duct or thermal insulation; and interior finishes or interior floor finishes need to be tested by the University of Pittsburgh's toxicity test before being used in buildings or factory manufactured homes [1][1]. All of the current test methods consist of three main components - the combustion system, the analytical system and the animal exposure system. The main thrust of this effort is the improvement of the combustion system in order to assure that the combustion products are similar to those found in real fires. Both the National Institute of Building Sciences (NIBS) and NIST have been exploring different toxicity test protocols using a radiant heat combustor designed by Southwest Research Institute [2]. The UPITT is testing a procedure which combines the NIST cone calorimeter and the University of Pittsburgh's animal exposure chamber.

With regard to the implementation of state-of-the-art analytical tools for identification and quantitation of toxic agents in fire atmospheres, NIST is implementing the use of Fourier Transform Infrared Spectroscopy for the continuous on-line measurement of multiple fire gases [3], ion chromatography for the measurement of acid gases such as $HC\ell$, HBr and HCN [4], and chemiluminescence for NO_x [5].

NIST has developed a simplified gas model (the N-Gas Model) to predict the toxic potency of complex gas mixtures found in fire atmospheres [6-9]. This empirical mathematical model predicts the acute lethality of rats during short term exposures and the 24 hour post-exposure period and is currently based on the toxic interactions of 4 gases - CO, CO_2, HCN and reduced O_2. Work at SwRI is progressing towards the inclusion of $HC\ell$ and HBr into this model [10]. In an effort to include NO_2 into the N-Gas model, NIST has just completed a series of tests that demonstrated the synergism of NO_2 and CO_2 [5]. At the end of this year, we hope to have a seven gas model which predicts both within and post-exposure deaths. The current approach has been incorporated into a computer hazard assessment methodology entitled HAZARD I [11].

HAZARD I, which was developed by NIST, is now available to the public [11]. This computer-based methodology allows one to define a specific fire scenario, calculate the development of hazardous conditions over time, determine the escape time needed by building occupants and estimate the resulting loss of life based on predicted occupant behavior and toxic gas and heat tenability criteria.

A bioanalytical screening test has been developed at NIST to determine whether the combustion products from materials are extremely toxic (i.e., low concentrations produce toxic effect) or unusually toxic (i.e., the toxicity of the combined major fire gases is not sufficient to account for the observed toxicity) [12]. This test is based on the N-Gas Model and is designed to minimize the use of animals.

Modeling of incapacitation from fire smoke continues to be a difficult problem primarily because the degree of incapacitation can range from incorrect decision making to inability to physically move. Many people have tried to deal with this problem in the past. Most recently, the University of

---

[1]Numbers in brackets refer to references listed at the end of this paper.

Pittsburgh has published both a running mouse and guinea pig model [13,14]. The Navy is also conducting some studies with humans who are exposed to various oxygen concentrations. In these experiments, the ability to perform mathematical calculations while undergoing different levels of work (stationary bicycle riding) is being measured [15]. Incapacitation as used in Hazard I [11] is based on physical incapacitation (inability to move) and the individual toxic gas data from the non-human primate work of D. Purser [16].

Work is continuing on the characterization of the smoke components and controlling factors in smoldering combustion [17,18]. Current work at NIST has been concerned with self-sustained smoldering of solid wood under controlled air supply conditions. Transition to flaming and extinction depends on the air flow rates. During stable smoldering, 3 to 4 mole-percent of the exhaust gases is carbon monoxide. Other smoldering combustion gases have also been characterized. This work has led to an increased understanding of smoldering propagation and flaming transition phenomena.

The research necessary to model and predict carbon monoxide generation from various fuels in enclosure fires both in large and small-scale test conditions is another area of study at NIST [19].

The effects of the molecular structure on flammability properties are being examined at NIST and Factory Mutual Research Corporation. In particular, these two groups are studying the effects of thermal stability and melt viscosity of the material on piloted ignition [20], flame spread [21], non-flaming gasification rate and heat release rate [22]. Engineering correlations for heat of combustion, its convective and radiative components, yields of CO and particulates as functions of molecular weight and aromatic, saturated and unsaturated bonds of the material structure have been suggested [23].

Work continues on the long-term study of the chemistry of soot formation at NIST, Pennsylvania State University and George Washington University [24-26]. Through the use of laser techniques (such as absorption, fluorescence, multiphoton ionization) and mass spectrometric methods, the production and destruction rates of intermediate hydrocarbons and radical pool species are being examined. Recently, the first quantitative radical measurements in hydrocarbon diffusion flames have been reported [25]. Carbon monoxide formation and oxidation in a methane/air flame and the relationship between soot and CO formation is being studied.

REFERENCES

1. New York State Uniform Fire Prevention and Building Code, Article 15, Part 1120, Combustion Toxicity Testing and Regulations for Implementing Building Materials and Finishes; Fire Gas Toxicity Data File. NY State, Dept. of State, Office of Fire Prevention and Control, Albany, NY 12231

2. Norris, J.C., National Institute of Building Sciences Combustion Toxicity Hazard Test. Proceedings of the Joint Meeting of the Society of Plastics Engineers and The Fire Retardant Chemicals Association, Grenelefe, Florida, March, 1988.

3. Nyden, M.R. and Chittur, K., Component Spectrum Reconstruction from Partially Characterized Mixtures. Applied Spect. 43:123-128 (1989).

4. Harris, R.H. and Paabo, M., Determination of Acid Gases in Combustion Products. To be presented at the Second International Ion Chromatography Forum, Boston, MA, Sept., 1989.

5. Levin, B.C., Paabo, M., Highbarger, L., and Eller, N., Synergistic Effects of Nitrogen Dioxide and Carbon Dioxide following Acute Inhalation Exposures in Rats. NISTIR 89-4105, National Institute of Standards and Technology, Gaithersburg, MD, June, 1989.

6. Levin, B.C., Paabo, M., Gurman, J.L., Harris, S.E., and Braun, E., Toxicological Interactions between Carbon Monoxide and Carbon Dioxide. Toxicology 47:135-164 (1987).

7. Levin, B.C., Paabo, M., Gurman, J.L., and Harris, S.E., Effects of Exposure to Single or Multiple Combinations of the Predominant Toxic Gases and Low Oxygen Atmospheres Produced in Fires. Fundam. Appl. Toxicol. 9:236-250 (1987).

8. Levin, B.C., Paabo, M., Gurman, J.L., Clark, H.M., and Yoklavich, M.F., Further Studies of the Toxicological Effects of Different Time Exposures to the Individual and Combined Fire Gases: Carbon Monoxide, Hydrogen Cyanide, Carbon Dioxide, and Reduced Oxygen. Polyurethane '88, Proceedings of the 31st Society of Plastics Meeting, Philadelphia, PA, Oct. 1988, Technomic Publishing Company, Lancaster, PA, p. 249 - 252.

9. Levin, B.C., Gurman, J.L., Paabo, M., Baier, L., and Holt, T., Toxicological Effects of Different Time Exposures to the Fire Gases: Carbon Monoxide or Hydrogen Cyanide or to Carbon Monoxide Combined with Hydrogen Cyanide or Carbon Dioxide. Polyurethane '88, Proceedings of the 31st Society of Plastics Meeting, Philadelphia, PA, October, 1988, Technomic Publishing Company, Inc., Lancaster, PA, p. 240 - 248.

10. Hartzell, G.E., Grand, A.F., and Switzer, W.G., Modeling of Toxicological Effects of Fire Gases: Further Studies on the Toxicity of Smoke Containing Hydrogen Chloride. J. Fire Sciences 2:368-391 (1987).

11. Bukowski, R.B., Peacock, R.D., Jones, W.W., and Forney, C.L., Technical Reference Guide for the Hazard I Fire Hazard Assessment Method.

Handbook 146, Vol. I, II, & III, National Institute of Standards and Technology, Gaithersburg, MD. 1989.

12. Levin, B.C. The N-Gas Model Screening Test for Assessing the Acute Inhalation Lethality of Smoke, Appendix A of Report by E. Braun entitled Implementation of N-Gas Model Screening Test for Assessing the Acute Inhalation Lethality of Smoke. NIST Report to the Navy, 1/1989.

13. Malek, D.E., Stock, M.F., and Alarie, Y., Performance Evaluation under Intoxicating Atmospheres. Fundam. Appl. Tox. 8:335-345 (1987).

14. Malek, D.E. and Alarie, Y., Ergometer Within a Whole Body Plethysmograph to Evaluate Performance of Guinea Pigs Under Toxic Atmospheres. Toxicol. Appl. Pharmacol. (in press).

15. Knight, D.P., Schlichting, C. & Dougherty, J.P., The Reversible, Non-Toxic Effects of Fire Products. Proceedings of the Live Fire Test Crew Casualty Assessment Workshop, Naval Sub. Base, Groton, CT, Oct. 1988.

16. Purser, D.A., Toxicity Assessment of Combustion Products. In The SFPE Handbook of Fire Protection Engineering, First Edition, Ed. by DiNenno, P.J., Beyler, C.L., Custer, R.L.P., Walton, W.D., and Watts, J.M., Jr., National Fire Protection Association, Quincy, MA, Section 1, Chapter 14, pp. 200-245 (1988).

17. Ohlemiller, T. and Shaub, W., Products of Wood Smolder and Their Relation to Wood-Burning Stoves, NBSIR 88-3767, National Bureau of Standards, Gaithersburg, MD, May 1988.

18. Ohlemiller, T., Effects of Some Physical Factors on Smoldering Combustion of Wood-Based Materials, Proceedings of American Chemical Society Symposium on Fire and Polymers, Dallas, TX, April 1989, in preparation.

19. Pitts, W.M., Executive Summary for the Workshop on Developing a Predictive Capability for CO Formation in Fire. NISTIR 89-4093, National Institute of Standards and Technology, Gaithersburg, MD, May, 1989.

20. Kashiwagi, T. and Omori, A., Effects of Thermal Stability and Melt Viscosity of Thermoplastics on Piloted Ignition. Twenty-Second Symposium (International) on Combustion, The Combustion Institute, pp. 1329-1338 (1988).

21. Kashiwagi, T., Omori, A., and Brown, J.E., Effects of Material Characteristics on Flame Spreading. Proceeding of the Second International Symposium on Fire Safety Science, pp. 107-117 (1989).

22. Kashiwagi, T., Omori, A., and Nambu, H., Effects of Melt Viscosity and Thermal Stability on Polymer Gasification, Combustion and Flame (Submitted for publication).

23. Tewarson, A., Smoke Point Height and Fire Properties of Materials, NIST-GCR-88-555, December 1988.

24. Tjossem, P.J.H. and Smyth, K.C., Multiphoton Ionization Detection of CH, Carbon Atoms, and O_2 in Premixed Hydrocarbon Flames. Chemical Physics Letters 144:51 (1988).

25. Smyth, K.C., Tjossem, P.J.H., Hamins, A., and Miller, J.H., Concentration Measurements of OH· and Equilibrium Analysis in a Laminar Methane/Air Diffusion Flame. Combustion and Flame (in press).

26. Hamins, A., Anderson, D.T., and Miller, J.H., Mechanistic Studies of Toluene Destruction in Diffusion Flames. Combustion Science and Technology (Submitted for publication).

Progress Report on Fire and Toxicity Chemistry in Japan

Hiroaki SUZUKI
Smoke Control Division
Building Research Institute
Ministry of Construction
Tatehara, Tsukuba-shi
Ibaraki-ken, 305
JAPAN

Studies on fire and toxicity chemistry have not made significant progress in number in these 16 months since the last UJNR meeting. One of reports of this field related to fire chemistry is the work of O. Sugawa and H. Yamamoto's which is dealing the change of smoke particles from wood and fire retarded wooden materials at various temperatures.[1] They have obtained that combination of molybdenum, bromine and phosphate compounds are effective for reduction of smoke particles from wooden materials. This phenomena seem to be based on the synergestic effect of the molybdenum compound.

Related to toxicity chemistry, some were reported by T. Morikawa, E. Yanai, T. Watanabe, T. Okada, and Y. Sato who have dealt with toxic gases from natural and synthetic polymers under different opening conditions using a full scale two-storey house of concrete construction.[2),3),4] A room on the first floor was used as the fire room. Various kinds and amounts of natural and synthetic materials were supplied for fire loads under some opening conditions. CO and HCN were estimated to be major toxicants. More amount of HCN were detected from synthetic polymers than natural ones in the same amount of nitrogen-containing materials. Smaller area of the opening tended to produce more toxic gases.

For analysis of CO-Hb in blood, rabbits were applied. Synthetic polymers showed higher toxicity than natural ones from the point of CO concentration in the combustion products, as well. HCN from synthetic materials may cause rabbits incapacious or dead.

T. Morikawa has also conducted a studay on evolution of toxic gases at smouldering conditions and its estimation.[5] Cotton, acrylic wool, sawdust and mosquito coil, tatami mat (made of straw covered with rush) were smolder using red hot charcoal as a heat source and CO, CO_2, O_2, HCN, Acrolein were analized by gas chromatography. He showed relationship between total toxicity index ($\Sigma(C_i/C_{fi})$) and toxicity of each gas. He confirmed the toxicity index of CO is higher than that of the sum of toxicity indexes of other toxicants.

T. Hirata, Y. Fukui, S. Kawamoto and M. Inoue have dealt with combustion toxicity of gases from plywood treated with retardants and with CCA presevatives. They have explained these in terms of chemical reaction mechanisms, and concerned with generation of CO and other toxicants. Details are mensioned in their paper entitled " COMBUSTION TOXICITY OF WOODS TREATED WITH RETARDANTS AND CCA PRESERVATIVES " of the 11th Joint Meeting of UJNR Panel on Fire Research and Safety.

References

1) O. Sugawa and H. Yamamoto; Fire Science & Technology Vol.9 No.1, P1, 1989

2) T. Morikawa and E. Yanai; J. of Fire Science, Vol.7, No.2, P131, 1989

3) E. Yanai and T. Morikawa; Annual conference on Fire Research, P79, Japan Association for Fire Science and Engineering, May 1989.

4) T. Morikawa, E Yanai, T. Watanabe, T. Okada, and Y. Sato; ditto, P83.

5) T. Morikawa; ditto, P75.

COMBUSTION TOXICITY OF WOODS TREATED WITH RETARDANTS AND CCA PRESERVATIVES

T. Hirata, Y. Fukui, S. Kawamoto, and M. Inoue
Forestry & Forest Products Research Institute,
Kukisaki, Inashiki, Ibaraki 305, Japan

ABSTRACT

Combustion gas toxicity of plywood treated with retardants, and of wood treated with CCA preservatives was determined and explained in terms of chemical reaction mechanisms, and generation of CO and other toxicants.

INTRODUCTION

A large amount of wood and wood-based materials such as plywood, particle board, and fiber board is used for buildings, furniture, fences, and so forth. Therefore, development of fire retardant and decay resistant wood and wood-based materials having a high level of safety is needed. Fire retardant plywood has been made with treatments by several retardants in the laboratory and evaluated by combustion tests.

On the other hand, for decay resistant wood, CCA which consists of compounds of copper, chromium, and arsenic has been used in the majority of wood preservatives because of advantages of its high efficiency and low cost of the treating process. However, combustion gases from CCA treated wood, especially gases from arsenic compounds are assumed to be acute toxicants. This paper presents results regarding the combustion gas toxicity of the fire retardant plywood and CCA treated wood.

EXPERIMENTAL

1. Samples
Three kinds of samples, fire retardant plywood, and CCA treated wood for oxidative pyrolysis and for a combustion test, were prepared.

Plywood (6.0 mm in thickness), made of red meranti wood and melamine-urea-formaldehyde resin glue, was treated with retardants, as shown in Fig. 1, where the solutions of ammonium phosphate and ammonium bromide in five different compositions (0:1, 1:3, 1:1, 3:1, and 1:0 in weight) were used in 20 % concentration. The concentration of boric acid solution was 5 %. Twelve parts of poly(ammonium phosphate) were mixed with 100 parts of the original resin solution. The plywood samples were cut into 22 x 22 cm for combustion tests and were conditioned at 22 °C, 45 % RH longer than three months.

The samples for the oxidative pyrolysis were sapwood of Japanese cedar ground to diameters between 0.35 and 1.0 mm. The ground wood was immersed in any one of three different concentrations of CCA 2, which consisted of CrO_3 (59-67 %), CuO (16-20 %), and H_2AsO_4 (17-21 %), and then freeze-dried. The CCA retentions of the three samples were 0.9, 3.7, and 7.9 % of the original wood weight.

Red lauan wood samples of 1 x 22 x 22 cm size and 0.44-0.54 specific gravity were impregnated with either CCA 2 or CCA 1-A which consisted of $K_2Cr_2O_7$ (50-60 %), $CuSO_4 \cdot 5H_2O$ (30-37 %), and $As_2O_5 \cdot 2H_2O$ (10-13 %) and used for the combustion toxicity test. Also these samples were conditioned at 22 °C, 45 % RH longer than three months.

2. Combustion gas toxicity test

In this test an apparatus, shown in Fig. 2, was used according to Ministry of Construction Notification 1231. Combustion gas from a sample, which was heated with electric heaters and LP gas flame, was first introduced into the chamber I (50 x 50 x 50 cm^3 volume) and stirred there. On the passage between the chamber I and the mouse exposure chamber (chamber II, 50 x 50 x 50 cm^3 volume) part of the gas was drawn off outside at a rate of 10 mL/min and the residue was then introduced into the chamber II. The heating time is 6 minutes and the mouse exposure time is 9 minutes plus the heating time (15 minutes). The electricity and gas supplies to the heaters were previously determined by test runs for a prescribed non-combustible specimen so as to follow a prescribed time-exhaust temperature curve.

The mice used were pedigreed (named DDY), female, 5 weeks old, and weighed between 18 and 22 grams. For each run, 8 mice on each tread mill were exposed to the combustion gas. The incapacitation time of a mouse is defined as a time when the rotation of the tread mill terminates. The combustion toxicity for each run was evaluated by Xs which was obtained according to $Xs = \bar{X} - \sigma$, where $\bar{X}$ is a mean incapacitation time and σ is the standard deviation.

3. Oxidative pyrolysis, and analysis of copper, chromium, and arsenic

Using an imaging furnace, about one gram of CCA treated wood was isothermally heated at temperatures between 505 and 1030 °C in an air atmosphere flowing at 150 mL/min, until the decomposable weight monitored by a balance was exhausted. This furnace raised the sample temperature from room temperature to the desired constant values within one minute. The pyrolysis volatiles were introduced into a series of three spiral traps through a glass tube heated at 300 °C. The first, second, and third traps were chilled by ice-water (0 °C), dry ice-methanol (about -60 °C), and liquid nitrogen (about -190 °C), respectively. Condensates in the traps were dissolved in acetone, methanol, or water. On the other hand, ash from the samples was completely dissolved in sulfuric acid mixed with nitric acid with heating at temperature below 200 °C for 8 to 16 hours. The prepared solutions were analyzed for arsenic, copper, and chromium by an atomic absorption photometer.

RESULTS

1. Combustion gas toxicity of plywood treated with retardants

The untreated plywood of all the samples gave the smalles mean of Xs, 5.67 min. Since this value is considerably smaller, compared to 6.66 min for untreated red lauan wood obtained by Uesugi and others(1), this plywood is found to have high gas toxicity.

In order to detect effects of the retardants on the toxicity, the average values of $\bar{X}$ ($\bar{X}ave$) for each group of different treatments are shown in Fig. 3, where the different treatments are first divided into three groups of treatments, with neither ammonium phosphate nor ammonium bromide, with ammonium phosphate but without ammonium bromide, and with ammonium bromide but without ammonium phosphate. Furthermore, each group is divided for treatments of poly(ammonium phosphate) and boric acid. In the first group of the above three addition of boric acid and/or poly(ammonium phosphate) to the untreated plywood is found to have made $\bar{X}$ave a little greater. In the second group ammonium phosphate, especially with boric acid, is found to greatly improve the gas toxicity of the plywood. Ammonium bromide showed small tendency to increase $\bar{X}$ave, compared to the untreated plywood, however, this tendency seems to be restrained by boric acid in contrast to the case of ammonium phosphate.

Plots of the contents of ammonium bromide against $\bar{X}$ were made in Fig. 4 to obtain effects of ammonium bromide mixed with ammonium phosphate. Changes in $\bar{X}$ with changing the ammonium bromide content are found to be different depending on the additives of poly(ammonium phosphate) and boric acid. Without boric acid, $\bar{X}$ seems to slightly increase with increasing ammonium bromide (therefore, decreasing ammonium phosphate), as shown by the linear regression lines. It is noted that the above great effect of ammonium phosphate on $\bar{X}$ was almost neutralized by mixture with ammonium bromide. For the samples coated with boric acid, $\bar{X}$ rather rapidly decreased with increasing ammonium bromide in the region of lower ammonium bromide content, and seems to have gradually leveled off or started to increase with further increase in ammonium bromide, as seen by the regression curves. This turn may be caused from that the above effect of ammonium bromide to increase $\bar{X}$ appeared after the effect of ammonium phosphate and boric acid on $\bar{X}$ had been canceled by increasing ammonium bromide and then decreasing ammonium phosphate.

Plots of the maximum CO concentration in the exposure chamber vs. $\bar{X}$ in Fig. 5 show that $\bar{X}$ steeply decreased with increasing CO up to around 1 % but the decrease became slower with further increase in CO. This trend is approximated by a hyperbolic curve being in accordance with Haber's rule. Sakurai(2) has obtained a similar relationship using mice which were exposed to an atmosphere consisting of pure CO and air. It is seen from the composition of ammonium phosphate to ammonium bromide given in Fig. 5 that although CO concentration is low, $\bar{X}$ generally decreased with increasing ammonium bromide.

2. Oxidative pyrolysis and combustion gas toxicity of CCA treated wood

Arsenic was found in the ash and condensates from the oxidative pyrolysis of the CCA treated wood. Arsenic recovered from the ash decreased (then, arsenic transferred into gas phase increased) with increasing temperature, while with increasing temperature the amounts of arsenic recovered from the two condensates at about -60 and -190 °C linearly increased and that from the 0 °C condensate increased gradually with accelerating rate, as shown in Fig. 6 for the sample in the 3.7 % CCA content (basically same figures were obtained from the other samples of the 0.9 and 7.9 % CCA contents though are not shown). Furthermore, it is found by comparison among the different CCA content samples that at temperatures lower than 800 °C, the smaller the CCA content, the lower the percentage of arsenic recovered from the ash.

The percentage of total arsenic recoveries decreased with increasing temperature to 700 °C for the 0.9 % CCA content sample or to 900 °C for the other samples. These trends reversed and began to increase with further increase in the temperature. Arsenic which was not recovered is assumed to be caught in compounds of high molecular weight along with tar in the glass path between the furnace and the first trap at 0 °C.

Analysis using the atomic absorption photometer does not give any information about chemical structures or molecular species of arsenic compounds. However, the molecular weight of the compounds would be lower in a condensate at lower temperature. AsH_3 (hydrogen arsenide) seems to be the only compound of arsenic products which condenses not at -60 but at -190 °C. Its melting and boiling points are -113.5 and -54.8 °C, respectively. Therefore, arsenic in the condensate at about -190 °C might come from AsH_3. Though the quantity of arsenic from this condensate is small, AsH_3 is well-known as a very strong and acute toxicant which is produced from reaction between an arsenic compound and nascent hydrogen. It is believed that this toxicant rather easily oxidizes to lose its acute toxicity in air.

The results of the analysis of the ash and the condensates for copper and chromium indicate that almost all of these elements remained in the ash. Copper and chromium recovered from all the condensates were less than 0.5 and 0.2 % of the initial amounts, respectively.

Influence of CCA on the incapacitation of mice is not sufficiently clear, as shown by the considerable scatter of the plots of CCA contents vs. $\bar{X}$ in Fig. 7, where two mutually contrary relationships are shown by linear regression lines which have low correlation coefficients. These indicate that $\bar{X}$ decreases with increasing CCA 1-A and that $\bar{X}$ increases with increasing CCA 2, respectively. The latter relationship is statistically significant at the 5 % level.

This incapacitation time can be related to two other factors, namely, the specific gravity of specimens and CO. The mean incapacitation time increased with increasing specific gravity, as shown in Fig. 8, where a linear line is given which has a 5 % significance level. Furthermore, $\bar{X}$ decreased with increasing maximum CO concentration in the exposure chamber, as shown in Fig. 9 where the relationsip is approximated by a regression curve. It is suggested from these figures that $\bar{X}$ variations depend not only on CCA but also on the specific gravity and CO generation.

DISCUSSION

1. Plywood treated with retardants

As shown in Fig. 3, $\bar{X}$ave for the samples treated with both ammonium phosphate and boric acid is larger than the value expected from addition of the two values of $\bar{X}$ave for each sample treated with a corresponding single retardant. On the contrary, $\bar{X}$ave for the samples treated with both ammonium bromide and boric acid is smaller than the value expected in the same way. Similar synergistic and antagonistic effects between the same retardants on heat release, ignitability, and smoke generation were previously found in the surface flammability of plywood(3). Therefore, these effects are probably due to the same mechanism in both combustion tests.

The mechanisms may be described as follows: In pyrolysis of wood, ammonium phosphate accelerates dehydration and then carbonization, while boric acid accelerates crosslinking reaction to produce stable char(4). Therefore, these two retardants cooperate to form a thicker and more stable char layer. This thermal insulation protects the inside of the wood and then restrains production of flammable gases. Thus, CO from the imperfect combustion of flammable gases would be given less by the treatments with these two retardants. On the other hand, ammonium bromide inhibits combustion of flammable gases by evolving hydrogen bromide into gas phase. Without ammonium phosphate, wood chemical structures stabilized by boric acid cause rapid gasification once decomposition commences(4-6) and increase in smoke(3). When the combustion of flammable gases, thus rapidly evolved from boric acid treated wood, is inhibited by halides, this imperfect combustion would give higher CO concentration than for wood treated with ammonium bromide or boric acid.

Production of CO generally increases with increasing smoke(7). This relationship, however, varied depending on the retardant treatments, as shown in Fig. 10. It is clear that the group treated with ammonium bromide yielded less CO than the group treated with neither ammonium phosphate nor ammonium bromide, nevertheless the former evolved more smoke than the latter. This suggests that the ammonium bromide treatment yielded other toxicants besides CO, because $\bar{X}$ tended to decrease with increasing the content of this salt, though the CO concentration was low, as shown in Fig. 5. Furthermore, it emerges that the two groups might casuse two different imperfect combustions due to the inhibitory effect of ammonium bromide and due to lack of oxygen, respectively.

Ammonium bromide would not directly produce HCN (hydrogen cyanide), because it decomposes at temperatures under 230 °C which is too low to produce HCN. It was found by ion chromatography for gas sampled from the exposure chamber in a preliminary test that plywood glued by urea-formaldehyde resin generated a large amount of HCN, which was probably produced also from the resin glue used for the present plywood. HCN would oxidize at high temperature, but in this study the oxidation had to be inhibited by hydrogen bromide. The inhibitory effect of ammonium bromide on the HCN oxidation was probably greater than the corresponding effect of lack of oxygen in the exposure chamber, as inferred from the larger smoke generation from the ammonium bromide treated plywood than that from the untreated plywood shown in Fig. 10.

2. Wood treated with CCA

Arsenic volatized in the oxidative pyrolysis seems to increase with increasing air supply, because under an air supply at a constant rate of 150 mL/min, the smaller the CCA content (i.e. the larger the air supply per unit CCA amount), the arsenic found in the ash was less. On the other hand, the arsenic from the two condensates (except for the 0 °C one) linearly increased with increasing temperatue, as shown in Fig. 6. In fact it may be difficult to develop an incinerator which has traps for these arsenic volatiles. Therefore, it is desirable to burn waste wood treated with CCA under conditions where temperature is lower than 500 °C and of the reduced air supply in order to prevent generation of arsenic into the atmosphere.

Although the reliability may not seem high due to the dispersion of the plots, the two contrary trends found in Fig. 7 must relate to the different arsenic compounds, if these trends are true. The relationship between $\bar{X}$ and maximum CO concentration in Fig. 9 seems to deviate from Haber's rule. It is interesting to note that the greater part of the plots for CCA 1-A are located under the regression curve. Therefore, $\bar{X}$ for CCA 1-A seems to have been more closely involved with other toxicants such as AsH_3 besides CO than for CCA 2.

CONCLUSIONS

1. Ammonium phosphate, especially with boric acid, much decreased the combus-

tion gas toxicity of plywood. This improvement was achieved with dehydration and carbonization by ammonium phosphate and with stabilization of wood chemical structures by boric acid.

2. Ammonium bromide decreased the combustion toxicity a little, but this improvement was reduced by boric acid. It is assumed that ammonium bromide inhibited not only the combustion of flammable volatiles but also the HCN oxidation. The rapid decomposition of wood structures stabilized by boric acid seems to have resulted in reducing the improvement given by ammonium bromide.

3. An acute toxicant, AsH_3 was produced in the oxidative pyrolysis of CCA treated wood. However, any solid conclusion about effects of CCA on the toxicity was not obtained in the combustion test. The gas toxicity of the CCA treated wood seems to be controlled by several factors such as generation of CO and AsH_3, and the specific gravity of specimens. In order to prevent generation of arsenic volatiles it is desirable to burn CCA treated wood at low temperature with less air supply.

References

1) Uesugi, S. et al.: J. Japan Wood Res. Soc., 27(5), 423-436(1981).
2) Sakurai, T.: Proc. Ann. Meeting Fire Prevention Soc. Japan, 1985, Tokyo, 135-138.
3) Hirata, T. et al.: J. Japan Wood Res. Soc., 34(4), 337-345(1988).
4) Hirata, T.: J. Japan Wood Res. Soc., 27(2), 125-135(1981).
5) Hirata, et al.: Bull. Government Forest Experiment Station, No. 200, 1967, 155-184.
6) Hirata, T. and K. E. Werner: J. Appl. Polymer Sci., 33(5), 1533-1556(1987).
7) Hirata, T. et al.: J. Japan Wood Res. Soc., 27(5), 419-427(1981).

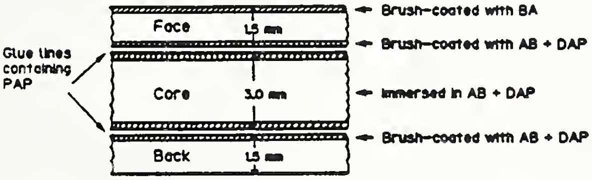


Fig. 1. Plywood sample.
AB: Ammonium bromide,
DAP: Diammonium phosphate,
BA: Boric acid,
PAP: Poly(ammonium phosphate)

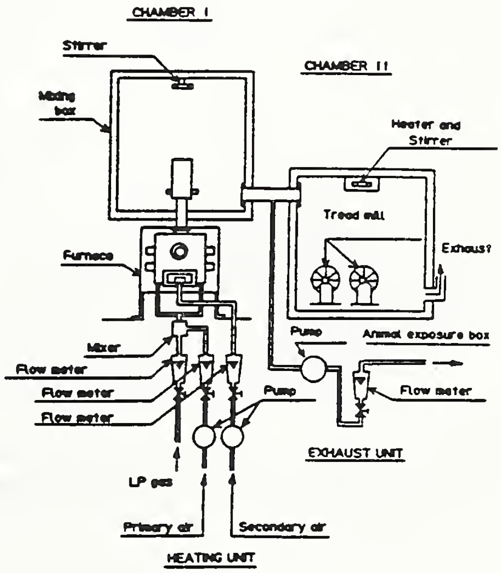


Fig. 2. Apparatus for combustion gas toxicity test.

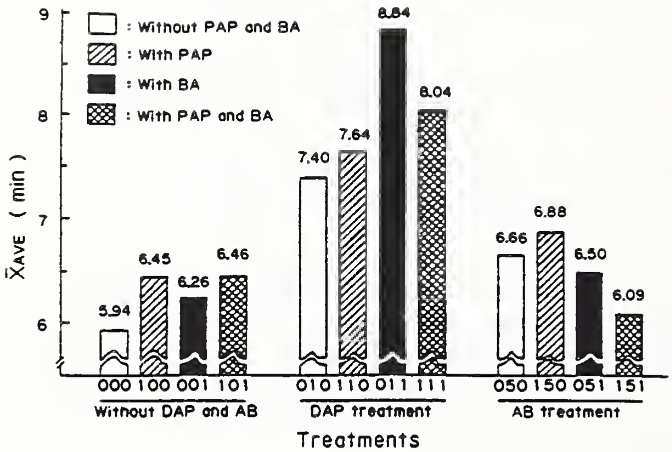


Fig. 3. Effects of retardants on incapacitation of mice.
X̄ave: Mean of mean incapacitation times.

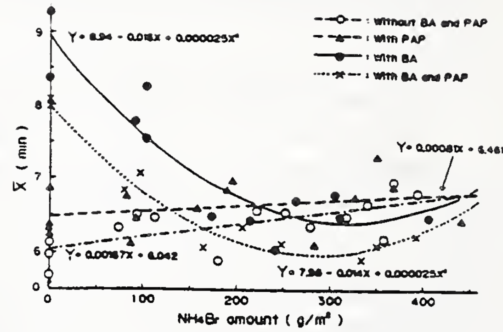


Fig. 4. Plots of ammonium bromide contents vs. incapacitation times.

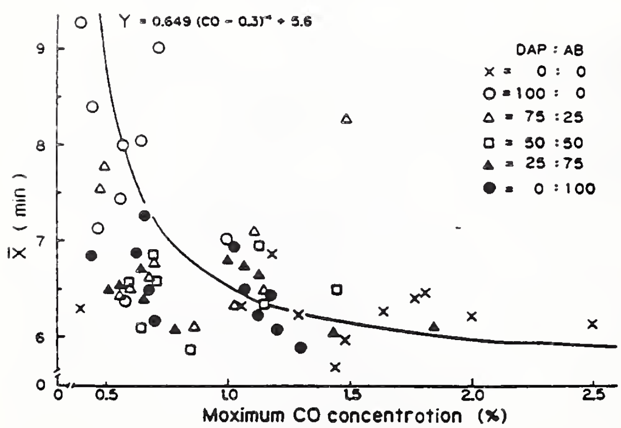


Fig. 5. Relationship between maximum CO concentrations and incapacitation times.

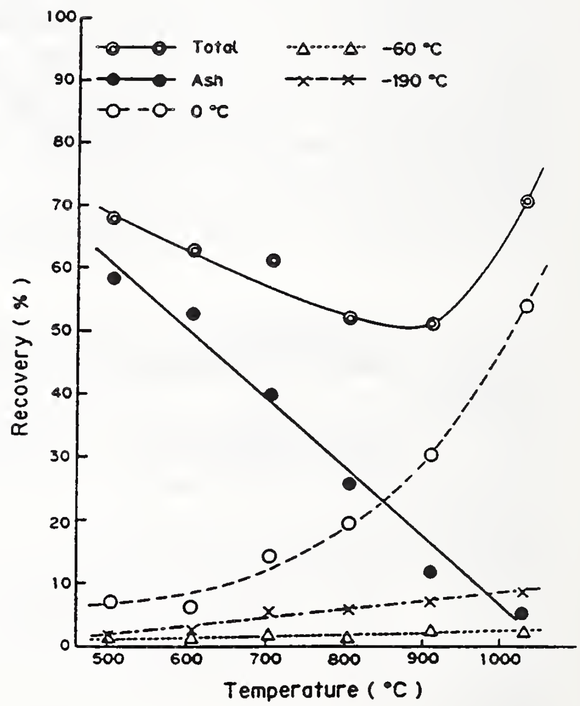


Fig. 6. Recovery of arsenic from ash and condensates at 0, -60, and -190 °C for wood in 3.7 % CCA content level.

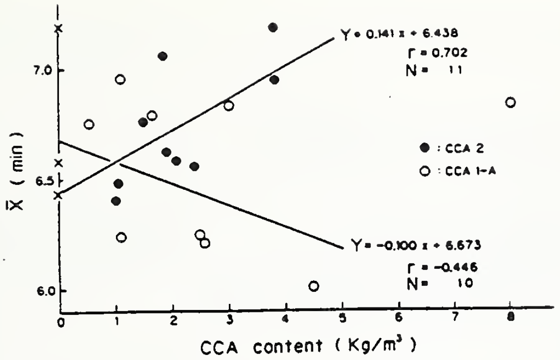


Fig. 7. Plots of CCA contents vs. incapacitation times.

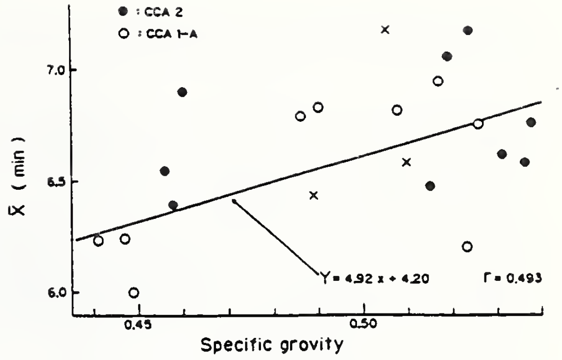


Fig. 8. Plots of specific gravity vs. incapacitation times.

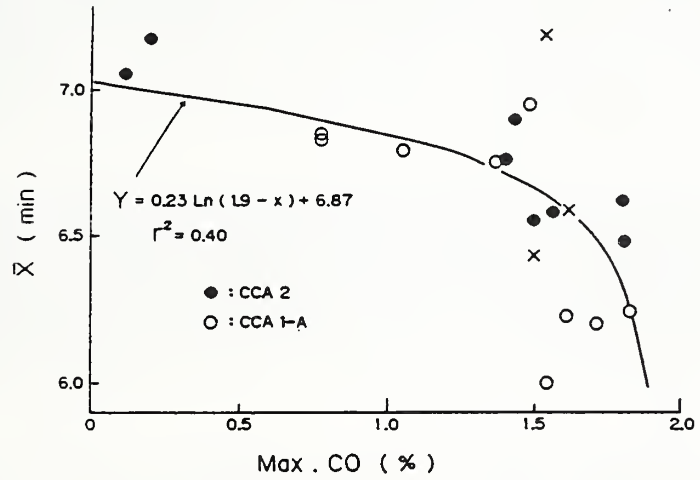


Fig. 9. Plots of maximum CO concentrations vs. incapacitation times.

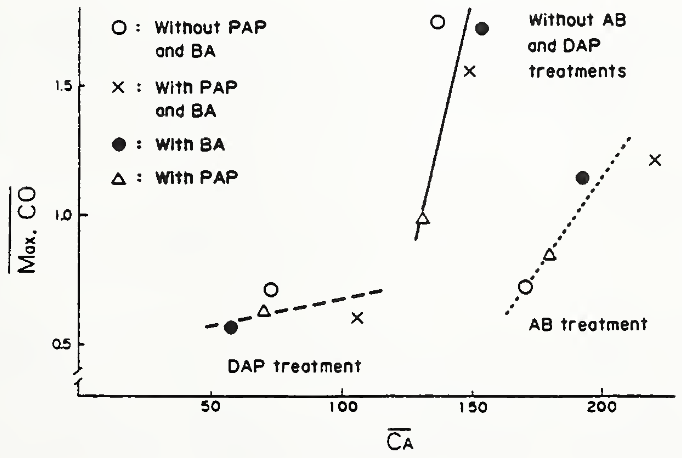


Fig. 10. Plots of mean maximum smoke density vs. mean maximum CO concentration.

$\bar{C}_A$: The maximum smoke density from surface flammability test(3).

Large-Scale Toxicity Correlations

VYTENIS BABRAUSKAS
Center for Fire Research
National Institute of Standards and Technology
Gaithersburg, MD 20899, U.S.A.

ABSTRACT

Some of the recent work done at NIST in the area of validating reduced-scale toxicity test methods against full-scale room fire data is reviewed. The agreements and disagreements obtained thus far are summarized. The current NIST research program for systematizing the validation process itself is also reviewed.

HYPOTHESIS

The simplest hypothesis that can be used in the validation of bench-scale toxicity data against full-scale data is the following: Is the yield of all toxicologically important gas species similar in the bench-scale tests and in the full-scale studies? We note that the definition of yield is that yield of gas X = kg X produced/kg fuel burned. To this end, several test series of data can be examined.

THE DATA EXAMINED

During the last few years, opportunities arose at NIST to complete 3 different test series where the objective was to investigate the relation between full-scale fire toxicity data and the data from reduced-scale test methods. The first two projects were conducted under the sponsorship of the Consumer Product Safety Commission (CPSC) — these will be referred to as the 1987 report [1] and the 1988 report [2]. Also reported on in 1988 was work sponsored by the Fire Retardant Chemicals Association (FRCA) [3]. Detailed data on all three of these projects have been published. In the present paper we will merely point out some of the most salient conclusions.

The two CPSC projects differed primarily in the large-scale test arrangements. The first series used a complex three-room layout, where most of the measurements were made in a room remote from the fire. The second test series focused on a single room, with measurements being made within that same room. For practical reasons, also, while the first series used mockups of entire upholstered chairs as the test item, the second series was simplified to using just a single chair cushion. The test specimens for both series were constructed of the same materials, and were two in number: cotton upholstery fabric paired with fire-retardant (FR) polyurethane foam, and the same fabric paired with a non-fire-retardant (NFR) polyurethane foam. The full-scale tests comprised three different scenarios: flaming, smoldering, and smoldering-to-flaming transition.

In addition to room fire tests, less-than-room-size tests were conducted. These included the furniture calorimeter [4], where the specimens can be of full, end-use size, but are tested in the open, not inside in room. Smaller-scale tests were conducted using the Cone Calorimeter [5] and the NBS Toxicity test [6].

An important objective of these studies was to find if yields of various toxic gases are similar between bench scale and full scale. Table 1 shows a summary of the results; details of the measurements made are all given in the original references cited. For a given test exposure (flaming, smoldering, or transition), the different tests often show an order of magnitude agreement, but not much closer. The smoldering and the transition exposures would especially be expected not to show good agreement, since neither the Furniture Calorimeter, the Cone Calorimeter, nor the NBS toxicity test were actually designed for the purpose of simulating cigarette smolder exposures. All could be modified to better represent such fire conditions, but such modifications were not undertaken as part of these studies.

The FRCA studies comprised a wider range of materials — 5 different types of materials were examined, each in a fire retarded and a non-fire-retarded formulation. The exposures examined were simpler, however, and only a flaming fire was studied. Table 2 shows the results for the FRCA test specimens in the less-than-room-size tests. For the room fire test portion of this program, the specimens were not tested individually. Instead, all FR commodities were tested together in one series of tests, while all NFR commodities were tested together in a second series of tests. Table 3 shows these results.

The above data are certainly not conclusive. Taken together, however, they to suggest that the yields of CO_2 and of the acid gas species ($HC\ell$, HBr) are similar among the tests to within a factor of 5. The data for HCN are inconclusive. For CO, it is clear that the bench-scale data do **not** predict the full-scale, except in the roughest order-of-magnitude sense. It is evident that a dedicated research program is needed to develop procedures which would predict the full-scale CO yields. Pitts [7] has outlined some of the steps that will need to be taken to achieve this predictability.

NEW WORK

The above considerations suggest that a simple hypothesis of all gas yields being scaled successfully is not appropriate. Thus, there has been started at NIST a new project in this area. For the Fiscal Year 1989, Congress provided a special appropriation so that a pilot study could be produced on the *methodology* required for validating reduced-scale toxicity test methods against full-scale room fires. The project itself includes only a limited amount of experimental work; its objective, however, has not been to provided lists of validated or invalid bench-scale tests, but, rather, to lay the groundwork for systematic future validation efforts. The work is now being completed and will be reported upon shortly [8].

To arrive at this improved methodology, the present situation can be summarized as follows. Even when a special CO prediction technique becomes available to solve the specific problems associated with that gas, it is clear that yields for the remaining gases will not be identical for all scales. This is not surprising when viewed in light of the actual combustion phenomena. Typical full-scale room fires show a progressive history: first ignition, then a small, spreading fire, later possibly reaching flashover, eventually burning mostly at charred surfaces, then dying out. Both the condition of the specimen and the external conditions (type of heating, oxygen concentration) will, in consequence, vary throughout the fire. A modern bench-scale test, by contrast, exposes the specimen to one set of combustion conditions throughout the burning. We emphasize here the 'modern.' Older fire test of various types often did try to create a time-varying exposure to the specimen. These were much less useful than today's tests, however. The modern test methods attempt to create simple exposure conditions, so that basic material fire properties of the specimen could be deduced. The older, simulation type of tests created an exposure history which did not correspond to actual full-scale conditions. Thus, such data had utility neither as material fire properties, nor as an assessment of hazard.

The proposed validation methodology being explored is based on recognizing this fact that a single bench-scale test cannot fully capture the essence of a full-scale scenario where the fire does not burn in a steady state. This is posed as the question: **Does the bench-scale test show the same primary toxic gases as the full-scale test?** If a given bench-scale test does this successfully for a suitably wide range of test materials or products, then it has been validated. Conversely, if it shows primary toxic gases which are not the same as in the full-scale tests, then the results of the proposed bench-scale test cannot be used to assess hazard for this fire scenario. Note that it is not required in this definition that yields or the ratios of the primary toxic gases be the same in the bench-scale test as in full scale. To insist on such equality would assure that only a single, unique combustion condition could be matched. (In the above, by 'primary gases' we mean gases that contribute an amount to the fractional effective dose, FED, which is greater than the uncertainty interval of the FED determination; a fuller discussion of the FED concept is contained in [3].)

Finally, our current understanding of CO production poses a unique difficulty in test design. The indications are that the quantity of CO produced depends at least as much on the full-scale ventilation and geometry as it does on any 'material properties' of the test specimen. This suggests that the proper way to take this aspect into account will be a combination of physical, bench-scale testing and a numerical calculation of expected CO yields. The exact mechanisms for doing this have not yet been worked out.

REFERENCES

1. Braun, E., Levin, B.C., Paabo, M., Gurman, J., Holt, T., and Steel, J.S., Fire Toxicity Scaling (NBSIR 87-3510). [U.S.] Nat. Bur. Stand. (1987).

2. Braun, E., Levin, B.C., Paabo, M., Gurman, Clark, H.M., and Yoklavich, M.F., Large-Scale Compartment Fire Toxicity Study: Comparison with Small-Scale Toxicity Test Results (NBSIR 88-3764). [U.S.] Natl. Bur. Stand. (1988).

3. Babrauskas, V., Harris, R.H., Jr., Gann, R.G., Levin, B.C., Lee, B.T., Peacock, R.D., Paabo, M., Twilley, W., Yoklavich, M.F., and Clark, H.M., Fire Hazard Comparison of Fire-Retarded and Non-Fire-Retarded Products (NBS Special Publication SP 749). [U.S.] Natl. Bur. Stand. (1988).

4. 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). [U.S.] Natl. Bur. Stand. (1982).

5. Proposed Test Method for Heat and Visible Smoke Release Rates for Materials and Products using an Oxygen Consumption Calorimeter (E-5 Proposal P 190), **Annual Book of ASTM Standards**, Vol. 04.07, American Society for Testing and Materials, Philadelphia (1986).

6. 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 (NBSIR 82-2532). [U.S.] Natl. Bur. Stand. (1982).

7. Pitts, W.M., Executive Summary for the Workshop on Developing a Predictive Capability for CO Formation in Fires (NISTIR 89-4093). [U.S.] Natl. Institute of Standards and Technology (1989).

8. Babrauskas, V., Harris, R.H., Jr., Braun, E., Levin, B.C., Paabo, M., and Gann, R.G., The Role of Bench-Scale Test Data in Assessing Full-Scale Fire Toxicity, report to be issued.

Table 1

Summary of yields found in NIST tests on upholstered chair specimens

Material	Test	Exposure	CO yield	CO_2 yield	HCN yield
NFR	Room test	flaming	0.09	1.9	0.002
	Furniture calorimeter	flaming	0.04	1.9	0.0006
	Cone Calorimeter	flaming	0.01	2.3	N.A.
	NBS Toxicity test	flaming	0.02	1.6	0.0017
	Room test	sm.-to-fl.	0.07 - 0.08	0.4	0.003
	Room test	sm.-to-fl.	0.11 - 0.12	2.2 - 2.6	N.A.
	Furniture calorimeter	sm.-to-fl.	0.12	3.6	0.001
	NBS Toxicity test	ramped	N.A.	N.A.	0.0105
	Room test	smolder	0.08 - 0.11	0.3 - 0.4	N.A.
	Furniture calorimeter	smolder	0.24	N.A.	< 0.0014
	Cone Calorimeter	smolder	0.03	1.7	N.A.
	NBS Toxicity test	non-flaming	0.03	0.2	0.0004
FR	Room test	flaming	0.10	1.3	0.004
	Furniture calorimeter	flaming	0.05	1.8	0.0018
	Cone Calorimeter	flaming	0.05	1.9	N.A.
	NBS Toxicity test	flaming	0.05	1.5	0.0057
	Room test	sm.-to-fl.	0.11 - 0.15	2.1 - 2.2	0.001
	Room test	sm.-to-fl.	0.11 - 0.14	0.6 - 0.7	N.A.
	Furniture calorimeter	sm.-to-fl.	0.13	1.9	0.007
	NBS Toxicity test	ramped	N.A.	N.A.	0.0130
	Room test	smolder	0.08 - 0.11	0.5	N.A.
	Furniture calorimeter	smolder	0.35	N.A.	< 0.0005
	Cone Calorimeter	smolder	0.03	1.7	N.A.
	NBS Toxicity test	non-flaming	0.04	0.3	0.0003

N.A. - not available

Table 2

FRCA series – Summary of yields found in less-than-room-size tests

Specimen	NFR /FR	CO (kg/kg) Cone Cal.	CO Furn. Cal.	CO Tox. Test.	CO_2 (kg/kg) Cone Cal.	CO_2 Furn. Cal.	CO_2 Tox.[d] Test.	HCN (kg/kg) Cone Cal.	HCN Furn. Cal.	HCN Tox. Test.	HBr (kg/kg) Cone Cal.	HBr Furn. Cal.	HBr Tox. Test.	HCl (kg/kg) Cone Cal.	HCl Furn. Cal.	HCl Tox. Test.
TV Cabinet H	NFR	0.015	0.12	0.084	2.28	1.39	2.09	—	—	—	—	—	—	—	—	—
TV Cabinet G	FR	0.109	0.37	0.18	0.67	0.74	0.78	—	—	—	0.069	0.082	0.017	—	—	—
Bus. Machine F	NFR	0.037	0.13	0.17	2.21	1.61	1.98	—	—	—	—	—	—	—	—	—
Bus. Machine A	FR	0.055	0.29	0.30	1.60	1.45	1.53	—	—	—	—	—	—	—	—	—
Chair T	NFR	0.020	0.01	—	1.62	1.89	—	0.002	0.001	—	—	—	—	—	—	—
Chair S	FR	0.051	[a]	—	0.964	[a]	—	0.005	—	—	—	—	—	0.023	—	—
Chair T[b]	NFR	0.016	—	0.025	1.71	—	2.05	0.002	—	0.0007	—	—	—	—	—	—
Chair S[b]	FR	0.055	—	0.15	0.81	—	1.19	0.0023	—	0.0032	—	—	—	0.022	—	—
Cable D	NFR	0.041	0.12	—	1.77	1.61	—	—	—	—	—	—	—	0.112	0.121	—
Cable K	FR	0.060	0.10	—	1.34	1.04	—	—	—	—	—	—	—	0.131	0.133	—
Cable D[c]	NFR	0.029	—	0.050[e]	2.19	—	2.38	—	—	—	—	—	—	ND	—	—
Cable K[c]	FR	0.135	—	0.13	1.00	—	1.26	—	—	—	—	—	—	0.093	—	—
Circuit Bd. C	NFR	0.014	0.10	0.075[e]	2.07	1.71	2.13	—	—	—	—	—	—			
Circuit Bd. L	FR	0.103	0.10	0.15	0.87	1.36	1.24	—	—	—	0.022	—	0.0043			

[a]Could not be determined reliably.
[b]Foam only, no cover fabric.
[c]Wire insulation only.
[d]Determined only from those tests where animals were not used.
[e]Excludes data from the highest mass loading tested, since presumed unrepresentative
—Not run
ND Not detected

Table 3

FRCA series – Comparison of CO yields to room fire data
CO yield (kg/kg)

Specimens	Room test	Cone Calorimeter	Furniture Calor.	NBS Toxicity test
NFR	0.18	0.02	0.09	0.074
FR	0.23	0.06	N.A.	0.155

N.A. – not available

Note: the specimens tested in the room tests comprised all 5 types of commodities (as described in Table 2) tested in two arrangements: one all-NFR, the second all-FR. For the other tests, the values reported are appropriately weighted sums.

Numerical Calculations and Computer Graphic Analysis of Window-to-Window Propagation of Building Fires

Kohyu Satoh and Daisuke Kozeki

Fire Research Institute of Japan
3-14, Nakahara, Mitaka, Tokyo 181, Japan

ABSTRACT

Building fires such as the "Andraus Building Fire" in Sao Paulo, the "Hotel New Japan Fire" in Tokyo and the "First Interstate Bank Building Fire" in Los Angeles have aroused great interest in the upward propagation of building fires. However, there have been little studies about the propagation of high-rise building fires via windows after the study of Yokoi, more than 30 years ago, who studied the behavior of hot gas flowing out of a window and the needed spandrel height to prevent fire spread upstairs.

The behavior of fire flows at openings such as doorways and windows have been numerically investigated by the authors. Here is attempted numerical simulations of the window-to-window fire propagation and in particular of the behavior of fires invading into the upstairs room via windows. And we made computer graphic animation video movies from the initiation in a lower room to the full development into the upstairs room. In addition, experiments using a 1/5 scale model showed that the flow patterns calculated are reasonable.

1. INTRODUCTION

In the world, high-rise buildings with many wide glass windows are increasingly constructed every year and so fires in them, too. In particular, fires of the "Andraus Building" [1] in 1972 in Sao Paulo, Brazil, the "Hotel New Japan" [2] in 1982 in Tokyo, Japan and the "First Interstate Bank Building" [3] in 1988 in Los Angeles, USA have aroused great interest in the upward extending building fires like in the movie "Towering Inferno". Although some might have been caused directly by the fire spread through the void space between slabs and walls, the fire spread via windows has clearly [2] been observed.

More than 30 years ago, Yokoi [4] [5] has studied the behavior of hot gas spurting out of a window of burning building and the needed spandrel height to prevent the fire spread upstairs. After that there have been some, but very little, studies about the fire propagation upwards via building outer surfaces. For example, Oguni et al. [6] and others [7] studied the fire propagation via combustible materials on verandas of disused aparment houses. (Verandas are horizontal projections and can deflect the upward flame. In Japan, they are also the places to dry washed clothes, blankets and mattresses in the sunshine, and at the same time in winters plastic containers of kerosene oil are stored there.) However, more basic phenomena of the via window fire spread over the building surfaces without any combustible materials are not fully clarified yet due to the difficulty of the large real scale experiments, and the fire accidents mentioned above are just the cases.

The behavior of fire flows, particularly of the mass flow rate, at openings such as doorway and window have numerically been studied by the authors[8 11]. Recently, Satoh [12] has numerically investigated the characteristics of fires flowing out of enclosures with an opening, either window-type or doorway-type. Periodic generation and decay of vortices around the opening were examined. Figure 1 shows the calculated isothermal patterns of flows in both types of enclosures. Immediately above the opening, some portion of the upward hot flow turns the flow direction downwards and the circulating flow generates a vortex.

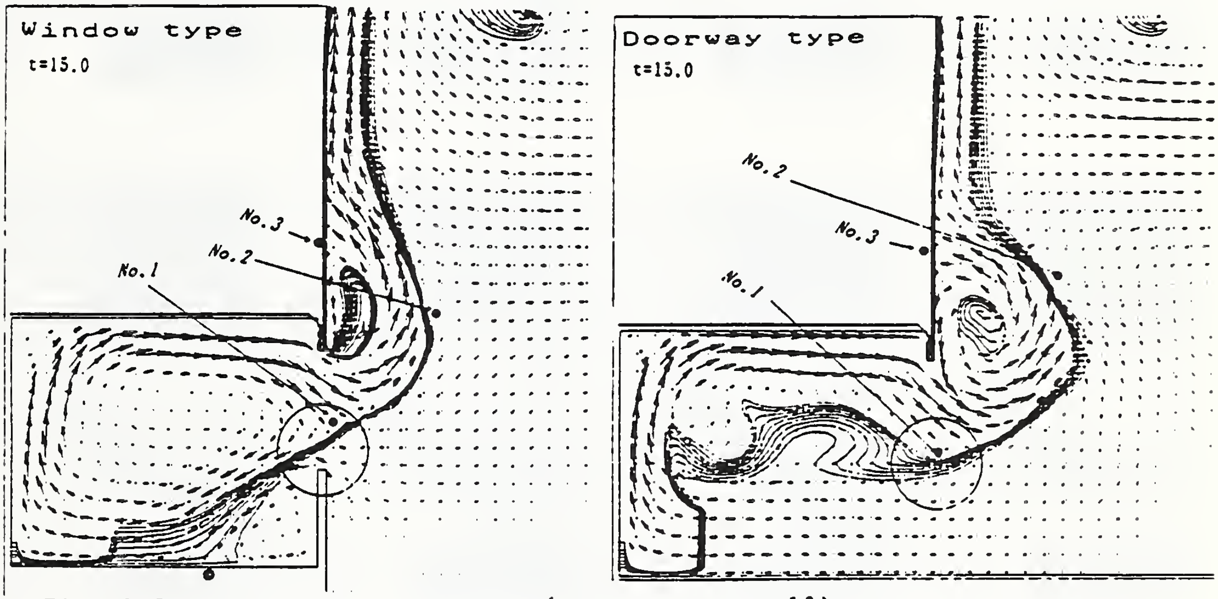


Fig. 1 Calculated flow patterns (previous study [12]) by velocity vector distributions and isothermal lines (isotherms are displayed only in the vicinity of the boundary of hot gas and cool air.)

However, neither this study nor Yokoi has examined the behavior of invasion of the fire into the upper room from the original room. It is uncertain how the upward flow is split into two directions, i.e. upward and into the upper room.

Here is attempted a numerical simulation of the window-to-window fire propagation, assuming the window glasses are open or already broken down in both the original fire room and the upstarirs room. Computer graphics (CG) supply large amount of information about the flows of fires. Hence we made CG animation video movies from the initiation of fire in a room to the full development of the fire in the room upstairs. Further 1/5 scale model fire experiments using liquid fuel were conducted.

2. NUMERICAL SCHEME

Numerical calculations were carried out using the almost same computer code as in the previous study [12] . The numerical scheme, the formulation of the finite difference equations and the other details of calculations are already shown in the references [13 17] and so no more are presented here. The calculations conducted here correspond to 1/5 scale model fire experiments. The flow domain was two-dimensional, similarly to the previous [12], and the total area was 1.98 (horizontal)×2.02 m(vertical). The basic cell was 2 cm square each. The fire room was 0.7×0.5 m(height) and the upstairs room had the same dimensions as the original fire room. The height of window was 0.38 m. Thus the outside area was 1.28(horizontal)×1.52 m(vertical). Although the burning of n-heptane was estimated to release 150-220 kW/m of heat, it is difficult to simulate quantatively the combustion phenomena of liquid fuel at present. Hence, in the calculations 70 kW/m volumetric heat release rate contributing to the convective buoyant energy was employed.

3. NUMERICAL RESULTS

Figure 2 shows the calculated flow patterns of the window-to-window fire propagation, which were chosen from the CG (computer graphics) animation movie (color in original).The original fire in the lower room was initiated at the place, on the floor, shown in the figure at 1.0 sec in Fig.2.

It can be seen from Fig.2 that a first block of the fire flow, due to the 70 kW/m of heat release in the two-dimensional enclosure with dimensions of 0.7×0.5 m (height), disappeared within 3 seconds from the top of numerical free boundary, abruptly just like a flash-over in a room. After the first block of the fire flow disappears at the upper free boundary, the boundary layer between the hot and cool air in the upper room are waving and slowly come down close to the floor, accompanying the oscillatory motion of the upward flow along the outer wall.

In Fig.1, vortices were created around the wall immeadiately above the window or doorway opening. In the case in Fig.2, too, a vortex was created almost at the same location as in Fig.1. This vortex moves upwards and so the hot flow along the outer wall or the window opening was pushed and bent left to right. Thus the hot fire flow invades into the room of upper floor.

Diffrently from Fig.2, Fig.3 shows the flow patterns of hot gas flow from a window opening in the case there is no rooms of upper floor with broken window glasses. Hence the upward flow from the window of the lower room moved along the vertical surface of the outer wall.

The flow patterns over the outer wall surfaces between Figs. 2 and 3 are quite similar on the whole. In particular the common flow behavior is seen at 9.5 and 11.5 sec in both Figs.2 and 3. In the four figures at the time, the hot flows are pushed ahead and inflated immediately above the top of the window of the fire room. In this way, the hot flow over the outer wall becomes fluctuating. This means that the glasses of upper room windows are heated up and cooled down repeatedly. This must be more severe exposures than constant heating to the glass surfaces to reach the break down of windows.

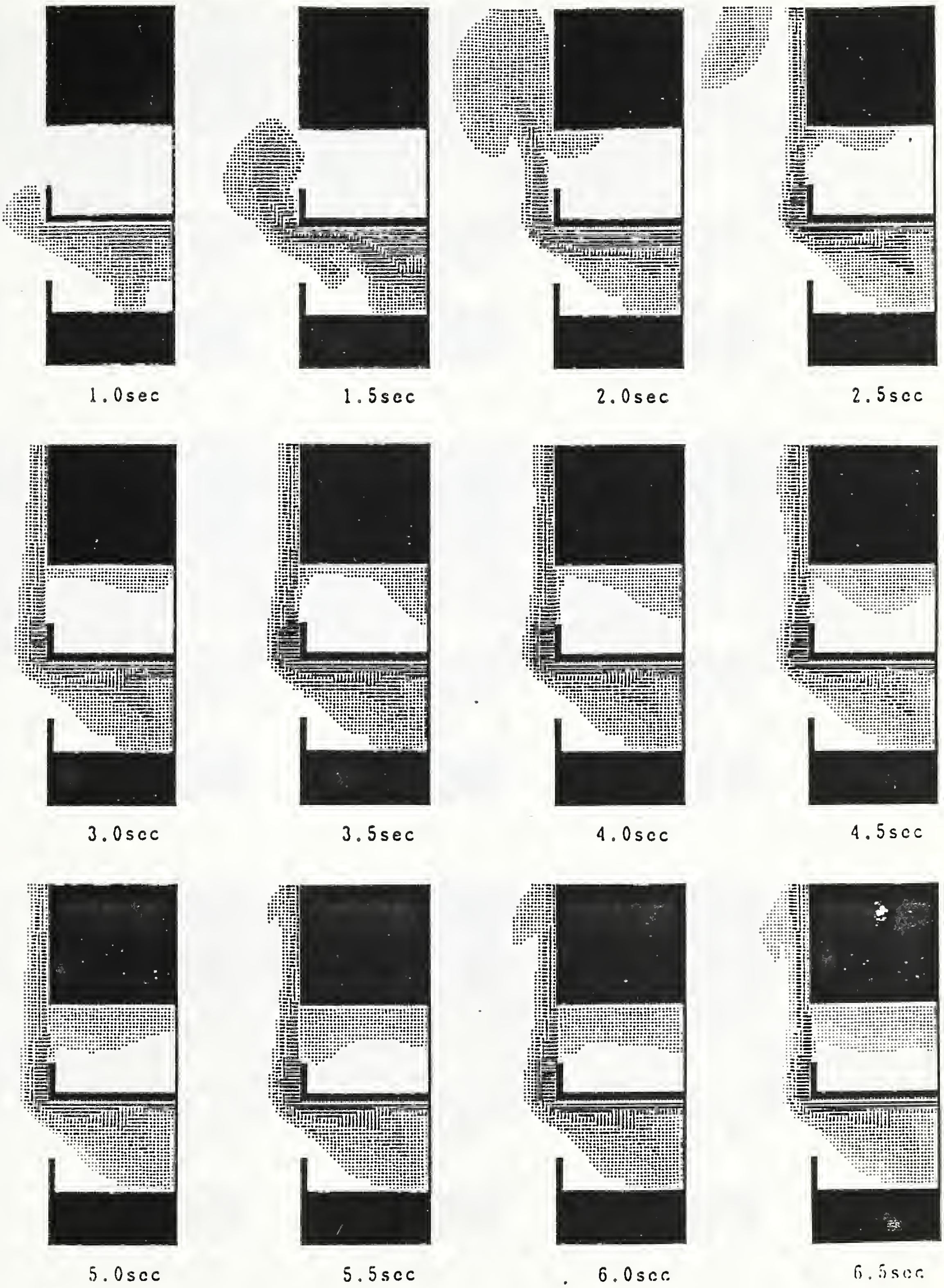
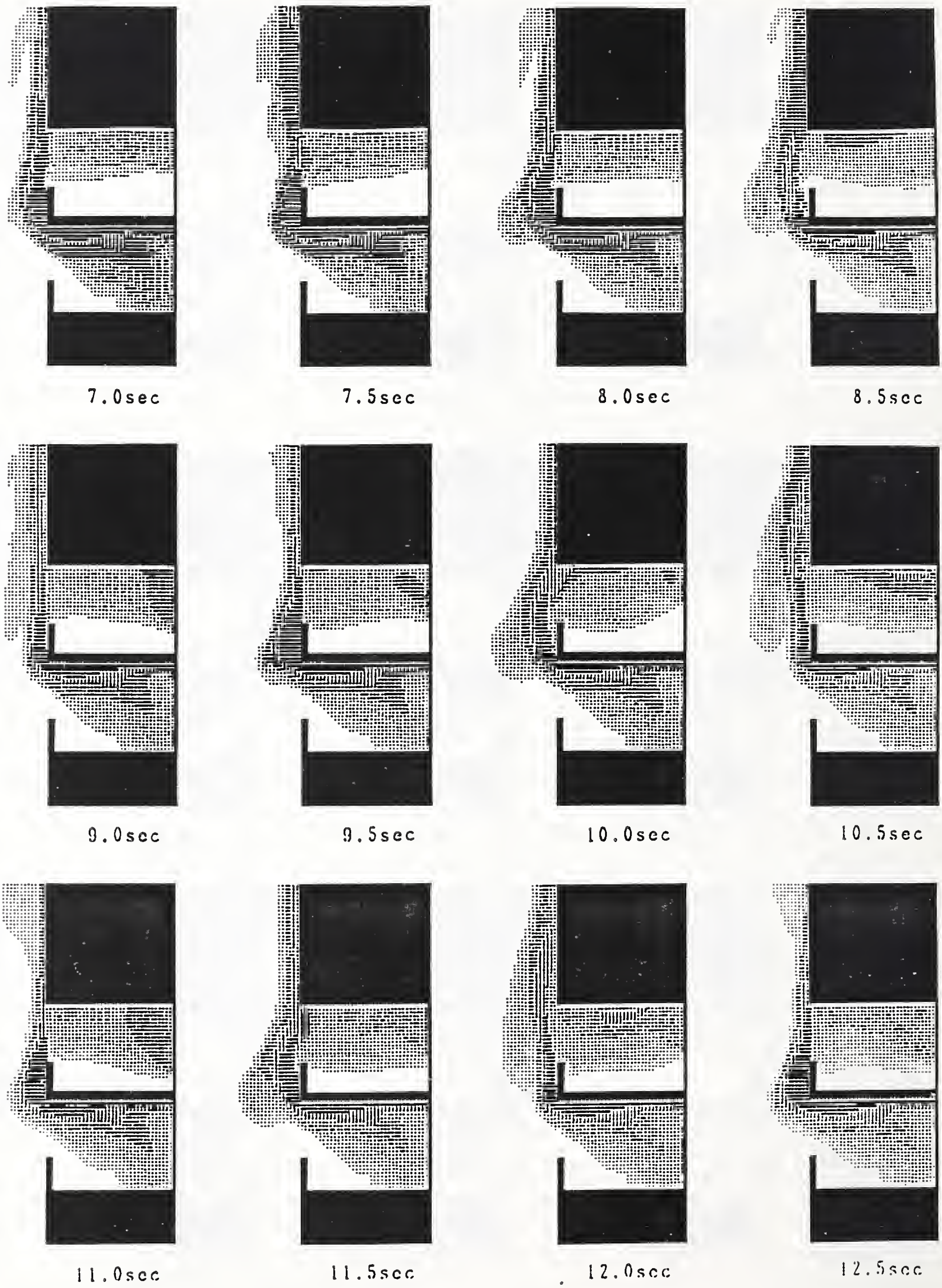


Fig. 2 Calculated flow patterns displayed by isotherms (multi-storied building)


7.0sec
7.5sec
8.0sec
8.5sec
9.0sec
9.5sec
10.0sec
10.5sec
11.0sec
11.5sec
12.0sec
12.5sec

(Continued)

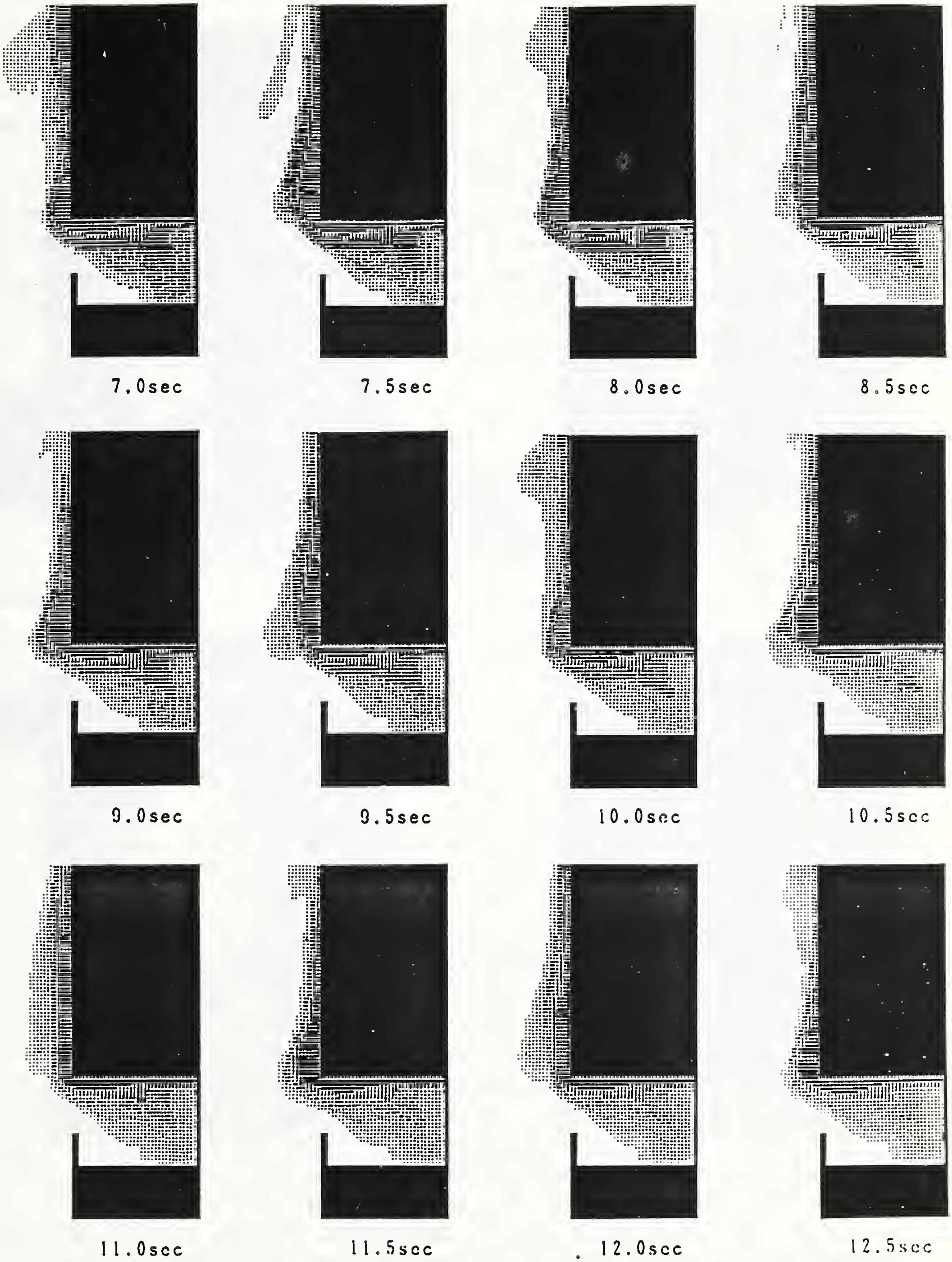


Fig. 3 Calculated flow patterns displayed by isotherms (single-storied building)

4. EXPERIMENTS

In the 1/5 reduced scale multi-storied building (0.7×0.5(height)×0.6 m) with an open window, either methanol or n-heptane was burned in a steel tray (0.14×0.03(liquid depth)×0.6 m). The fire flame of n-heptane was ejected long upwards from the window, but the methanol fire flame was comparatively weak in buoyancy and the flame height was short.

In the upper room with an open (broken) window, the temperatures near the the ceiling was measured, using methanol fuel. Figure 4 shows the temperature variation at two locations (one is near the window and the other is near the inner wall). The temperatures were highly oscillating, in particular at the location near the window, but the difference between the both was about 50℃.

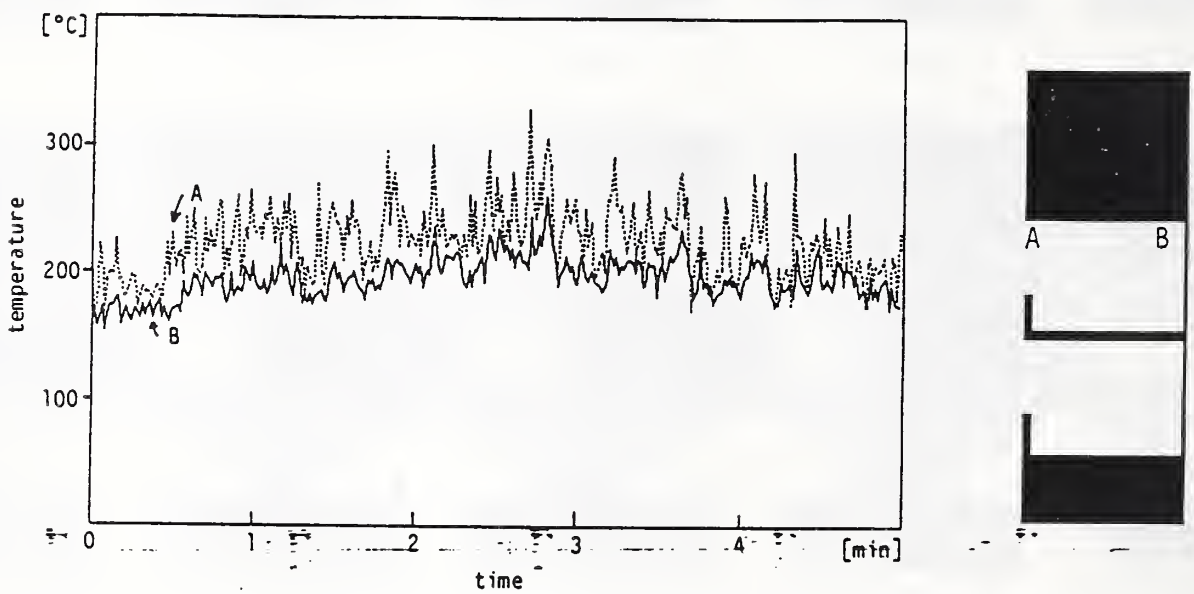


Fig. 4 Temperature variation at two locations (A and B) in the upper room measured experimentally. (fuel : methanol in the steel tray)

Figure 5 shows the photoes of the n-heptane flames burning in the steel tray mentioned above. In the experiments, the ejected n-heptane flames were highly oscillatory in the cases of both broken glass windows (case A) and non-broken windows (case B) of the room of the upper floor. The ejected upward flame was vertically pushed to the wall and window, and moved vertically. The side views of the upward flames between the cases (A) and (B) show that the flame shape and the height are almost the same as seen in photoes A and B of Fig.5. However, the oscillatory motion in the case (A) was affected by the open (broken) window compared with that in case (B).

The n-heptane flame in the original fire room covered all the floor area due to the high evaporation rate. In addition, the photo D in Fig.5,which was taken at the shutter speed of 1/125 sec, shows the detailed structure of the flame and vortices.

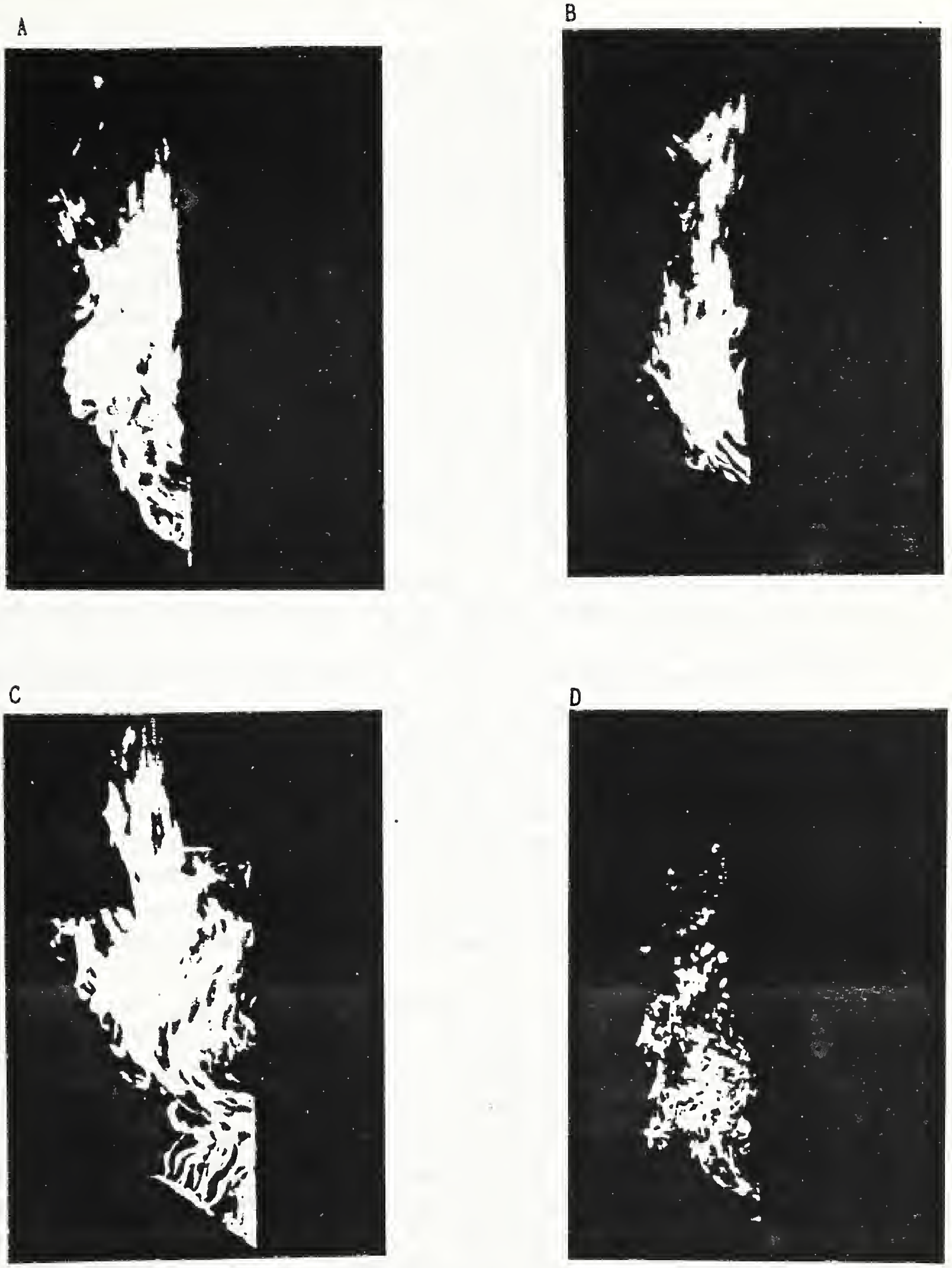


Fig.5 Burning flames of n-heptane ejected from a window and moving upwards.
photo A : closed window (case (B)), photoes B-D : open window (case(A))
photoes A-C : shutter speed=1/30 sec, ptoto D : 1/125 sec
Photo C shows the flame which covers the whole area of the floor
of original fire room and invades into the upper room.

5. DISCUSSIONS

The ejected flame of n-heptane became so long above the window of the original fire room as seen in Fig.5 in this experiment. Although the liquid fuel may not always be appropriate for the building fire simulations and the scale effect may be considerable in the reduced scale model, the aspects of the burning fire on the outer walls are very similar to the photos in journals and news papers reporting such large fire accidents as mentioned above indicating long ejected flames and reaching the windows of upper floor, even when the outer walls of the building were non-combustible.

Recently Oleszkiewicz [18] studied to provide data for the evaluation of hazard of fire spread along the building facade, using the test facility of the ASTM Standard Burn Room, in which propane gas burners were installed to produce fire plume. The shape of the plume, shown in the report, above the window is very similar to those shown in Figs.2 to 4 of this study.

The ejected n-heptane flames in the experiments were highly oscillatory in the cases of both broken glass windows (case A) and non-broken windows (case B) of the room ofthe upper floor. The ejected upward flame was vertically pushed to the wall and window in the experiments. This phenomena are very similar to the motion in the animation movie of computer graphics based on the numerical calculation.

It is considered that the oscillatory motion of the upward flame over the wall could affect the break down of window glasses repeating to heat and cool down. Window-to-window fires are accelerated by the existence of combustible materials near the window and the ceiling in the upper room.

Since recently high-rise buildings in the world are increasing year by year, the possibility of via window fire spread is still existent and may increase. Due to the difficulty of the large scale building fire experiments, numerical simulations are effective to analyse the flame behavior invading into the upper room and the spread of fire upstairs, and could be more significant.

6. CONCLUSIONS

It was found from the numerical calculations and the 1/5 reduced scale model experiments that the ejected fire flame from the original fire room is strongly pushed towards the building walls. The upward flow shows oscillatory behavior. The upward flames are almost similar in shape and length in both cases of the broken window and closed window. However, the oscillatory motion was affected by the existence of the window opening.

Numerical calculations showed that the generation of vortices around the area immediately above the window of the original fire room. In addition, the photo taken at the fast shutter speed showed the existence of vortices in the flame.

Numerical calculations are effective to analyse the flame behavior invading into the upper room and the spread of fire upstairs.

REFERENCES

1)Whitaker, E.H.:"The Sao Paulo Fire", Fire, Vol.64, No.803, 565 (1972)

2)"Report of Hotel New Japan Fire (in Japanese)", Bulletin of Japanese Association of Fire Science and Engineering, Vol.32, No.3, 22 (1982)

3)Klem, T.J.:"Fire Investigation Report - First Interstate Bank Building Fire Los Angeles, California", Fire Investigation Division of National Fire Protection Association, U.S.A. (1988)

4)Yokoi, S.:"Study on the Prevention of Fire-Spread Caused by Hot Upward Current", Building Research Institute of Japan, (1960)

5)Yokoi, S.:"Trajectory of Hot Gas Ejected from a Window of a Burning Concrete Building", Journal of Japanese Association of Fire Science and Engineering, Vol.8, No.1, 1 (1958)

6)Oguni, K. et al.:"Real Scale Fire Experiment of Fire Resitive Apartment House ", Proceedings of 1983 Annual Fire Conference of Japan, p.55 (1983)

7)Hayashi, K. et al.:"Experimental Study of Upward Fire Propagation from an Opening of Fire Room (in Japanese)", Report of Fire Research Institute of Japan, No.57, 49 (1984)

8)Satoh, K. :"Three-Dimensional Numerical Study of Fire-Induced Ventilations in Enclosures", Report of Fire Research Institute of Japan, No.59, 45 (1985)

9)Satoh, K.:"Experimental and Finite-Difference Study of Dynamic Fire Behavior in a Cubic Enclosure with a Dooray", ibid., No.55, 17 (1983)

10)Satoh, K. :"Three-Dimensional Field Model Analysis of Fire-Induced Flow in an Enclosure with a Doorway Opening", ibid., No.60, 53 (1985)

11)Satoh, K. :"Three-Dimensional Numerical Study of Buoyant Convective Flow in a Tunnel-Shaped Enclosure", ibid., No.60, 65 (1985)

12)Satoh, K. :"Oscillatory Behavior of Fire Flow Burning on Building Walls", ibid., No.67, 45 (1989)

13)Yang, K.T., Lloyd, J.R., Kanury A.M. and Satoh, K.:"Modeling of Turbulent Buoyant Flows in Aircraft Cabins", Combustion Science and Technology, Vol.39, 107 (1984)

14)Patankar, S.V. and Spalding, D.B.:"A Calculation Procedure for Heat, Mass and Momentum Transfer in Three-dimensional Parabolic Flow", International Jounal of Heat anmd Mass Flow, Vol.15, 1787 (1972)

15)Satoh, K.:"A Numerical Study of Dynamic Fire Behavior", JSME International Journal (Series B), Vol.31, No.3, 402 (1988)

16)Satoh, K. :"A Numerical Study of Ceiling Jets Based on "T" Pattern Flames", Proceedings of the 2nd International Symposium on Fire Safety Science, Tokyo, Hemisphere Publishing Corporation, p.159 (1988)

17)Ku, A.C., Doria, M.L. and Lloyd, J.R.:"Numerical Modeling of Unsteady Buoyant Flows Generated by Fire in a Corridor", Proceedings of 16th International Symposium on Combustion, Combustion Institute, p.1373 (1976)

18)Oleszkiewicz, I.:"Experimental Studies of Fire Spread along Building Facades", Proceedings of 20th Fall Meeting of Eastern Section Combustion Institute at NBS, paper No.99 (1987)

STUDY ON COMBUSTION PROPERTY OF CRUDE OIL
- A JOINT STUDY BETWEEN NIST/CFR AND FRI -

Hiroshi Koseki
Fire Research Institute, Mitaka, Tokyo, 181 Japan

G.W. Mulholland
National Institute of Standards and Technology
Center for Fire Research, Gaithersburg MD, 20899 USA

and Tadahisa Jin
Fire Research Institute, Mitaka, Tokyo, 181 Japan

ABSTRACT

In order to understand the combustion properties of crude oil pool fires, an experimental study was done in Fire Research Institute(FRI) large scale test facility. The radiative output, burning rate, and the concentrations of CO, CO_2, and smoke (above the flame tip) were measured during the burning of Arabian light crude oil. Several different size tanks were used to study the scale effect.
Crude oil burned less rapidly and gave off less thermal radiation compared with heptane, but when water boiling occurred the burning rate and thermal radiation increased by a factor of two or more. Water boiling is a kind of boilover phenomenon and which intensity is most related with tank size and fuel layer thickness.

INTRODUCTION

Because of the wide abundance of crude oil in various storage facilities, it is important to study crude oil burning concerning fire safety. The smoke emission from the burning of crude oil has become a subject of concern in regard to the proposed burning of certain crude oil spills. While it is recognized that the burning of crude oil is a serious safety issue, regarding huge smoke emission and boilover phenomenon, there has been relatively little research on this topic[1,2,3,4]. Therefore a joint study between Center for Fire Research(CFR) of National Institute of Standards and Technology (NIST) and Fire Research Institute(FRI) was performed in the FRI large scale test facility. This paper introduces this US-Japan joint study briefly.

EXPERIMENTAL

In Figure 1, a schematic of the experimental setup is shown. Tanks were placed at the center of the test facility which is 24m × 24m and 20m high. Wind effects were small compared to outdoor tests, but still there were effects from the outside wind for some of the tests.
We burned Arabian light crude oil in 0.6m, 1m and 2m diameter circular pans and in 2.7m square pan. We measured burning rate, external radiation, smoke

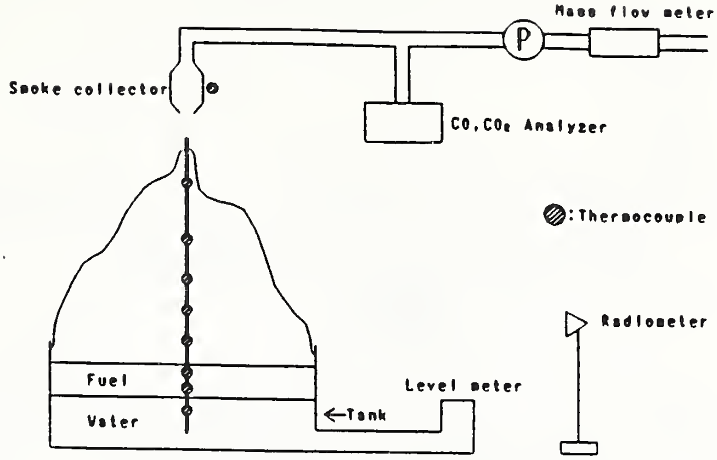


Figure 1 Schematic diagram of the apparatus

emission, concentrations of CO and CO_2 above the flame tip. Near the end of the combustion process, water boiling and splashing was observed. We call this phenomenon "thin layer boilover" to distinguish the boiling effects in our test from the hot zone boilover discussed by Hasegawa[1].

Burning rate was measured with a float-type level meter connected with the piping of the tank. So the burning rate was represented as fuel level regression rate. When thin layer boilover occurred, splashing water to outside of tank gave errors in the calculation of burning rate, but we obtained net value by canceling this effect from the water level difference during the experiment.

Radiation from the entire flame to surroundings was measured by three thermopile-type radiometers which cover a wide angle. They were oriented toward the flame axis and located at L/D=3 and L/D=5 where D is the tank diameter and L is the radial distance from the tank center to the radiometer. Smoke, CO and CO_2 were collected above the flame tip. The gas flowed through a cold trap and flow meter before entering the CO, CO_2 analyzer.

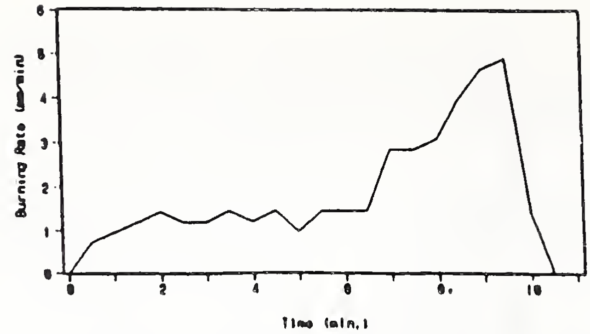
The temperatures inside and near the flame and in the fuel and water were measured using 0.3 mm diameter Chromel-Alumel thermocouples sheathed with a 1.6 mm diameter stainless steel tube. Two thermocouples were embedded in the fuel and one was in the water. Each thermocouple bead was placed along the centerline of the pan. The outputs of these sensors were corrected of error by radiation, and recorded on a pen-type recorder and/or digital data acquisition system.

RESULTS AND DISCUSSION

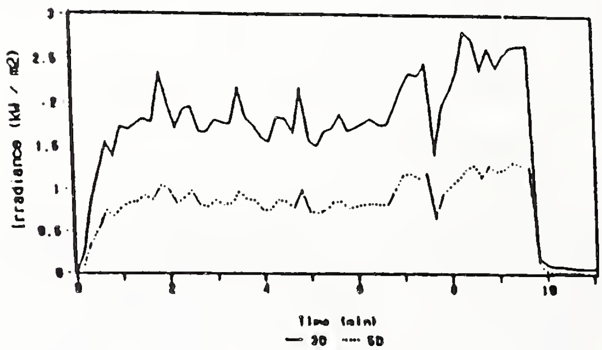
Burning rate

Figure 2(a) shows the time history of a 0.6m tank fire. About one minute after ignition, the burning rate is in quasi-steady state. In the later period it increased to about four times as much as that of steady state condition due to thin layer boilover.

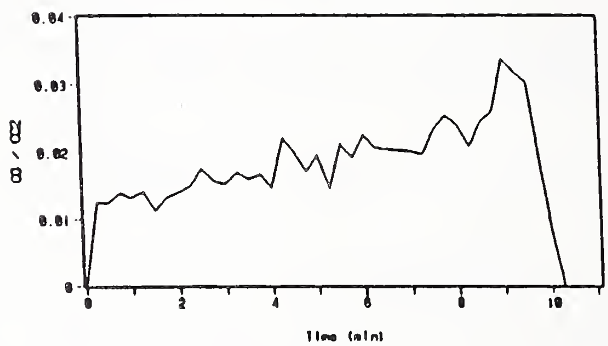
Figure 3 shows the relationship between burning rate and tank diameter, D. With a square tank, D was calculated with the equation; $D=(4/\pi)^{1/2}\cdot W$. Here W is the length of one side. For reference, Mulholland et al.'s small scall tests data[5] and others large scale tests data[6,7,8] are shown. These data were obtained by several different investigators, but gave almost one



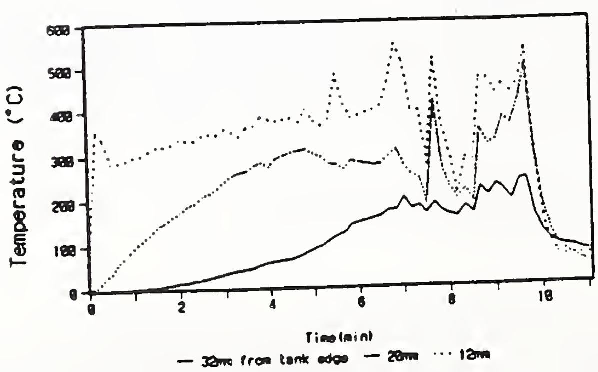
(a) Burning rate



(b) Irradiance at L/D=3 and L/D=5



(c) CO/CO_2



(d) Temperature in the fuel and water

Figure 2 An example of time history
(0.6 m crude oil fire)

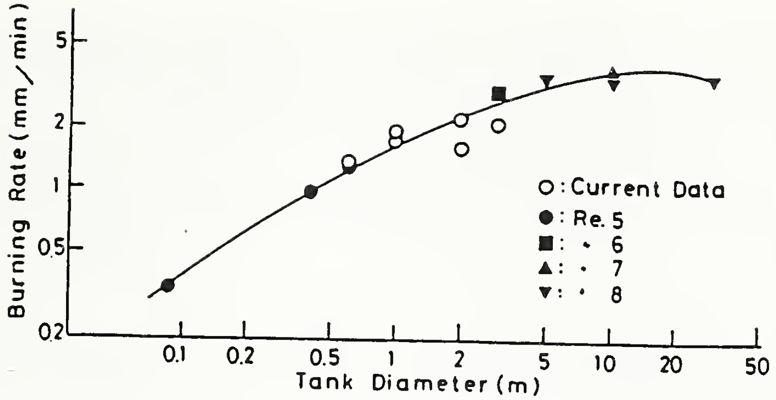


Figure 3 Relationship between burning rate and tank diameter

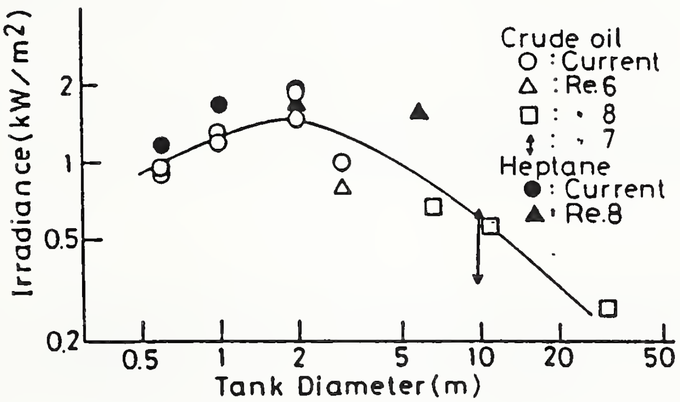


Figure 4 Relationship between radiative output and tank diameter

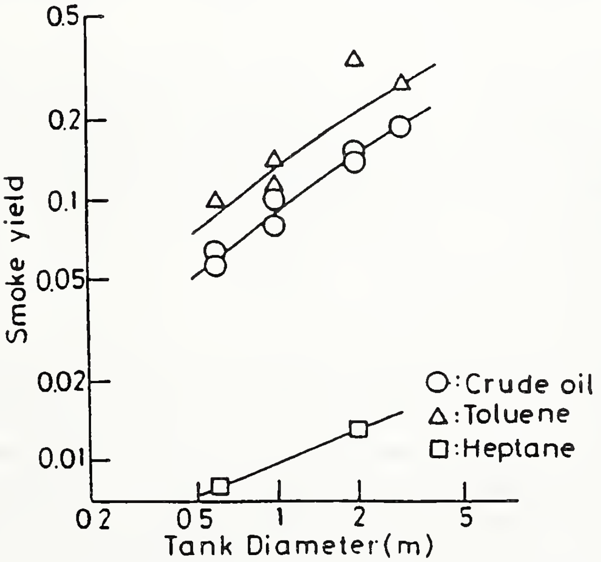


Figure 5 Relationship between smoke yield and tank diameter

line. In these size tanks, the burning rate increased with increasing tank size up to maximum at about 10-20 m in diameter.

Radiative outputs

Figure 2(b) shows the time history of radiative outputs at L/D=3 and 5 in the same test of Figure 2(a). When thin layer boilover occurred, radiative outputs also increased, but not as much as the burning rate.

Figure 4 shows the relationship between radiative output at L/D=5 and the tank diameter. For reference, some others data[6,7,8,9] are shown including heptane data. While the burning rate is constant for tank diameter greater than 2m, it appears that the radiation decreases for tank diameter greater than 2m. This indicates smoke blockage effect on external radiation is large but smoke blockage on internal radiation is small in crude oil and heptane flame. Radiation from heptane fire is larger than that of crude oil in any size tanks, and does not decrease as rapidly as does the radiation from the crude oil fires at large scale.

Radiative fraction

Radiative fraction, X, is represented as:

$$X \equiv Q_{rad} / Q_{tot}$$

Here, Q^{o}_{ad} is the total radiative power output. Assuming isotropy it is simply the flux times the spherical surface area:

$$Q_{rad} = 4\pi L^2 q$$

where q is the irradiance measured by the radiometer at L/D=5. Q_{tot} is the net calorific potential of the flame assuming complete combustion.

In steady state burning, X is about 0.3-0.4, but when thin layer boiling occured it went down to about 0.2. This change is large compared to measurement errors associated with the splashing of the water. The reason for the decrease in the radiative fraction is a slight reduction in the temperature caused by the water vapor, which has a high specific heat.

Smoke emission

Smoke was collected above the flame tip. At this height the averaged temperature was about 100℃. A useful measure of smoke emission used by Mulholland et al.[5] is smoke yield, ε, which is defined as the mass of smoke aerosol generated per mass of fuel consumed. We calculated the smoke yield, ε, by the carbon balance method:

$$\varepsilon = Y_s \cdot F_c$$

Here Y_s is the carbon mass in the smoke aerosol, as a fraction of the carbon mass in the total combustion products (CO_2, CO and smoke aerosols) and F_c is the mass fraction of carbon in the fuel, measured as 0.838 by elemental analysis. Figure 5 shows the relationship between smoke yield, ε, and tank diameter. Mulholland et al's data[5] shows ε of the large scale fire are similar to the small scale one, but the results indicates that the larger the tank is, the larger smoke yield is. Future testing is needed to verify this difference. We also have found the difference with Bard et al data[10]. They proposed the volume fraction method in the flame, which is larger than our current and previous data[5]. Their data is larger than us, because they ignored some soot oxidation occurs in the upper portion of the flame. Still intermittent region of the flame, oxidation reaction has continued. We also collected smoke for observation with a transmission electron microscope(TEM). TEM photographs gave similar value in size distribution to Evans et al.[2].

Concentration of CO and CO_2 above the flame tip

The CO and CO_2 were collected along with the smoke just above the flame tip. The concentration of CO_2 was about 0.3%-0.5 %, and that of CO was about 50-500 ppm. Figure 2(c) shows the time history of the ratio of CO and CO_2 concentrations. When thin layer boilover occurred, this ratio possibly due to the flame quenching on the probe. The ratio of CO/CO_2 is a measure of combustion efficiency.

Figure 6 shows the relationship between the ratio of CO/CO_2 and tank diameter. Data is limited but it indicates that the ratio increased with tank diameter. So the combustion efficiency decreased with increasing tank size as shown by an increase in smoke and CO. In 1m diameter crude oil tank fire, it was about 90 %, and it decreased to 75 % in 2.7 square tank fire.

Temperature in the liquid

Figure 2(d) shows time history of temperature in the fuel and water. In 0.6m tank fire, initial free board was 1 cm, and the fuel level decreased after ignition. The upper thermocouple was just above the fuel surface, and it recorded the initially, rapidly increasing gas temperature just above the fuel. When the thin layer boilover occurred, the temperature at this point fluctuated by a sizable amount as the boiling water/oil contacted the thermocouple.

Thin layer boilover phenomenon

Water boilover was found to occur near the end of the combustion process, and a considerable amount of oil spilled over the rim of the test tank. The burning rate and radiative output increased when the boiling occurred. The magnitude of the boiling effects, Ψ, was defined as:

$$\Psi \equiv V_{bo} / V_{st}$$

V_{st} means the burning rate in steady state condition, and V_{bo} means the maximum burning rate in boiling occurred.

Figure 7 shows the relationship between Ψ and tank diameter. According to Evans et al.[2], fuel thickness is an important factor in regard to the boiling effect, so here in every test we set it at 2cm in first series. The boiling effect, Ψ, decreased with increasing tank size. We did not observe a significant boiling effect in the largest test. According to Arai et al.[3], boiling occurs for fuels with boiling point temperature higher than that of water. To test their results, we burned kerosene(bp: about 150-300℃), toluene(bp: 111℃) in the same condition with crude oil(tank diameter: 1m, fuel thickness: 2cm). Figure 8 shows the time history of burning rate in kerosene and toluene 1m diameter tank fires. We did not observe boiling phenomenon for these fuels. This indicates that the cause of the boiling effect is not simply controlled by the boiling temperature of the fuel. Not only boiling point of fuel, we believe that a second condition necessary for boilover is that the steady state burning rate, v_{st}, should be less than the hot zone regression rate, v_{hz} sufficiently because of lip effect. We varied the fuel thickness in the various size tank fire to determine the influence of fuel layer thickness on the intensity of thin layer boilover. Figure 9 shows the relationship between Ψ and fuel thickness. The thicker fuel

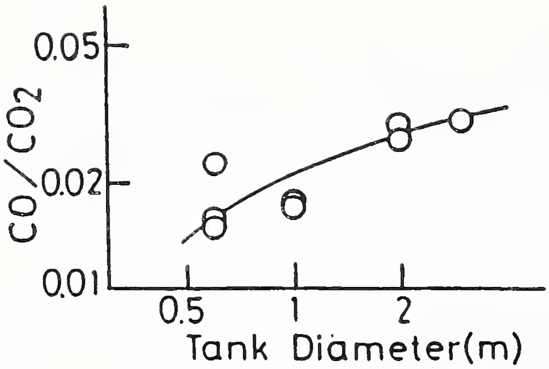


Figure 6 Relationship between CO/CO_2 and tank diameter

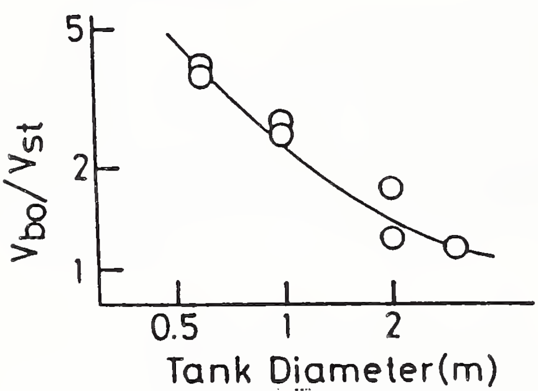
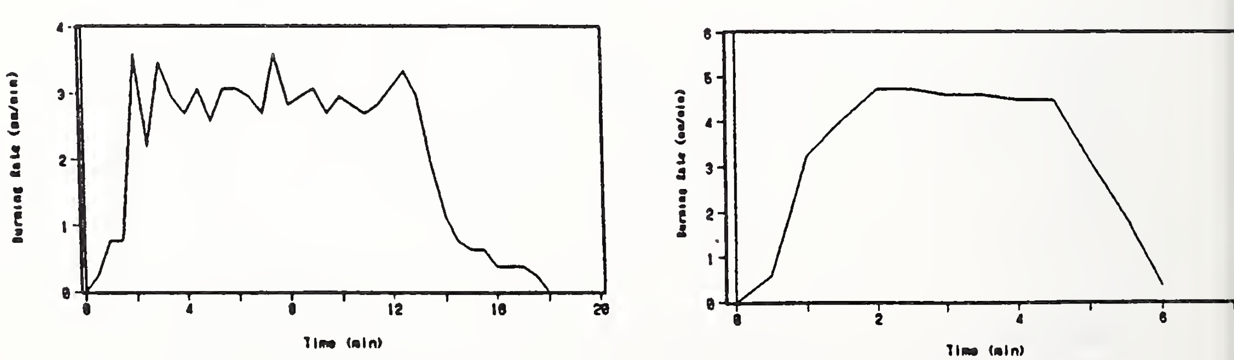


Figure 7 Relationship between V_{st}/V_{bo} and tank diameter



(a) kerosene (b) toluene

Figure 8 Time history of burning rate

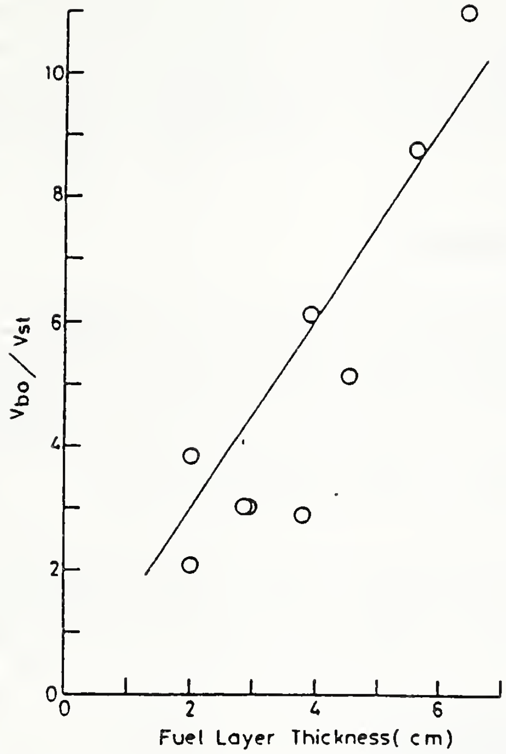


Figure 9 Relationship between V_{bo}/V_{st} and fuel thickness

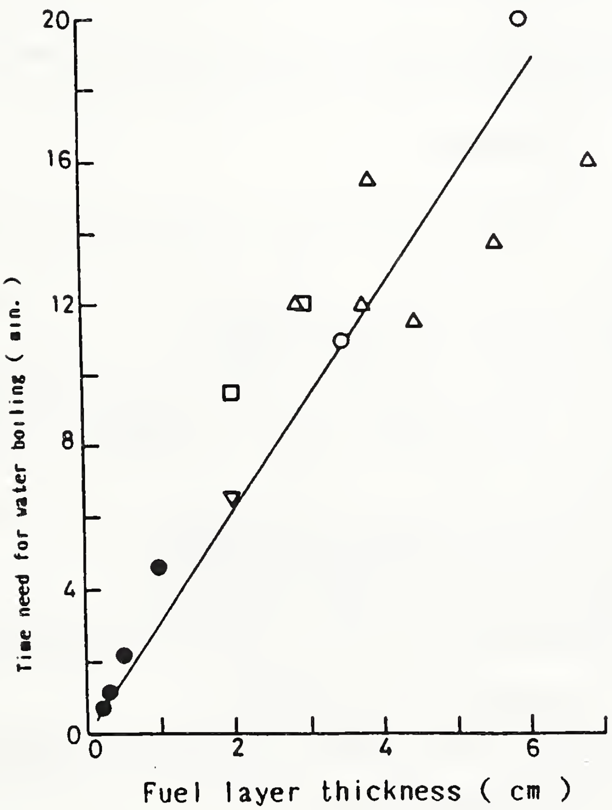


Figure 10 Relationship between time to occur thin layer boilover and fuel thinkness

○:0.3m diameter tank △:0.6m diameter tank
□:1m diameter tank ▽:2m diameter tank
●:Reference[2]

layer is, the more violent thin layer boilover is. Figure 10 shows the relationship between boilover time and initial fuel thickness. The thicker the fuel layer is, the longer the time for the hot zone to reach the water layer, and at the same time, the thicker the hot zone has grown. The hot zone model for "real boilover" developed by Hasegawa[1] maybe helpful in modeling this process, and Saito[11] simple model can not be applied in this phenomenon. Following Hasegawa, we obtained $v_{hz} \fallingdotseq 3.1$(mm/min) in the range of our experiment. Therefore, when burning rate is much larger than 3.1mm/min, boilover should not be occurred.

CONCLUSIONS

1 In steady state condition, burning rate and radiation in crude oil fire are less for crude oil than for heptane. The burning rate increases with tank size up to about 3m at which point the burning rate is independent of tank size. The thermal radiation at a position of five pool diameters from the center of the pool increases for increasing tank size up to 2m and then decreases for larger tanks due to smoke blockage effect.

2 In the end of combustion process, water boiling occurred for crude oil. Burning rate and radiative output increased, but in larger tanks, a boiling effect was not observed. In thick crude oil layer tank fire, we found intensity of thin layer boilover is stronger and changes to " real boilover".

ACKNOWLEDMENTS

The authors acknowledge Mr.Miyazaki of FRI for helping the test. The work was partially funded by the Science and Technology Agency of Japan.

REFERENCES

1 Hasegawa,K., Proceedings of the Second International Symposium on Fire Safety Science p.221(1988).
2 Evans,D., Mulholland,G., Gross,D. and Baum,H., Proceedings of the tenth arctic marine oil spill program technical seminar(1987).
3 Arai,M., Saito,K., Altenkirch,R.A.,"Experimental Study of the Boilover Phenomenon for Liquid Fuels on a Water Sublayer", University of Kentucky.
4 Brzustowski,T.A. and Twardus,E.M., 19th Symp. Inter. on Combustion Combustion Institute P.847(1982).
5 Mulholland,G.W., Henzel,V. and Babrauskas,V., Proceedings of the Second International Symposium on Fire Safety Science p.347(1988).
6 Yumoto,T., Fire Research Institute Report No.33, p.23(1971).
7 Fire Research Institute, Technical Report of FRI No.8(1975).
8 Japan Society of Safety Engineering,"Report of Oil Tank Fire Experiment" (1979).
9 Koseki,H. and Yumoto,T., Fire Technology 24(1)p.33(1988)
10 Bard S. and Pagni,P.J. Proceedings of the First International Symposium on Fire Safety Science p.361(1985).
11 Saito,K., Combustion Science and Technology (in press)

FIRE AND SMOKE PHYSICS SESSION

Review of Progress in the Fire and Smoke Physics Area

EDWARD E. ZUKOSKI
California Institute of Technology
Pasadena, California 91125

A brief review of recent literature concerned with fire and smoke physics is given here for the period 1987 to 1989.

1. SCALING TECHNIQUES

Because of the great expense involved with full scale testing, the use of small scale test apparatus has intrigued most experimentalists involved with all types of fire tests and the development of standard tests. Unfortunately most subscaled tests have not proved to be convincingly useful because all scaling parameters can not be held constant simultaneously.

Quintiere addresses the general scaling problem and bases scaling laws on dimensionless parameters which he developes from the governing differential equations. He applies his results to a wide range of small scale tests under conditions for which many of the scaling parameters can be ignored and shows that satisfactory correlations can be obtained between small and large scale tests.

2. PROPERTIES OF SMOKE

CORROSION: The presence in smoke of trace species such as hydrochloric acid can produce corrosion in a wide variety of materials and on diverse surfaces which are exposed to the smoke, and the corrosive effects can cause considerable financial loss even though no serious thermal effects are present. Two examples are: smoke damage to computing equipment in the First Interstate Bank was a serious problem in areas which were 45 floors above the fire floor; and the Navy has developed a serious interest in the corrosion problem because of damage to computing equipment produced by smoke from fires involving cable insulation.

Papers by Hirschler and Smith, Galloway and Hirschler, and O'Neill discuss various aspects of the corrosion problem including the rate of transport and condensation of corrosive materials, and the rate of attack of these gases on various surfaces. Particular emphasis was placed on HCl formed from the combustion of halogenated materials. O'Neill was concerned that discriminatory standards might be developed to prevent some of these problems and that these standards would adversely effect the plastics industry.

A recent conference on this subject, (Corrosive Effects of Combustion Products, 13-14

October 1987, London), was organized by the Fire and Materials Center, QMC, in association with ISO, IEC, ASTM, and BSI.

COMPOSITION OF SMOKE: A number of recent papers have delt with the smoke or the products of combustion produced by fires burning in a variety of ambient conditions and with a wide range of fuels. These include literature surveys on the combustion products of polystyrenes by Gurman et al, and on polyvinal chloride by Huggett and Levin. The effects of various properties of the atmosphere which surrounds the fire on species production rates are discussed by Morikawa, Nakaya, Zhubanov and Gibov, McIlhagger et al, and Trzeszcynski et al.

Babrauskas has used the cone calorimeter to study the properties of smoke produced by combustion of fire-retarded plastics in the presence of external irradiance. Substantial effects on species production were observed as conventional fire retradants were added, and large differences in production rates of soot and species were observed for cable coverings which met the same military specifications. McIlhagger et al present interesting information on the effects of the oxygen mass fraction of the ambient atmosphere on the particle size of the soot produced in polystyrene fires in a small apparatus. Other papers on the properties of soot include several concerning experimental studies of the optical Habib and Vervisch, and by Charalampopoulos and Chang.

3. MODELING SMOKE MOVEMENT

CORRIDOR FLOWS: Gravity currents produced in corridors by hot gas supplied by a fire have been modeled with an $\epsilon - k$ field method by van de Leur et al which used the original constants proposed by Launder and Spalding. Buoyancy terms are included in the calculations and their effect is modeled with a Richardson number correlation based on the local values for the current depth and average velocity. Heat transfer between the current and the ceiling of the corridor are included is a dominant effect. Another paper by Liew et al describes in less detail computations with an $\epsilon - k$ model for a similar corridor like geometry. The results agree qualitatively with the experimental results of Chobotov and Zukoski. Both results emphasize the extreme importance of heat transfer between the hot gas current and the corridor ceiling in modeling these flows.

These papers clearly show the importance of heat transfer in corridor or tunnel flows. No one has yet explored the implications of this result in describing the development of the hot layer within the corridor subsequent to the arrival of the hot gas current at a closed end of corridor. Because of the large horizontal temperature gradient in the corridor, produced by heat transfer to the ceiling, the hot gas layer which develops later will certainly contain a large vertical temperature gradient. The presence of this gradient may make difficult or impossible the application of the usual two-layer zone model to flows in corridors.

4. PLUME MODELING

FIRE PLUMES: Continued interest in the structure of large buoyancy controlled diffusion flames has resulted in a number of papers. One of these by Hasemi attempts to correlate a number of the properties of the flow in the flame. He shows that correlations for the properties of large buoyant diffusion flames change as the heat release for a given diameter increases. These results emphasize that comparisons of data must be correlated with a Q^* like parameter and that data with different Q^* values should not be included in the same correlation.

Heskestad and Delichatsios have reexamined a large body of entrainment data for the flaming region using quite different approaches, and have suggested two correlations for entrainment into the flame. The Heskestad does make use of the Q^* dependence discussed above in developing his correlations.

A paper by Fisher et al concerns an experimental investigation of the distribution of soot within an ethanol pool fire and the radiant properties of the flame. Since up to 40% of the chemical energy released in these large flames is immediately radiated away, this is a key process. Heat release rates in the 10 to 40 KW range were studied.

Adiga et al use an $\epsilon - k$ numerical code to model pool-like gas flames of propane and show that the inclusion of radiant heat transfer has a large effect on their results.

Gross has measured the lengths of flames which impinge on a solid ceiling in the absence of side wall effects and in a corner geometry. He used large heat release rates, 100 to 400 KW, and fires generated by gas burners with diameters up to 0.54 m and wood cribs.

WALL PLUMES: Cooper, and Jaluira and Kapoor discuss the importance of natural convective flows arising on vertical surfaces during the early stages of a room fire and show that interactions of these currents with the interface between the hot and cold layer can cause considerable transport of gas between the layers.

5. COMPARTMENT FIRE MODELS

A number of papers concern the applications of various models for the prediction of the development of layers in the two-layer models for a single room. The room filling problem is discussed by Bengston and also by Fusegi and Farouk who considered very large spaces. Hinkley (1988), and Fusegi and Farouk show that the influence of radiant heat transfer must be considered in room filling models. Finally, Hinkley (1989) describes the results of the application of a zone model to the effect of smoke venting on the operation of arrays of sprinklers. A large number of examples are calculated and several are compared with experiments. A paper by Jamaluddin and Smith discusses the general problem of radiant heat transfer in a rectangular compartment and the application of the discrete ordinates method.

Keski-Rahkonen have developed a model to explain how windows break during a fire. Including a rational description of window breaking in models of fires in compartments when closed windows are initially present will be an important step.

6. REFERENCES

Adiga, K. C., Ramaker, D. E., Tatem, P. A. and Williams, F. W. (1989) "Modeling Pool-like Gas Flames of Propane," *Fire Safety Journal*, Vol. 14, pp. 241–250.

Babrauskas, Vytenis (1989) "Smoke and Gas Evolution Rate Measurements on Fire-retarded Plastics with the Cone Calorimeter," *Fire Safety Journal*, pp. 135–142.

Bengtson, S. (1988) "Reducing Risk," *Fire and Materials*, Interflam '88, 4th International Fire Conference, pp. 172–178.

Charalampopoulos, T. T. and Chang, H. (1988) "*In Situ* Optical Properties of Soot Particles in the Wavelength Range from 340 nm to 600 nm," *Combust. Sci. and Tech.*, Vol. 59, pp. 401–421.

Chobotov, M. V. (1987) "Gravity Currents with Heat Transfer Effects," Ph.D. Thesis, California Institute of Technology.

Cooper, L. Y. (1988) "Ceiling Jet-Driven Wall Flames in Compartment Fires," *Combust. Sci. and Tech.*, Vol. 62, pp. 285–296.

Delichatsios, M. A. (1987) "Air Entrainment into Buoyant Jet Flames and Pool Fires," *Combustion and Flame*, Vol. 70, pp. 33–46.

Fischer, S. J., Hardouin-Duparc, B. and Grosshandler, W. L. (1987) "The Structure and Radiation of an Ethanol Pool Fire," *Combustion and Flame*, Vol. 70, pp. 291–306.

Fusegi, Toru and Farouk, Bakhtier (1988) "Numerical Study on Interactions of Turbulent Convection and Radiation in Compartment Fires," *Fire Science & Technology.*, Vol. 8, No. 1, pp. 15–28.

Galloway, F. M. and Hirschler, M. M. (1989) "A Model for the Spontaneous Removal of Airborne Hydrogen Chloride by Common Surfaces," *Fire Safety Journal*, Vol. 14, pp.251–268.

Gandhi, P. D. and Kanury, A. M. (1988) "Thresholds for Spontaneous Ignition of Organic Solids Exposed to Radiant Heating," *Combust. Sci. and Tech.*, Vol. 57, pp. 113– 128.

Gross, Daniel "Measurement of Flame Lengths under Ceilings," *Fire Safety Journal*, Vol. 15, pp. 31–44.

Gurman, Joshua L., Baier, Laura and Levin, Barbara C. (1987) "Polystyrenes: A Review of the Literature on the Products of Thermal Decomposition and Toxicity," *Fire and Materials*, Vol. 11, No. 3.

Heskestad, Gunnar (1986) "Fire Plume Air Entrainment According to Two Competing Assumptions," Twenty-first Symposium (International) on Combustion/The Combustion Institute, pp. 111–120.

Huggett, Clayton and Levin, Barbara C. (1987) "Toxicity of the Pyrolysis and Combustion Products of Poly (Vinyl Chlorides): A Literature Assessment," *Fire and Materials*, Vol. 17, No. 3.

Habib, Z. G. and Vervisch, P. (1988) "On the Refractive Index of Soot at Flame Temperature," *Combust. Sci. and Tech.*, Vol. 59, pp. 261–274.

Hasemi, Y. (1988) "Deterministic Properties of Turbulent Flames and Implications for Fire Growth," *Fire and Materials*, Interflam '88, 4th International Fire Conference, pp. 45–52.

Hinkley, P. L. (1988) "Comparison of an Established Method of Calculation of Smoke Filling of Large Scale Spaces with Recent Experiments," *Fire Science & Technology.*, Vol. 8, No. 1, pp. 1–8.

Hinkley, P. L. (1989) "The Effect of Smoke Venting on the Operation of Sprinklers Subsequent to the First," *Fire Safety Journal*, Vol. 14, pp. 221–240.

Hirschler, M. M. and Smith G. F. (1989) "Corrosive Effects of Smoke on Metal Surfaces," *Fire Safety Journal*, Vol. 15, pp. 57–93.

Jaluria, Yogesh and Kapoor, Kamlesh (1988) "Importance of Wall Flows at the Early Stages of Fire Growth in the Mathematical Modeling of Enclosure Fires," *Combust. Sci. and Tech.*, Vol. 59, pp. 355–369.

Jamaluddin, A. S. and Smith, P. J. (1988) "Predicting Radiative Transfer in Rectangular Enclosures Using the Discrete Ordinates Method," *Combust. Sci. and Tech.*, Vol. 59, pp. 321–340.

Kashiwagi, T., Ohlemiller, T. J. and Werner, K. (1987) "Effects of External Radiant Flux and Ambient Oxygen Concentration on Nonflaming Gasification Rates and Evolved Products of White Pine," *Combustion and Flame*, Vol. 69, pp. 331-345.

Keski-Rahkonen, Olavi (1988) "Breaking of Window Glass Close to Fire," *Fire and Materials*, Vol. 12, No. 2.

Liew, S. K., Hall R. C. and Deaves, D. M. (1988) "Smoke Control — Problems and Solutions," *Fire and Materials*, Interflam '88, 4th International Fire Conference, pp. 164–171.

McIlhagger, R., Hill, B. J. and Brown, A. J. (1988) "Effect of Environmental Conditions on Smoke Propagation," *Fire and Materials*, Vol. 12, No. 1.

Morikawa, Tokio (1988) "Evolution of Toxic Gases from Burning Polymeric Materials in a Small-scale Box Model," *Fire and Materials*, Vol. 12, No. 2.

Nakaya, Ichiroh (1987) "Prediction Model of CO, CO_2 and O_2 Concentrations in Compartment Fires Using Wood Fuel," *Fire and Materials*, Vol. 11, No. 4.

O'Neill, T. J. (1989) "Assessing the Corrosion Risk of Plastics in Fires," *Fire Safety Journal*, Vol. 15, pp. 45–56.

Quintiere, J. G. (1989) "Scaling Applications in Fire Research," *Fire Safety Journal*, Vol. 15, pp.3–29.

Trzeszczyński, Jerzy, Włodarczak, Daniela and Bójko, Teresa (1987) "The Influence of Pressure on Combustible and Toxic Properties of Materials," *Fire and Materials*, Vol. 11, No. 3.

Van De Leur, P. H. E., Kleijn, C. R. and Hoogendoorn, C. J. (1989) "Numerical Study of the Stratified Smoke Flow in a Corridor: Full-scale Calculations," *Fire Safety Journal*, Vol. 14, pp. 287–302.

Zhubanov, T. B. and Gibov, K. M. (1988) "Oxygen Index and Minimum Limiting Rates of Polymer Combustion," *Fire and Materials*, Vol. 12, No. 4.

Zukoski, E. E. (1987) "Heat Transfer in Unwanted Fires," Proceedings of the ASME-JSME Thermal Engineering Joint Conference, Hawaii, Vol. 1,

PROGRESS REPORT ON FIRE AND SMOKE PHYSICS IN JAPAN

Yuji Hasemi
Building Research Institute

A short review on progress in fire and smoke physics after the last UJNR meeting is given. However, since considerable part of the progress will be reported by the authors of original papers, the review will introduce mostly studies which will not be presented at this meeting. Following journals and preprints are reviewed for this purpose.

a)Proceedings of the Annual Meeting of the Architectural Institute of Japan(AIJ), 1989.

b)Proceedings of the Annual Meeting of the Japanese Association for Fire Science and Engineering, 1989.

c)Proceedings of the 26th Combustion Symposium, 1988.

Diffusion Flames

Extensive studies have been made on the modeling of such engineering properties of turbulent diffusion flames as extinction limit, radiation and flame height.

Tatsuta and Ito investigated into the influence of water addition on the behavior and extinction limit of methanol fires by experiments. They found considerable decrease of heat release rate due to water addition with extinction at water concentration=90%, and attributed this reduction to the combustion heat to latent heat ratio. They suggest that suppression of alcohol fires by water should be made with cold water while the fuel temperature is still low.

Hayasaka and Koseki proposed an engineering calculation method of properties of diffusion flames from tank fires. The model is based on the heat balance around the flame, and includes a radiation model with the concept of the mean beam length. Calculation on fires from large tanks shows good agreement with previous experiments.

Nohara, Hasemi and Nishihata reported flame height correlations for low Q^* region ($Q^*<0.1$)using hydrocarbon-hydrogen mixtures as the fuel. They found that flame height for a given Q^* is larger for propane than for methane. It is also found that propane-hydrogen mixture generates larger flame than methane -hydrogen mixture of the same equivalent molecular weight. These results are unexpected from theories on which Q^* or Froude number analysis depends.

Flame Spread

Typical problems of flame spread along combustible surfaces in fire safety may relate to upward horizontal surface, liquid fuel or ground soaked with liquid fuel, or vertical or downward surface in building fires. This report will mention only on the former situation.

Masuda and Ito reported observations of "pulsating flame propagation" along alcoholic fuels. From careful observation of aluminum powders, they attributed this characteristic phenomenon to the alternate appearence of flame spread governed by the convection beneath the fuel surface and that caused by the combustible gas mixture formed intermittently beyond the flame.

Ishida reported a model experiment on the effectiveness of a vertical barrier for the suppression of flame spread along ground soaked with liquid fuels. The barrier height to the height of flammable mixture layer ratio is found to be the dominant factor on this effectiveness.

Takeno and Hirano reported experiments and analysis on the flame spread along the surface of solid-liquid mixtures. This study seems to be enforcement of their previous works on flame spread along glass beads soaked with liquid fuels: in its analysis they have pointed out the significance of the size of beads, and have shown that flame spread for large beads is governed by the convection in the liquid phase.

Field Models

Development of large capacity computers during the last decade has made the field modeling possible to serve for engineering purposes in fire safety problems. Considerable part of the recent works in the field modeling are related to the application of the models to specific problems or modification of models for engineering purposes.

Morita and Hirota examined the economy of computer time by the use of irregular cells, and found that computer time can be reduced to approximately 1/4 the case using square cells without significant difference in the calculation result.

Satoh, Miyazaki and Kawasaki reported calculation of air movement in a tunnel fire. They compared the result with experiments, and found that the models of turbulence still need modification for such strongly turbulent and high temperature environment.

[REFERENCES]

Ishida, H.: Influence of barrier on the flame spread on the ground, (c).
Masuda, D., and Ito, A.: On the flame spread on liquid fuels, Part2, mechanism of

pulsating flame spread, (c).

Morita, M., and Hirota, M.: Numerical calculation of hot gas movement using irregular size and shape cells, (b).

Nohara, M., Hasemi, Y., and Nishihata, M.: Influence of fuel composition on the properties of turbulent diffusion flames in low Q^* region, (b).

Satoh, K., Miyazaki, S. and Kawasaki, M.: Numerical calculation of hot gas movement caused by liquid fire in a tunnel, (b).

Takeno, K., and Hirano, T.: Influence of liquid properties on the flame spread along the surface of solid-liquid mixture, (c).

Tatsuta, S., and Ito, K.: Influence of water addition on the burning behavior of methanol, (c).

Hayasaka, H., and Koseki, H.: Studies on the combustion and radiative heat transfer in tank fires, (c).

UNSTEADY-STATE UPWARD FLAME SPREADING VELOCITY ALONG VERTICAL COMBUSTIBLE SOLID AND INFLUENCE OF EXTERNAL RADIATION ON THE FLAME SPREADING VELOCITY

Yuji Hasemi and Masashi Yoshida
Building Research Institute

Akinori Nohara
Faculty of Science and Technology
Science University of Tokyo

1. INTRODUCTION

Upward flame spread along a vertical combustible solid is a typical process leading to hazardous growth of an enclosure fire. In previous papers[1,2], one of the authors(Y.H.) has proposed an engineering model of steady-state upward flame spread based on the concept of ignition and flame spread as a result of inert heating of the solid to an ignition temperature. However, while the steady-state flame spreading velocity may be useful as a practical measure to evaluate firesafety performance of lining materials, the concept of steady-state flame spread is still somewhat unusual, since the nature of upward flame spread in unwanted fires is essentially transient. In This paper, an unsteady-state solution of spontaneous upward flame spread is obtained on the basis of the experimental relationship on the heating of the unburnt surface by the flame[1].

In actual fires, it should be also noted that flame spread along a wall tends to start after it has been preheated from fire source etc. In full scale fire experiments, flame spreading velocity along a vertical solid becomes often several times the spontaneous flame spreading velocity. In this paper, measurements of flame spreading velocity are made on vertical PMMA slabs under different levels of external radiation from radiant panels. Exploratory analysis is made to correlate flame spreading velocity and conditions of external radiation.

2. AN UNSTEADY-STATE SOLUTION OF UPWARD FLAME SPREADING VELOCITY

Figure 1 describes the concept of upward flame spread based on Refs.1,2. Ignoring the vertical heat conduction and assuming the dependence of incident heat flux on height divided by flame height, surface temperature $T_w(x)$ at the height x can be represented by

$$T_w(x) - T_0 = \int_0^t \dot{q}_w^{-}(x/Q_\ell^{*2/3}\xi)\,\phi(t-\tau)\,d\tau \qquad (1)$$

where ξ is the location of pyrolysis front at the time τ, and $Q_\ell^{*2/3}\xi$ is proportional to the flame height. Insignificance of the vertical conduction relative to the horizontal one in a combusting vertical PMMA slab was established by Ito and Kashiwagi[3].

The location of the pyrolysis front at time, t, can be calculated by substituting T_{ig} and x_p into T_w and x respectively in equation(1) as

$$T_{ig} - T_0 = \int_0^t \dot{q}_w^{-}(x_p/Q_\ell^{*2/3}\xi)\,\phi(t-\tau)\,d\tau \qquad (2)$$

An explicit solution of equation(2) for x_p may be found if there is some functional relation between $x_p/Q_\ell^{*2/3}\xi$ and $t-\tau$; the following is a typical case satisfying this condition.

$$x_p/\xi = f(t-\tau), \quad Q_g^* = \text{const.} \tag{3}$$

The only form of the solution of equation(3) for x_p is

$$x_p = x_{p0}\exp(\alpha t), \quad V_p = dx_p/dt = \alpha x_p \tag{4}$$

where x_{p0} is the initial location of the pyrolysis front, and $\alpha \equiv f'(0)$ is a constant which is determined by substituting this relation into equation(2).

Equation(4) implies that flame spread satisfying equation(3) starts at an infinitely small source at the bottom of a vertical slab, and the pyrolysis zone advances at a velocity proportional to the height of the pyrolysis front; the proportionality of V_p to x_p is consistent with the results reported in previous experimental works on spontaneous vertical flame spread, e.g. $V_p \propto x_p^{0.964}$ [4]. It is in contrast with the steady state flame spread, where both pyrolysis length and flame spreading velocity are constant; practically, the steady-state flame spreading velocity is expected to give the upper bound of flame spreading velocity for arbitorary initial conditions while equation(4) may correspond to its lower bound, since larger pyrolysis length must result in stronger preheat of unburnt surface. It may be also noteworthy that, according to equation(3), time necessary for the advancement of pyrolysis front from x_a to x_b depends only on x_b/x_a. In this sense, equation(3) implies a sort of similarity in the process of flame spread.

The central problem in solving equation(2) is the determination of α. Using $\phi(t) = 1/\sqrt{\pi k\rho c t}$, $d\tau = d\xi/\alpha\xi$, and $\alpha t = \ln(x_p/x_{p0})$, equation(2) becomes

$$T_{ig} - T_0 = \lim_{x_{p0}\to 0}\int_{x_{p0}}^{x_p} \frac{\dot{q}_w(x_p/Q_g^{*2/3}\xi)}{\sqrt{\pi k\rho c\ln(x_p/\xi)}}\frac{d\xi}{\sqrt{\alpha}\,\xi} \tag{5}$$

Using $\lambda = \ln(x_p/x_{p0})$, and transforming equation(5) to obtain an expression for α

$$\alpha = \frac{1}{\pi k\rho c(T_{ig}-T_0)^2}\left[\int_0^\infty \dot{q}_w\{\exp(\lambda)/Q_g^{*2/3}\}/\sqrt{\lambda}\,d\lambda\right]^2 \tag{6}$$

Finally, equation(4) yields

$$V_p = \frac{x_p}{\pi k\rho c(T_{ig}-T_0)^2}\left[\int_0^\infty \dot{q}_w\{\exp(\lambda)/Q_g^{*2/3}\}/\sqrt{\lambda}\,d\lambda\right]^2 \tag{7}$$

Interestingly, the form of equation(7) is close to the steady state flame spreading velocity [2], which can be described as

$$(V_p)_{\text{steady state}} = \frac{x_p}{\pi k\rho c(T_{ig}-T_0)^2}\left[\int_0^\infty Q_g^{*1/3}\dot{q}_w(\lambda+1/Q_g^{*2/3})/\sqrt{\lambda}\,d\lambda\right]^2 \tag{8}$$

As discussed in previous papers [1,2], the unburnt area above the pyrolysis front can be divided into three regions according to the relative location to the flame, i.e. the solid flame(referred to as region I, $x/Q_g^{*2/3}x_p < 2.8$), the intermittent flame(region II, $2.8 < x/Q_g^{*2/3}x_p < 10$), and the plume(region III, $x/Q_g^{*2/3}x_p > 10$)*. In order to compare the contribution of each region to the flame spreading velocity, calculation of the integrals in equations (7) and (8) is made on respective regions(Figures 2 and 3). As seen in Figure 2, value of the

---

* Height of flametips by visual observation is $5\sim6\ Q_g^{*2/3}x_p$. This division is based on the distribution of heat flux to the wall surface.

integral for the region I is very close to that for the whole area(integrated from 0 to ∞); this implies that, if equation(3) is satisfied, spontaneous flame spread is governed mostly by the heating by the solid flame. In the steady-state flame spread, contribution of the other regions is more significant.

According to the above discussions, equation(7) divided by equation(8) would give the ratio of the lower bound to the upper bound of the spontaneous flame spreading velocity. This ratio is represented by

$$\Psi = \left[\int_0^\infty \bar{q}_w \{\exp(\lambda)/Q_\ell^{*2/3}\} / \sqrt{\lambda}\, d\lambda \Big/ \int_0^\infty Q_\ell^{*1/3} \bar{q}_w (\lambda + 1/Q_\ell^{*2/3}) / \sqrt{\lambda}\, d\lambda \right]^2 \quad (9)$$

Figure 4 shows this ratio and flame spreading velocity divided by $x_p/\pi k \rho c(T_{ig} - T_o)^2$ as a function of Q_ℓ^*. Ψ is expected to be a measure of predictability of flame spreading velocity in the sense that , if Ψ value is close to unity, flame spreading velocity under arbitorary condition must fall within a narrow range between the above two solutions. For usual wall fires in buildings, Q_ℓ^* is considerably less than unity and, therefore, Ψ value is expected to be within the range of 0.5~0.7. It is noteworthy that $\psi = \pi k \rho c(T_{ig} - T_o)^2 \cdot V_p/x_p$ is very sensitive to Q_ℓ^* especially in the relatively low Q_ℓ^* region; this implies that a small change in heat release rate may result in dramatic change in the flame spreading velocity.

3. FLAME SPREAD ALONG VERTICAL COMBUSTIBLE SOLID UNDER EXTERNAL RADIATION

While the above discussion has assumed spontaneous flame spread, preheat of the wall surface by external radiation is often anticipated in actual fires. In order to examine the acceleration of flame spreading velocity by external radiation, flame spreading velocity was observed for vertical slabs of PMMA and oak heated by radiant panels.

The acceleration of upward flame spread by external radiation is related to two processes. One is the acceleration of pyrolysis in the pyrolysis zone; this will result in the increase of flame height and finally the increase of incident heat flux from the flame to the unburnt area. The other is rise of temperature of the unburnt surface. Increase of flame height due to external radiation is reported in Ref.5.

In this experiment, a simplest condition for external radiation is assumed; external radiation is assumed to have continued so that the rise of surface temperature due to the external radiation, ΔT, has become constant by the initiation of the flame spread. In this situation, the first effect of external radiation can be evaluated by substituting T_o by $T_b = T_o + \Delta T$, while the first effect can be estimated by the increase of ψ value as a result of the increase of Q_ℓ^*. The strong dependence of ψ on Q_ℓ^* as shown in Figure 4 implies significance of the first effect.

Figure 5 shows the experimental set-up. The specimen is approximately 1.1m high, 0.7m wide, and 16mm thick. Each specimen was ignited with fuel pills at the bottom after the rate of the surface temperature change had become less than 2K/min. Location of the pyrolysis front is determined from the temperature history at the slab surface; the instance at which a flat plateau starts in the temperature-time curve is defined as the arrival of pyrolysis front at each location of thermocouples. Figures 6~8 show examples of the measured histories of surface temperature. Flame over the slab surface was recorded by the video camera; height of flametips were measured for reference from the videotapes.

Figures 9~11 show summary of the histories of the location of pyrolysis front thus obtained and the height of flametips. The levels of external radiation, 0.0, 2.3 and 4.7kW/m², were chosen such that $\dot{q}_e$ would become considerably lower than the incident heat flux from the flame to the slab surface. These levels are still comparable with the usual critical radiation intensity for evacuation in fire, 2.0~2.5kW/m².

The result shows that the flame spreading velocity is still approximately proportional to the height of pyrolysis front when the pyrolysis zone has become enough greater than the ignition source, and that flame spreading velocity can be accelerated even by such weak radiation. Time from the arrival of flametips to the arrival of pyrolysis front is approximately constant for each situation. These imply that the similarity anticipated for the process of spontaneous flame spread is still generally effective for weakly heated surface. It is noteworthy that the surface temperature at the arrival of flametips is considerably higher than T_b. This implies a significant role of heat flux from the upper region of the turbulent flame in the preheat for the flame spread.

Finally, Table 1 shows a summary of the relation between $\alpha = V_p/x_p$ and $\pi k \rho c(T_{ig}-T_b)^2$. In this correlation, $k\rho c$ and T_{ig} are taken as $0.66 kW^2/m^4K^2s$ and 373K resepectively. The obvious increase of the ratio of the two properties, ψ, with $\dot{q}_e$ seems to reflect the increase of Q^*_ℓ, or pyrolysis rate by the external radiation. ψ values estimated from Figure 4 using usual values of the combustion properties of PMMA are also compared; ψ values predicted from only material properties are found to be 30~40% lower than the present experiment. This difference seems to be due to either overestimate of heat release rate or underestimate of $k\rho c$.

REFERENCES

1. Hasemi, Y., Fire Science and Technology, Vol.4, pp.75-90(1984).
2. Hasemi, Y., Proc. First Intern'l Symposium on Fire Safety Sci., pp.87-96(1985).
3. Ito, A., and Kashiwagi, T., Combustion and Flame, (1988).
4. Orloff, L., de Ris, J., and Markstein, G.H., Fifteenth Symposium(Intern'l) on Combustion, pp.183(1974).
5. Quintiere, J.G., Harkleroad, M., and Hasemi, Y., Combust. Sci. and Tech.(1986).

TERMINOLOGY

D_p	characteristic fuel size(pyrolysis front)
Q_ℓ	heat release rate by combustion per unit width
Q^*_ℓ	dimensionless heat release rate per unit width defined as $Q_\ell / \rho_o C_p T_o \sqrt{gD^3}$
T_{ig}	ignition temperature
T_o	ambient temperature
T_w	temperature of wall surface
V_p	flame spreading velocity
c	specific heat of wall material
k	thermal conductivity of wall material
g	gravitational acceleration
$\dot{q}_e$	external radiation
$\dot{q}_w$	incident heat flux to wall surface
$\dot{q}_{rr}$	surface reradiation
t, τ	time

x height from the bottom of fuel

V_p location of pyrolysis front

α constant, defined as V_p/x_p

ρ density of wall material

ρ_o density of ambient air

ξ location of pyrolysis front at the time τ

ψ $\pi k \rho c(T_{ig} - T_b)^2 V_p/x_p$

Table 1 Comparison of experimental and theoretical flame spread properties

	experiment				calculation		
$\dot{q}_e$ (kW/m²)	T_b (℃)	$\pi k \rho c(T_{ig}-T_b)^2$ (kW²/m⁴s) x 10^5	V_p/x_p (1/s)	ψ (kW²/m⁴s²)	Q_ℓ (kW/m)	Q^*_ℓ (−)	ψ (kW²/m⁴s²)
0.0	23	2.54	0.0031	787	77	0.20	1100
2.3	70	1.90	0.0048	912	92	0.24	1550
4.7	92	1.64	0.0063	1033	107	0.28	1770

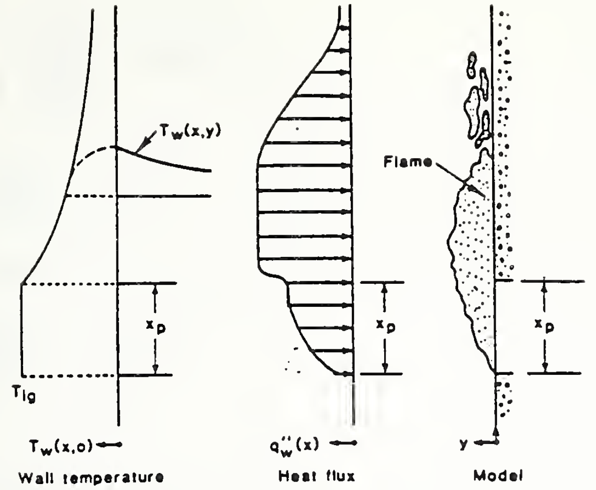


Figure 1 Concept of Upward Flame Spread along Vertical Combustible Solid

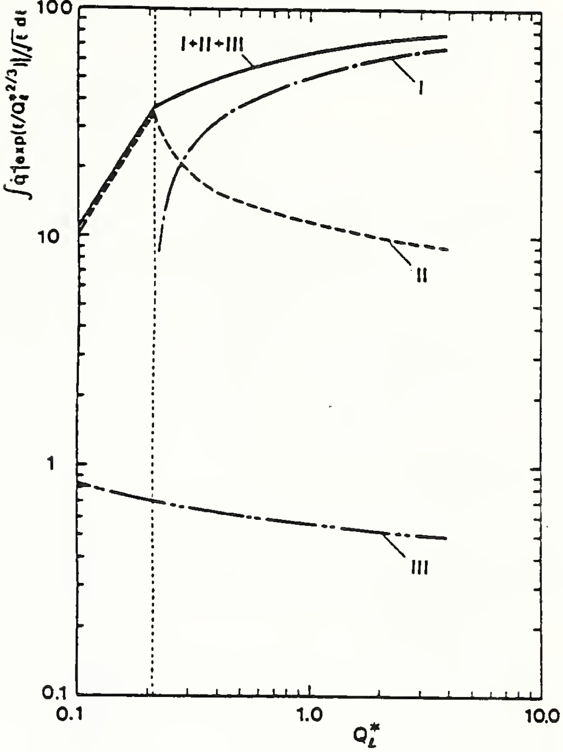


Figure 2 $\int q^{-}\{\exp(\xi/Q_\ell^{*2/3})\}/\sqrt{\xi}\,d\xi$ vs. Q^*_ℓ

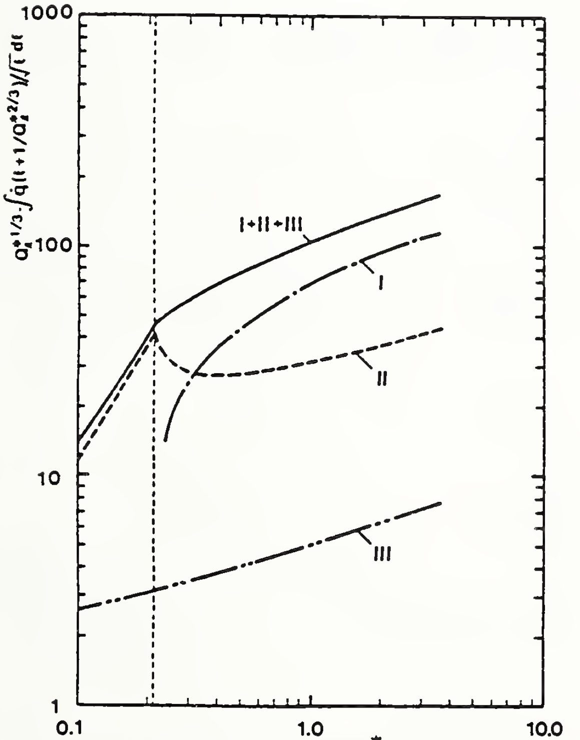


Figure 3 $Q_\ell^{*1/3}\int q^{-}(\xi+1/Q_\ell^{*2/3})/\sqrt{\xi}\,d\xi$ vs. Q^*_ℓ

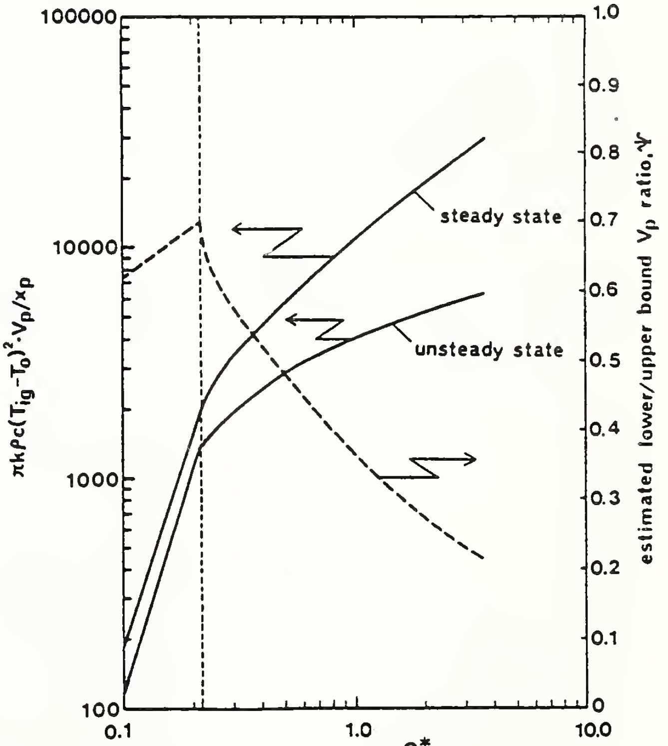
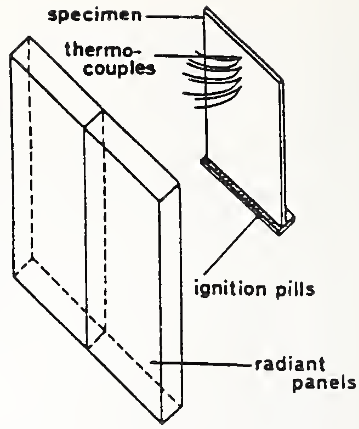


Figure 4 $\pi k\rho c(T_{ig}-T_o)^2\cdot V_p/x_p$ and estimated lower/upper bound V_p ratio, Ψ vs. Q^*_ℓ

Figure 5 Experimental Set-up.



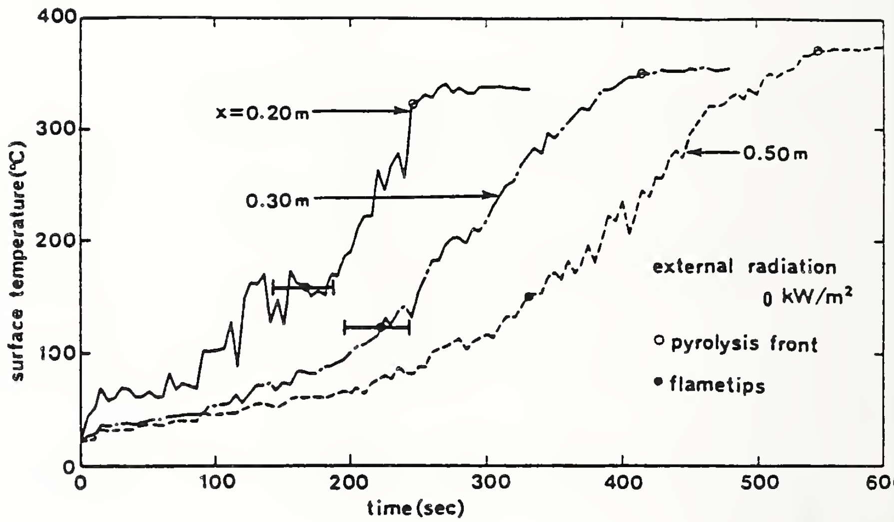


Figure 6 Time History of Surface Temperature ($\dot{q}_e'' = 0.0kW/m^2$)

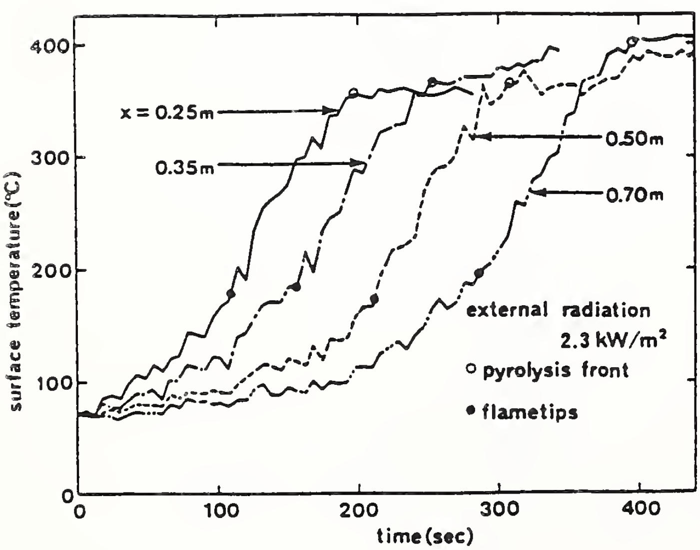


Figure 7 Time History of Surface Temperature ($\dot{q}_e'' = 2.3kW/m^2$)

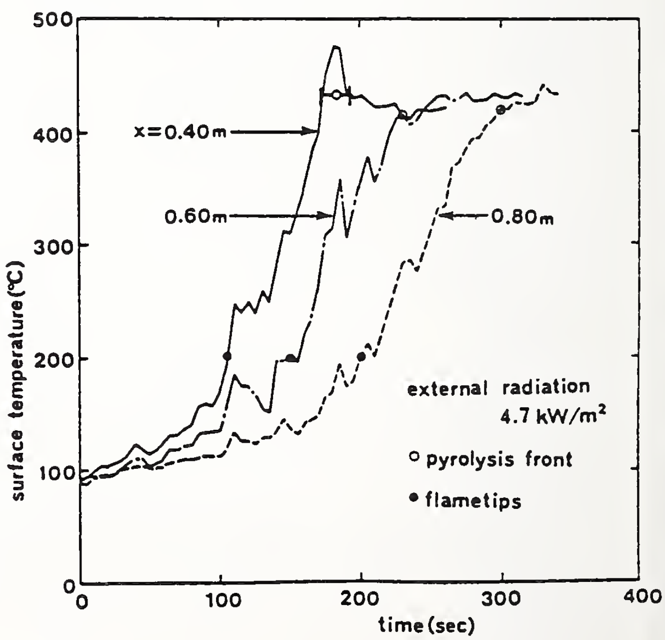


Figure 8 Time History of Surface Temperature ($\dot{q}_e'' = 4.7kW/m^2$)

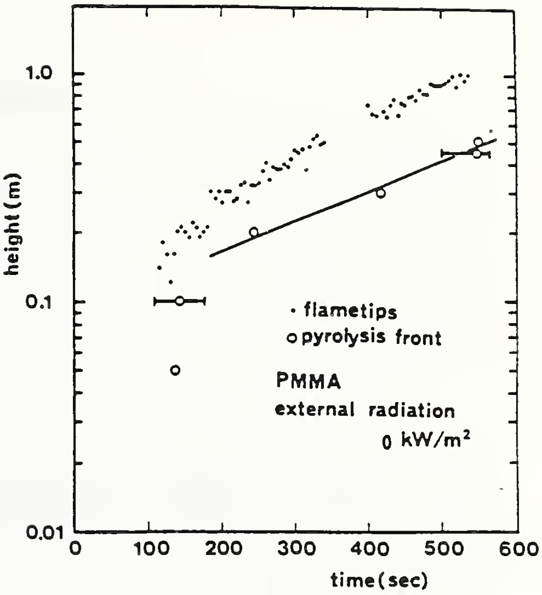


Figure 9 Location of Flametips and Pyrolysis Front
($\dot{q}_e$ = 0.0kW/m²)

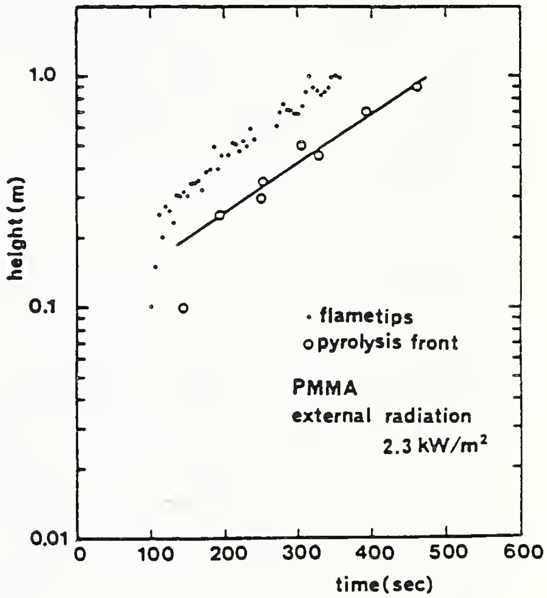


Figure10 Location of Flametips and Pyrolysis Front
($\dot{q}_e$ = 2.3kW/m²)

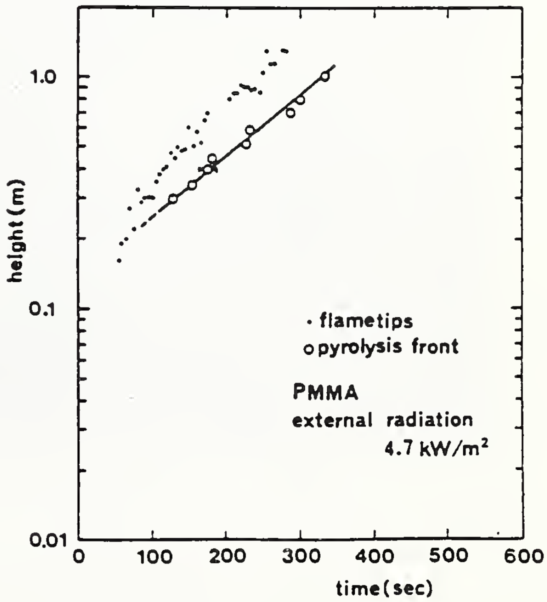


Figure11 Location of Flametips and Pyrolysis Front
($\dot{q}_e$ = 4.7kW/m²)

CONCURRENT TURBULENT FLAME SPREAD

L. Zhou and A.C. Fernandez-Pello
Department of Mechanical Engineering
University of California
Berkeley, CA 94720

ABSTRACT

The rate of flame spread over the surface of thick PMMA sheets has been measured as a function of the velocity and turbulence intensity of a forced air flow concurrent with the direction of flame propagation. It is shown that the flow turbulence has a strong influence on the flame spread process. For all turbulence intensities, the flame spread rate increases approximately linearly with the flow velocity, although the slope is smaller for larger turbulence intensities. For a given flow velocity, the spread rate decreases as the turbulence intensity is increased, the effect being more pronounced for larger flow velocities. These effects appear to be due to a strong influence of the turbulence intensity on the flame length, which decreases as the turbulence intensity is increased, thus reducing the net heat flux from the flame to the unburnt combustible. The results are significant since the prediction of the flame length and spread rate as a function of the problem parameters are important factors in the development of room fire models.

1. INTRODUCTION

In most practical situations, the spread of fire occurs under turbulent flow conditions. Since the flow turbulence effects both the heat transfer and the chemical kinetic mechanisms that control fire spread, it is necessary to determine how these controlling mechanisms are affected by turbulence in order to predict the spread of fire under realistic conditions. Among the different modes of fire spread the concurrent, or flow assisted, mode of flame spread is the fastest and most hazardous because the flames are pushed ahead of the burning region by the gas flow, which facilitates the transfer of heat from the flame to the unburnt material. This mode of flame spread is particularly affected by flow turbulence because the heat transfer to the unburnt material occurs over the large region bathed by the downstream flame, and the flame characteristics are strongly influenced by turbulence. Thus, the study of concurrent turbulent flame spread is of great interest in the fire development modeling, and in the establishment of flammability test methods.

The only works published to date on turbulent flame spread are those of Orloff et al. [1] for upward turbulent flame spread over large PMMA sheets, and of Saito and co-workers [2,3] for upward turbulent spread of flames over PMMA and wood sheets. In these works, the gas flow is buoyancy induced, and the turbulence is naturally generated depending on the sample scale. The studies concentrate in measuring the rate of flame spread dependence on scale [1] or the magnitude of an imposed radiant flux [2]. With the exception of the study of Zhou et al. [4] for opposed flow flame spread, no systematic studies have been performed to date to observe the effect of flow turbulence intensity on the rate at which flames spread over the surface of a solid fuel. In the present work, a parametric study is carried out of the spread of flames in a concurrent turbulent forced flow with the objective of determining what is the effect of turbulence intensity on the rate of flame spread, and to infer through these measurements how turbulence affects the different mechanisms controlling the spread of the flame.

2. EXPERIMENT

The experimental apparatus consists of a laboratory scale combustion tunnel, designed to conduct combustion experiments under varied flow conditions, and the supporting instrumentation, based primarily on optical and thermocouple measuring methods. The tunnel has a 0.89 m long settling chamber with a rectangular cross section 0.3 m by 0.18 m, which supplies gas flow to the tunnel test section through a converging nozzle with a reduction area of 5.5 to 1. The test section is 0.6 m long and has a rectangular cross section 0.13 m wide and 76 mm high. The side walls are made of 6 mm Pyrex glass to enable visual observation and optical diagnostic access, and the floor and ceiling sides are made of 25.4 mm thick Marinite sheet. The tunnel is mounted horizontally on a three axis positioning table.

The gas flow in the tunnel is supplied from centralized compressed air and the flow rates controlled and measured with critical nozzles. Turbulence is generated by means of grids, or perforated plates, placed at the exit of the tunnel converging nozzle. A prescribed turbulence intensity is obtained through a combination of flow velocity and plate blockage ratio. This means of turbulence generation, however, cannot provide high turbulence intensity at very low flow velocities. The distribution of turbulence intensity through the test section is characterized by an initial region, approximately 50 mm where the turbulence decays sharply, followed by a 0.2 m region of relatively constant turbulence, and a final region where the turbulence decays again due to entrainment effects at the test section exit. The gas velocity and turbulence intensity are measured with a one component Laser Doppler Velocimeter (LDV) operating in the forward scattered mode. The laser source is a Spectra Physics Ar-Ion laser with a 2 W total output power. The signal is processed with a TSI frequency counter and transferred to an IBM/AT micro-computer. The experimental installation also includes a Schlieren system with a 45 cm diameter collimated light beam that is used to provide qualitative information about the effect of the flow turbulence on the flame and thermal layer structure. In addition the installation contains a network of thermocouples for gas and solid phase temperature measurements.

The fuel specimens are 12.7 cm thick PMMA (Rohm and Hass, Plexiglas G) sheets, 76 mm wide by 0.3 m long. They are mounted flush in the tunnel Marinite floor with their upstream edge placed 15 mm from the tunnel convergent nozzle exit. The flame spread process is initiated by igniting the top upstream edge of the sheet with an electrically heated nichrome wire placed in close contact with the PMMA. The flame spread rate is measured from the surface temperature histories as given by thermocouple placed at fixed intervals along the fuel surface. Eight Ch.-Al. thermocouples 0.127 mm diameter are embedded on the PMMA with their beads flush with the PMMA surface at distance 32 mm apart. The thermocouples output is processed in the micro-computer. With the surface temperature histories, the rate of spread of the pyrolysis front is calculated from the time lapse of pyrolysis arrival to two consecutive thermocouples and the known distance between the thermocouples.

3. RESULTS

The measurements of the flame spread rate over PMMA sheets as a function of the concurrent air flow velocity are shown in Fig. 1 for several values of the turbulence intensity. It is seen that the spread rate increases approximately linearly with the flow velocity, and that the slope decreases as the turbulence intensity decreases. The dependence of the concurrent flame spread rate on the turbulence intensity is presented in Fig. 2. It is seen that the spread rate decreases as the turbulence intensity increases, and that the effect is more pronounced for larger flow velocities. These results are very interesting and somewhat surprising since this mode of flame spread is controlled by heat transfer from the flame to the fuel, and it is well known that turbulent boundary layer heat transfer is larger than the laminar flow one. The results, which appear to be due to a strong effect of the turbulence intensity on the flame length, are very important not only because they introduce new aspects about the flame spread process not previously predicted, but because it may have significant influence in the application of flame spread formulas in models of room fire development.

The mechanisms by which turbulence affects the flame spread rate can be inferred from the theoretical analysis of the spread process. A simplified heat transfer model of the flame spread provides the following expression for the rate of spread [2]

$$V_f = q^2\, l_f/(k\rho c\,(T_p - T_i))^2 \qquad (1)$$

where q is the surface heat flux, l_f the flame length, $k\rho c$ are the thermal properties of the solid and T_p and T_i the solid pyrolysis and initial temperatures respectively. The flow velocity and turbulence intensity can affect both q and l_f and through them the flame spread rate. Thus, it is important to determine how turbulence affects these parameters. In the work performed to date, we have not measured these effects directly. However, it is possible to deduce them approximately from the surface temperature histories. The flame length is determined with the spread rate and the time required for the surface temperature at a thermocouple position to rise from ambient to the pyrolysis value. The surface heat flux is calculated from the time variation of the surface temperature by assuming that the fuel behaves as a semi-infinite solid. The calculated variation of the flame length with the flow velocity and turbulence intensity are presented in Figs. 3 and 4 respectively. Figure 3 shows that the dependence of the flame length on the flow velocity is different depending on the turbulence intensity. For low turbulence intensities, the flame length increases with the flow velocity and for large turbulence intensities, it decreases. From the results of Fig. 4 it is seen that for all flow velocities the ratio of flame length to pyrolysis length decreases as the turbulence intensity is increased. The effect is more marked for large flow velocities. These effects seem to be due primarily to the convective cooling of the reaction zone by the cold air induced toward the flame by the turbulent eddies.

In order to obtain more information about the mechanisms causing the shortening of the flame length with the turbulence intensity, a Schlieren system was constructed and applied to produce Schlieren images of the flame. The Schlieren system has a collimated light beam 0.5 m in diameter. It consists of a Tungston lamp light source, beam expanding and converging lenses and two 0.5 m parabolic mirrors. A characteristic example of the flame images obtained with this system is shown in Fig. 5. It is seen that as the flow turbulence intensity increases, more cold air is introduced into the flame zone and the mixing of the flow becomes more intense. These are the effects that appear to cause the shortening of the flame length with the turbulence intensity.

The calculated variation of the surface heat flux downstream of the pyrolysis front with the turbulence intensity is shown in Fig. 6. It is seen that the heat flux is only weakly affected by the flow turbulence, decreasing slightly with the turbulence intensity for large flow velocities and increasing slightly for low flow velocities. All of the above results have been combined in Fig. 7 where the ratio V_f/Ul_f (deduced from Eq. (1)) is plotted versus the flow turbulence intensity. It is seen that this ratio is independent of the flow velocity and turbulence intensity, which indicates that the effect of the flow turbulence on the flame spread rate takes place primarily through the flame length.

4. CONCLUSIONS

The results of this study show that flow turbulence has a strong influence on the flame length and on the concurrent flame spread rate. Both the observed shortening of the flame length and decrease of the flame spread rate as the turbulent intensity is increased are significant observations since the prediction of flame lengths and rates of flame spread as a function of the environmental conditions are important factors in the development of room fire models and the establishment of material flammability tests.

Given the potential impact of the present results on the theoretical prediction of the spread of flames, it is important to extend the work to the study of the other aspects of the process. For example, it is important to know how turbulence affects the flame spread process in a vitiated environment, or how the characteristics of the flow turbulence (free flow or boundary layer turbulence) may quantitatively affect the rate of spread for a given turbulence intensity. Also important is to know if and how turbulence affects the rate of mass burning in the pyrolyzing region, the rate of soot production and the radiative properties of the flames.

ACKNOWLEDGEMENTS

This work was supported by the National Bureau of Standards under Grant No. 60NANB7D0737. Partial funds for the experimental facility were provided by a National Science Foundation Engineering Research Equipment Grant No. CBT-8506292.

REFERENCES

1. Orloff, L., De Ris, J. and Markenstein, G.H., "Upward Turbulent Fire Spread and Burning of Fuel Surface," 15th Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, PA, p. 183, (1975).

2. Saito, K., Quintiere, J.G. and Williams, F.A., "Upward Turbulent Flame Spread," 1st International Symposium on Fire Safety Science, Hemisphere Publishing Company, P. 75, (1986).

3. Saito, K., Williams, F.A., Wichman, I.S. and Quintiere, J.G., "Upward Turbulent Flame Spread on Wood Under External Radiation," 24th National Heat Transfer Conference, Pittsburgh, PA, August 1987.

4. Zhou, L., Fernandez-Pello, A.C. and Cheng, R., "Flame Spread in an Opposed Turbulent Flow," submitted to Combustion and Flame, (1988).

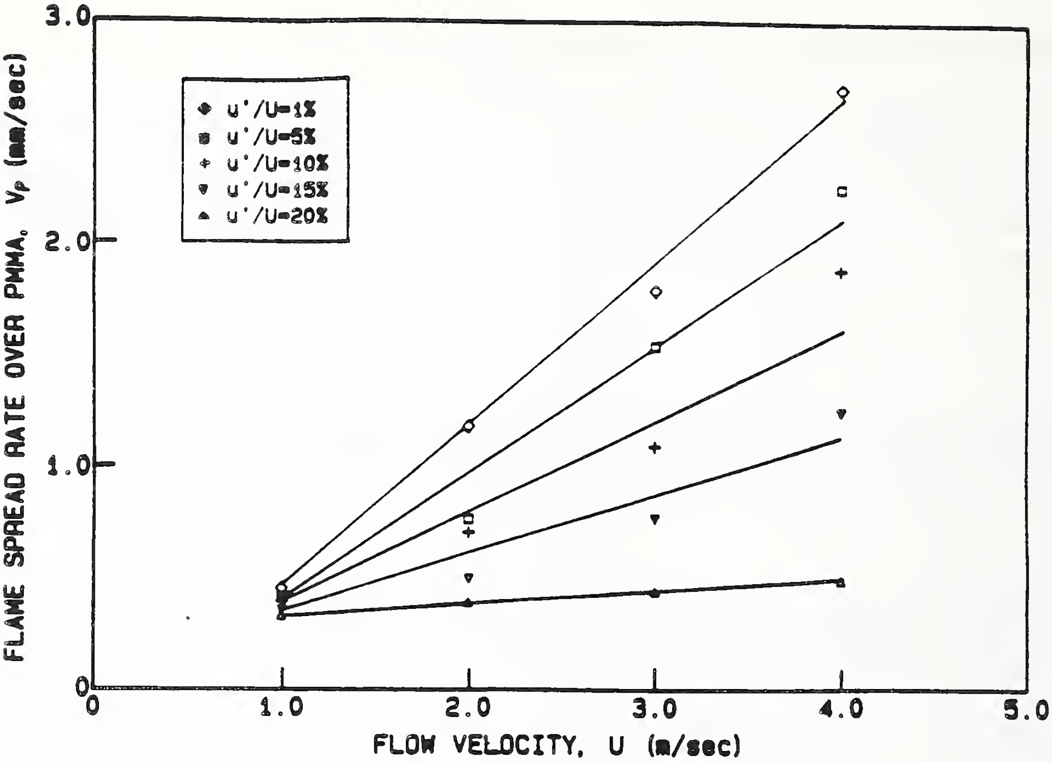


FIGURE 1.

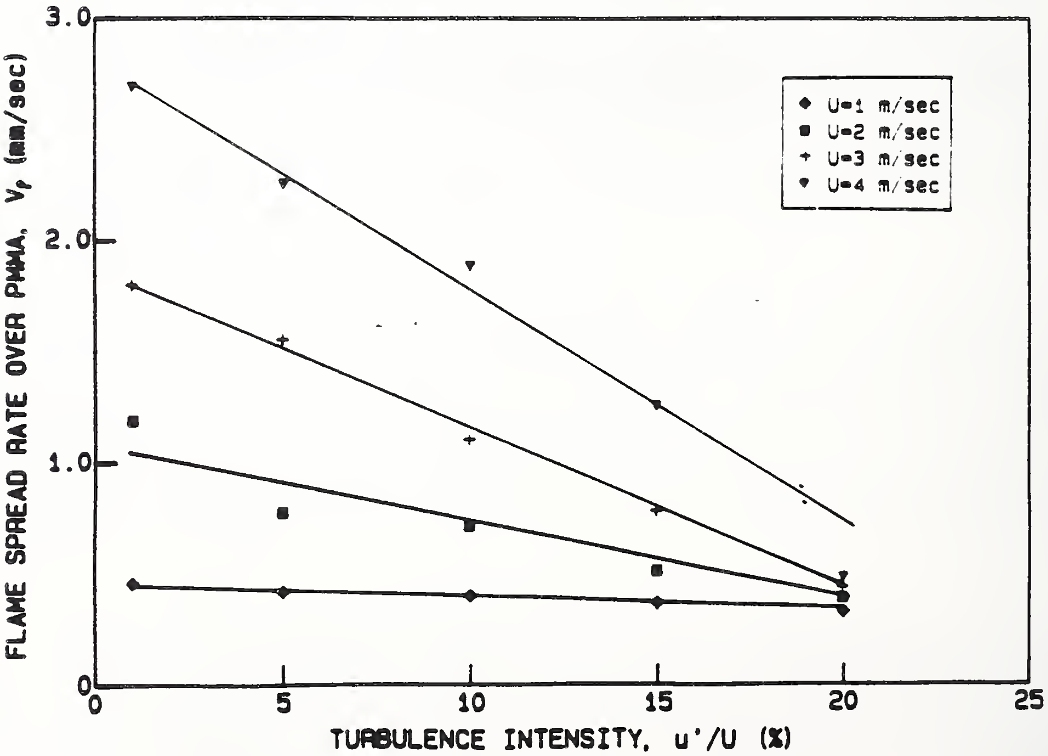


FIGURE 2.

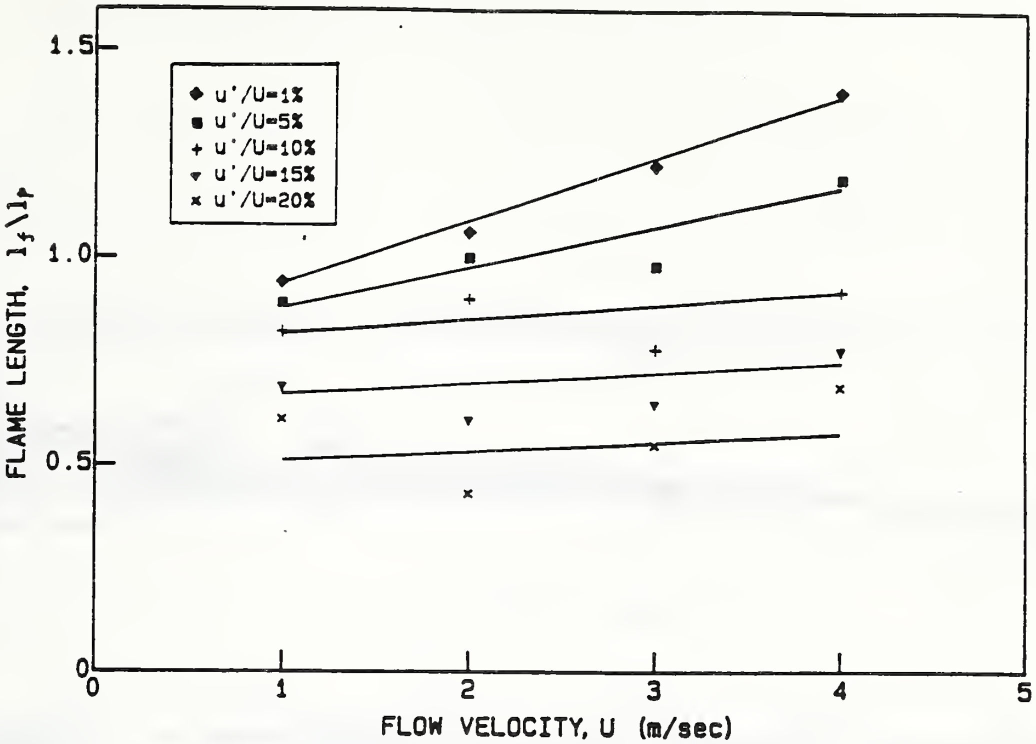


FIGURE 3.

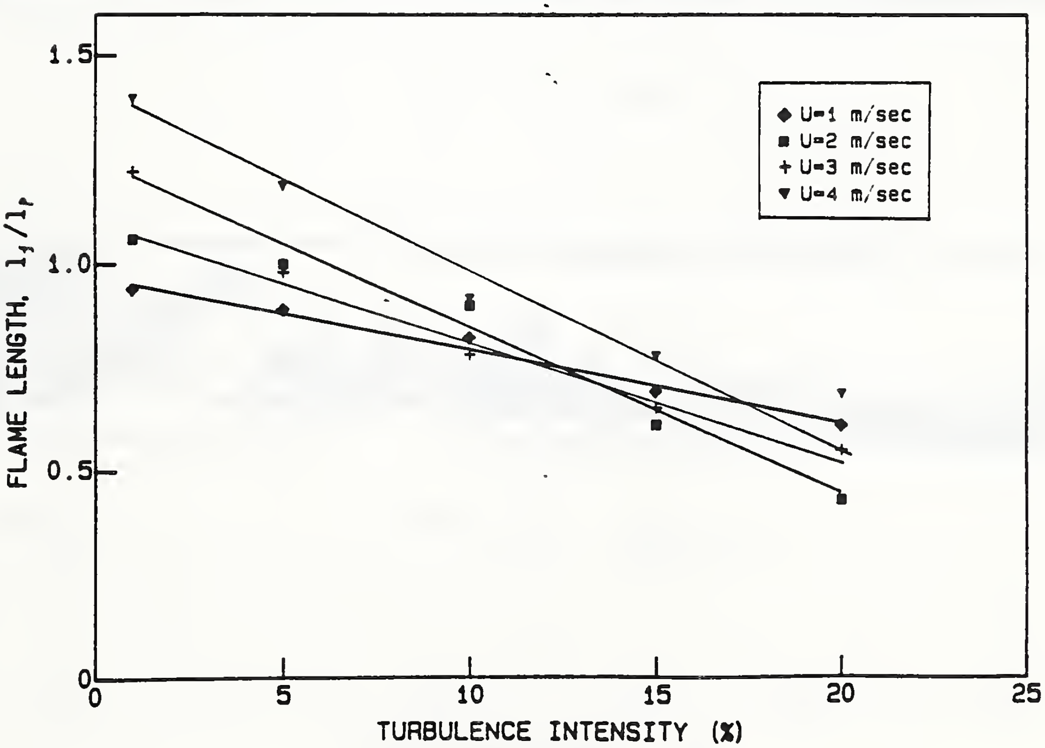
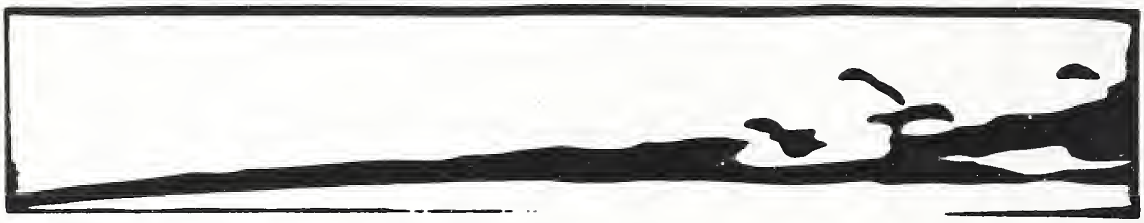


FIGURE 4.



U = 3 m/sec u'/U = 1%

U = 3 m/sec u'/U = 5%

U = 3 m/sec u'/U = 15%

FIGURE 5.

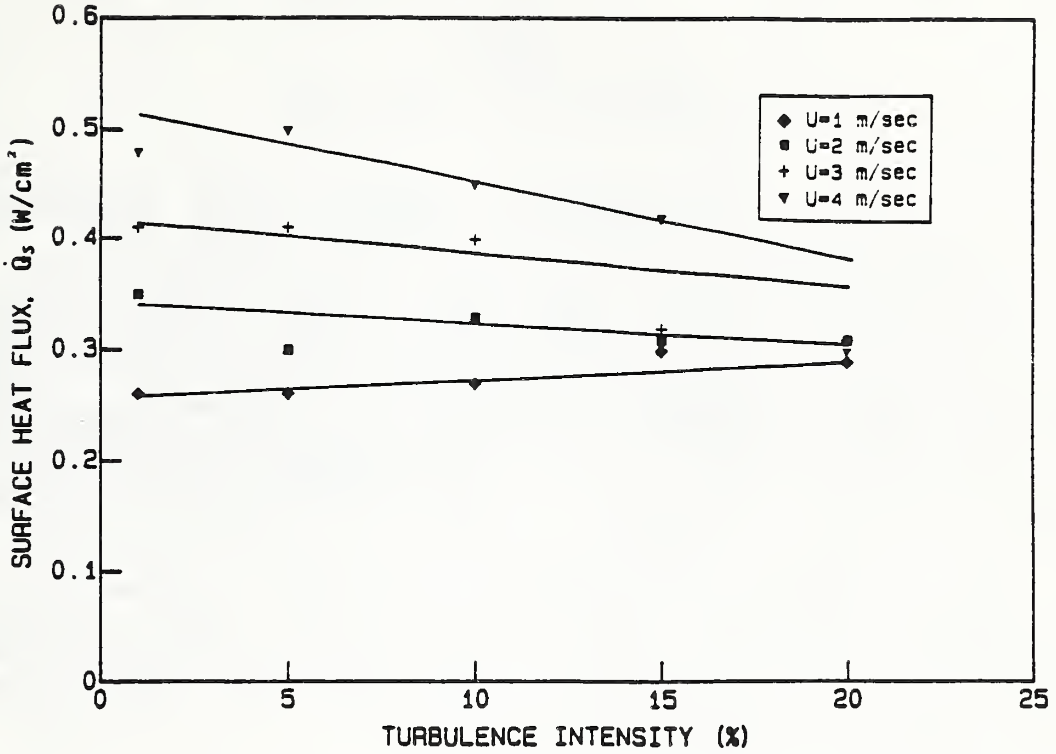


FIGURE 6.

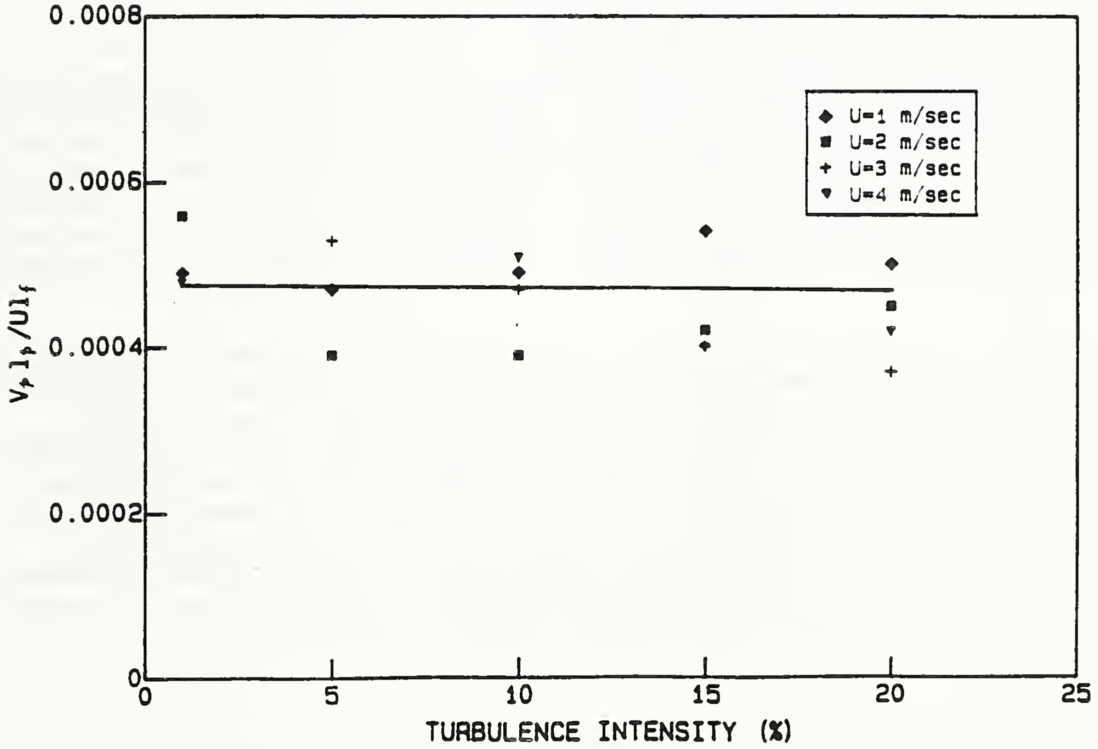


FIGURE 7.

Collaborative Experiment of Interior Lining Materials

Y. Hasemi

Building Research Institute

Development of a rational evaluation method of interior lining materials is one of the problems of internationally common interest in fire safety engineering. Most of the industrialized countries have their own standards and testing methods on fire safety performance of lining materials; however, the conventional evaluation methods do not always represent fire growth mechanisms in actual building fires, probably since fire growth mechanisms were only poorly understood when these evaluation methods were developed. Recently, Nordic countries have started a research program to develop some rational testing methods of interior lining materials as preparation for the planned European market unification in 1992. Adoption of combustion models of lining materials in room fire computer models has been attempted at NIST. Also in Japan, development of a performance based evaluation method of interior lining materials is an urgent necessity, since, from a scientific viewpoint, the present Japanese standard is significantly based on whether combustion takes place or not, and as its result combustible materials tend to be eliminated from the market of lining materials.

Most of the current studies related to the evaluation of interior lining materials are based on some mathematical modeling. Recent work on wall fires by Saito, et al., describes flame spread as a function of the height of flame from pyrolysis zone which is further determined by the mass consumption rate of the fuel. This model seems to be consistent with the basic idea of the treatment of wall fires in the FIRST, in which wall fire is characterized by mass burning rate. For room configuration, Karlsson proposed a model of fire growth on lining materials, and was able to explain experimental results on a few specific materials using his model. His model is also based on the concept of flame spread as a result of inert heating of the material surface to an ignition temperature. Hasemi has also proposed a model of wall flame spread to explain flame spreading velocity from material properties.

Each model of fire spread has to be validated against experiments in realistic conditions if it is desired to serve as a scientific basis for evaluation methods. However, the major problem in advancing the scientific approach in this field is the fact that every group is too small and research facilities of each group are quite limited. Probably, it is difficult for every group to carry out all steps from basic property measurements to full scale experiments or from basic analysis to comprehensive computer models. Necessity and utility of some collaboration or coordination in this field arises from this circumstance.

At the last UJNR meeting in Tsukuba, Quintiere and Hasemi discussed the possibility of collaboration between NIST and BRI, and the visit of Dr. Parker of NIST to BRI for heat release analysis of wood was very beneficial and incentive to BRI. During his stay at BRI, it was pointed out that full scale wall fire experiments using the BRI's new radiant panels (approx. 2.5m wide and 3.2m high) as the heat source for external radiation would be useful for the validation of various models of wall flame spread and for the accumulation of data as a basis for the further development of the mathematical models.

In the FY 1989, several large scale wall fire experiments are planned, using this facility. The specimen will be PMMA and plywood (Douglas fir). Upward and downward flame spread will be observed for the range of external radiation approximately 0≈10 kW/m^2. Mass loss rate, surface temperature and flame height can be measured using the present BRI experimental apparatus. The experiments will be continued and extended if the FY 1990 budget for this program is approved.

The North American Wood Industry Room Fire Test and Predictive Modeling Program

JAMES R. SHAW
Weyerhaeuser Fire Technology Laboratory
Weyerhaeuser Company
P.O. Box 188 Lab B
Longview, Washington 98632, USA

ABSTRACT

The Fire Research Program sponsored by the National Forest Products Association (NFoPA) includes research and development of predictive fire growth models. Using the OSU ROOM Model as a base and the ASTM Proposed Standard for Room Fire Test of Wall and Ceiling Materials for validation, fire growth models are being developed that can predict the contribution to a compartment fire buildup from wall lining materials. Input data from the OSU Rate of Heat Release apparatus is being evaluated concurrently with the Cone Calorimeter and LIFT Apparatus input. Early validation studies show good correlation between model predictions and actual room fire results.

1. INTRODUCTION

Through the National Forest Products Association (NFoPA), the United States and Canadian Wood Products Industries embarked on a broad scope fire research program in the mid 1980's. This certainly did not mark the beginning of fire research on wood but was an attempt to coordinate all the different independent programs and projects into a more comprehensive program where priorities, objectives and results could be shared by all participants. This report will describe the goals and some of the elements of the program and also provide technical results in one of the key research areas. It will become evident that room fire tests and predictive fire modeling are integral parts of the complete program. Keep in mind that the major focus of this research is on the properties and behavior of wood and wood products used in building construction.

The ultimate long range goal of the research is to be able to incorporate fire growth, heat transfer and structural response models into a system capable of describing a compartment or building fire from ignition to structural collapse. We recognize that this goal will take many years to accomplish but intermediate goals and objectives toward that end are being achieved.

The complete Wood Industry Fire Research Program covers three major areas:

1. Predictive Fire Models
    - a. Fire Growth
    - b. Heat Transfer
    - c. Structural Response
2. Fire Property Data Base Development on Wood Products
3. Smoke Toxicity Test Development and Product Evaluation

This report will concentrate on the Fire Modeling Research and the various test methods being used in this effort.

2. HISTORICAL PERSPECTIVE

Before discussing any of the approaches and results of the specific fire research projects, a brief look at the current method of building passive fire safety into our buildings is necessary. If the model codes in the United States and the National Code in Canada are reviewed, it is found that building materials are regulated on the following basis:

1. Combustible or noncombustible classification (as determined by the ASTM E 136 Test).

2. Allowable heights and areas of the building.

3. Flame spread and smoke developed classifications (as tested by ASTM E 84).

4. Fire endurance (as measured by ASTM E 119, ASTM E 152, ASTM E 163 and ASTM E 814).

5. Location of building on property.

In each of the cases where a fire test is used as a measure of the acceptability of the product, material or assembly, a single fire exposure scenario is used. For example, there is a specified time/temperature curve (ASTM E119) which is followed in all fire resistance testing of walls, floors, roofs, columns, beams, doors and windows. This is not a criticism of the standards and code bodies promulgating and referencing these tests, however, it is an acknowledgement of the limitations of this approach to passive fire safety. In some cases these limitations may be overly conservative and restrictive and in others they may be too permissive; we just do not know. The wood industry supports and participates in the fire modeling effort because we believe that this approach will permit a better and more thorough assessment of the total fire hazard of a system.

3. APPROACH TO FIRE RESEARCH

The approach taken in actually conducting the research has been to:

1. Place a research associate at the National Institute of Standards and Technology Center for Fire Research to work closely with other fire research scientists (currently Mr. Marc Janssens holds this position).

2. Contribute to wood fire research programs at selected U.S. universities.

3. Support the fire research at the U.S. Department of Agriculture Forest Products Laboratory.

4. Grant research funds to government, independent and company laboratories such as NIST, Forintek of Canada and Weyerhaeuser Company.

There is a NFoPA Fire Research Program Advisory Committee that oversees the total program and makes recommendations to the Association on allocation of funds. This group also reviews the progress of the researchers and provides input on industry needs.

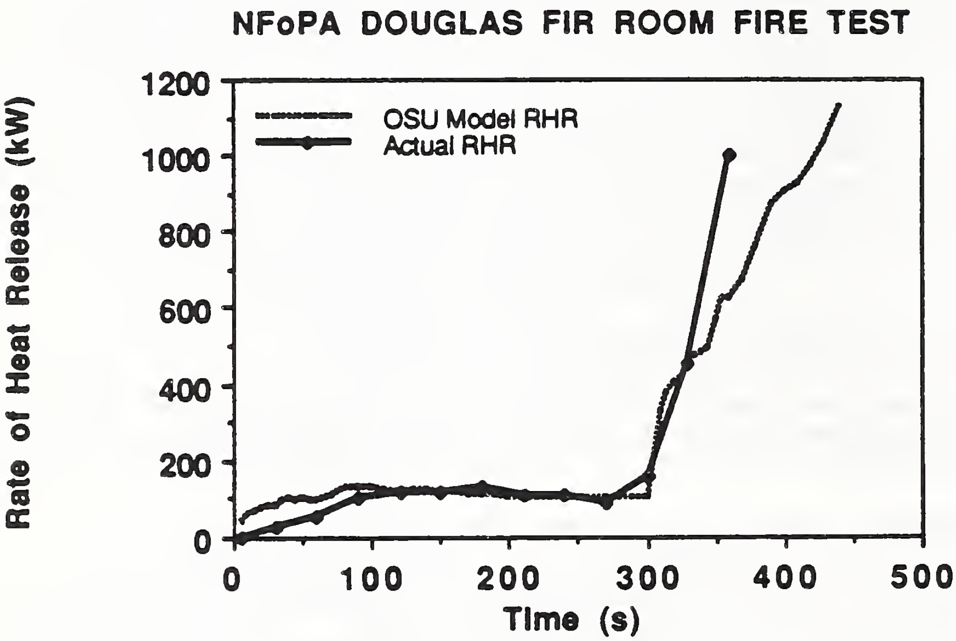
3. PROJECT DESCRIPTION AND CURRENT RESULTS

The work in predictive fire modeling, specifically, room fire growth modeling, is one of the most exciting and active areas of research. There are several researchers working in this area on different aspects of the problem.

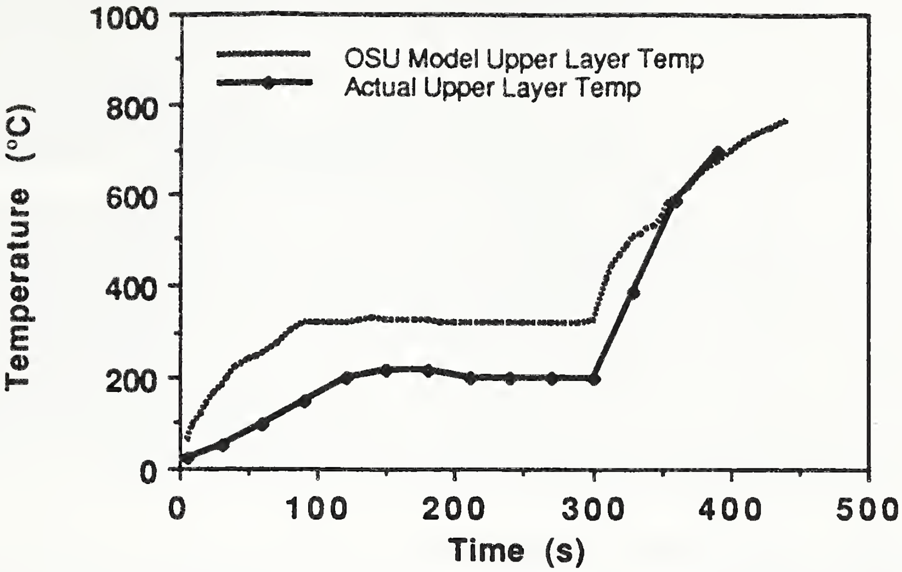
Bill Parker at the Center for Fire Research is developing a predictive model for charring and heat release rate of wood. Small scale tests developed by Parker are being used to develop input data for the model. Without going into the technical details of this work, good correlation using this model to predict the heat release rate of wood at low external fluxes has been achieved but inconsistencies exist at higher heat fluxes. Better agreement may be accomplished by improving the empirical input data. Mr. Parker recently spent three weeks in Japan conducting research in this area with Dr. Yuji Hasemi.

Until these types of predictive models are available and validated, empirical heat release data is being used as input to room fire growth models such as the OSU ROOM Model authored by Dr. Ed Smith of Ohio State University. The OSU ROOM Model uses the empirical heat and smoke release and flame spread data generated by the OSU Rate of Heat Release Apparatus to predict the fire growth in a room with a single ventilation port and combustible wall linings. The major strength of the model is its ability to evaluate the potential of wall linings to produce compartment flashover.

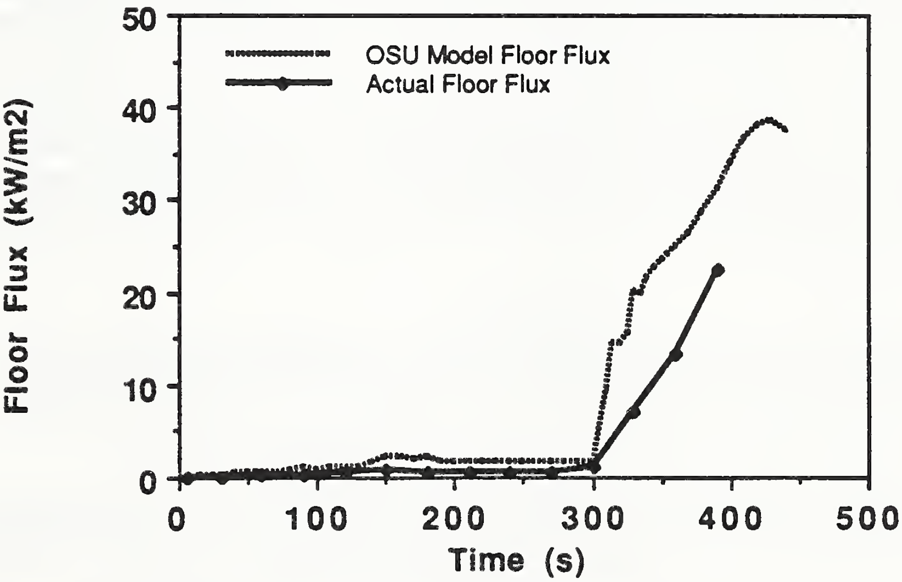
Using the Room Fire Test and the OSU ROOM Model, validation of the Model was attempted in a test with 1/2" Douglas fir plywood on two walls. The following graphs show the actual rate of heat release, upper layer temperature and floor flux of the 8' x 12' x 8' room and compares theses actual results with the predictions of the Model. The gas burner ignition source placed in the back corner of the room was controlled to deliver a 40 kW fire for five minutes, a 160 kW fire for 5 minutes and then a 0 kW fire for the final 5 minutes of the 15 minute test.



NFoPA DOUGLAS FIR ROOM FIRE TEST



NFoPA DOUGLAS FIR ROOM FIRE TEST



The predicted heat release from the OSU ROOM Model agrees quite well with the actual heat output during the first five minutes of the test. After the propane flow was increased to 160kW the model predicts a slower rate of growth on to flashover than actually occurred. Because there was a delay in the measurement of the heat released from the room, the data has been shifted to compensate for the timing error. The predicted upper layer temperature does not agree with the actual temperatures (average of the five TC's in the ceiling excluding the burner TC) during the first five minutes and the Model tends to overcompensate as the room reaches flashover conditions. The predicted heat flux on the floor also agree very well with the actual results during the first five minutes but deviates as the fire grows rapidly. Obviously more work is needed in refining the Model to improve the predictive output. James White of Weyerhaeuser has been working closely with Dr. Smith in changing the subroutines to improve the output. Another point where the input data could be improve is in the measurement of the flame travel rate.

Marc Janssens has modified the basic OSU ROOM Model and named it CORNWALL (Corner and Wall Fire Growth Model). The input data is collected from the Cone Calorimeter and the Lateral Ignition Flamespread Test (LIFT) apparatus instead of the OSU Rate of Heat Release Apparatus. The flashover time prediction from this model was also in good agreement with the actual fire results.

In order to assess the factors that significantly affect the results of a room fire test on combustible wall linings, a sensitivity study was conducted at the Forest Products Laboratory. The factors chosen in the study were:

1. Location of Burner (Corner and Wall)
2. Profile of Burner
    - A. 40 kW for 15 min.
    - B. 40-160-0 kW for 5 min at each level
    - C. 40-80-120 kW for 30 sec at each level then 160 kW for the remaining 13.5 minutes
    - D. 40-100-160 kW for 5 min at each level
3. Lining Material on Ceiling and Two Walls (Gypsum and Ceramic Fiber Blanket)

The results showed that when placed in the corner the burner was significantly more harsh than when placed in the wall position. Flashover times were reduced dramatically in the corner exposure. The burner profiles study yielded the very predictable results with "A" being the least severe and "C" being the most severe. The "B" (40-160-0 kW) exposure demonstrated a broad band of results on wood products with a wide range of flame spread characteristics. For example, an ASTM E 84 Class A flame spread, fire retardant treated plywood (FRT PW) did not flashover the room during the 15 minute test while a Class C flame spread product caused flashover during the 40 kW exposure. The "A" (40 kW only) exposure allowed several combustible wood materials to survive the test without flashover occurring. On the other end of the spectrum, the "C" (40-80-120-160 kW) exposure compressed the combustible wall materials into a very narrow band of flashover times.

The choice of noncombustible lining on the ceiling and the other two walls also impacted the rate of fire growth in the room. The highly insulative property of the ceramic fiber blanket caused the flashover times to be significantly reduced compared to the gypsum lining tests. Again, the effect was to compress the results of various combustible wall linings into a more narrow range.

Subsequent to the sensitivity test a series of room fire tests were conducted on six different wood panel products with a range of flame spreads from Class A to high Class C. The burner was placed in the corner of the room and the B (40-160-0 kW) burner profile was used:

WOOD PRODUCT	FLAME SPREAD CLASS
1/2" FRT Southern Pine Plywood	High Class A
1" Redwood	High Class B
1/2" Douglas Fir Plywood	Low Class C
1" Southern Pine	Mid Class C
1/2" Particleboard	Mid Class C
1/2" Oriented Strand Board	High Class C

Flashover times ranged from no flashover in 15 minutes to less than five minutes. The rank order of products from least to greatest time to flashover was:

1. Oriented Strand Board
2. Southern Yellow Pine, Particleboard
3. Douglas Fir, Redwood
4. Fire Retardant Treated Douglas Fir PW

These results suggest very reasonable agreement between flame spread classifications as determined by the 25' Tunnel and the fire growth rates as determined by flashover in a room fire test.

Hao Tran (FPL) and Marc Janssens, who generated these results, plan to determine the heat release and flame spread characteristics of these six materials and then model the tests using the CORNWALL Model. James White will model the fires using the most recent version of the OSU ROOM Model and the OSU RHR.

4. APPLICATION OF MODELING RESEARCH

The fire growth modeling and room fire testing will eventually be used as evidence for proposing changes in the model building codes. Specifically, the proposal will recommend that fire performance of structural elements and assemblies be based on the fire growth scenario probable for that building and the major factors influencing the fire and smoke development. This would allow trade-offs in the building design and materials without sacrificing fire safety. Architects and building owners would gain greater flexibility.

Another very practical use of this modeling work has been its use in new product and assembly development. Right now an E 119 fire can be used in the exposure scenario and prediction of the fire endurance of the assembly can be made. Additional information on the progress being made in this area will be forthcoming.

5. CONCLUSION

The progress made to date in this modeling and room test program is encouraging despite some obvious needs for improvement. Researchers participating in this work remain committed to achieving the goals set out at the beginning of this paper and look forward to reporting future progress.

6. REFERENCES

Parker, William J. Determination of the Input Data for a Model of the Heat Release Rate of Wood, ASTM Special Technical Publication 983, Pennsylvania, 1988.

Smith, E.E., and S. Satija, "Release Rate Model for Developing Fires," ASME, The American Society of Mechanical Engineers Technical Division, New York, 1981, pp. 1-11.

Tran, Hao C., and Marc L. Janssens, "Room Fire Test for Fire Growth Modeling--A Sensitivity Study," For Publication in Journal of Fire Sciences, Technomic Publishing Company, Pennsylvania, 1989.

Fire Risk Analysis: General Conceptual Framework For Describing Models

JOHN R. HALL, JR.
National Fire Protection Association,
Quincy, Massachusetts, USA.

AI SEKIZAWA
Fire Research Institute,
Tokyo, Japan.

ABSTRACT

Despite more than a decade of work in Japan, the U.S., and elsewhere on the development of models and methods for fire risk analysis, the basic terms still are used in many different ways by different modelers, producing confusion over not only best methods but also objectives. In this paper, a fundamental conceptual framework is defined that underlies many different fire risk analysis models. Those models that do not fit this framework may be seen to have different purposes, which should be differentiated by different terms (such as fire hazard analysis), or to be using the term "risk" to refer colloquially to any potentially dangerous situation, however identified or measured. The use of this framework should help to clarify developments in fire risk analysis without excluding any worthwhile method.

1. BACKGROUND

The past decade has seen a proliferation of models and analysis methods labeled as risk analysis tools for fire protection problems. While there has been significant progress along several lines and some practical impact on real decisions, there remains a frustratingly large degree of disagreement and confusion over basic purposes and terminology. In most other areas of fire science, disagreements, however strong, tend to be over the validity of alternative means to achieve a particular modeling objective. In fire risk analysis, disagreements often are more fundamental and involve the basic objectives of modeling.

2. PURPOSE

The field of fire risk analysis would benefit from the development of a conceptual framework sufficiently broad that it can encompass any modeling approach to the analysis of fire risk, however unusual. This framework also should be able to explain how any modeling approach excluded from its broad definition of fire risk analysis fits into the still larger universe of models for generating information on the development and effects of fire. This paper is intended to provide such a framework and to provide summary overviews of known models in the fire risk arena.

3. BASIC CONCEPTS

(a) Let U be the universe of all possible fire situations. That is, each element of U is defined by a complete physical description of a fire; the environment in which it began, developed, and ended; and the consequences of its occurrence. The terminology used to describe elements of U is not standardized among researchers, which accounts for the use here of the new term "fire situation". Some of the terms that have been used include the following:

(i) Scenario. A "scenario" is sometimes used to describe a single element of U (that is, a single fire situation). Alternatively, a "scenario" may refer to groups of elements that share those characteristics that define the initiation, growth, and termination of the fire but which may differ with respect to other characteristics. These other characteristics might include the type of building, vehicle, or other property involved; the number and characteristics of occupants; or physical properties of the building, vehicle, or other property that do not affect the fire development but do affect the harm caused to people or property.

(ii) Exposure. The "exposure" in a fire situation refers to those characteristics of an element of U that specify the number of persons and the quantity of property that may be affected by the fire and their characteristics. "Property" may be used broadly to mean not just the asset value of fixed objects but also the functional capacity of property (such as its ability to sustain productive operations or its ability to support human habitation).

(iii) Context of Use. The "context of use" in a fire situation is a second-order grouping of elements of U because it refers to the context of use of something, typically a particular product, material, assembly, process, operation, or building or other property which is to be the focus of the fire risk analysis. The item (product, material, or assembly), activity (process or operation) or property (building or other property) provides a first-order basis for grouping. (Each fire situation either involves some version of that item, activity, or property, or it does not.) Once it is known that the item, activity, or property was involved - and if involved, which version was involved - then one can specify second-order groupings based on the context of use of that item, activity, or property. For example, if the item of primary interest were upholstered furniture, then the context of use would include the specifications of the building in which the furniture is located, the locations of the pieces of upholstered furniture in the building, and other characteristics of the building and occupants (such as interior finishes, types and locations of other contents proportion of smokers among the occupants) that could be factors in the development of a fire involving upholstered furniture.

(b) Probability Density Function of the Universe of Fire Situations. Let p(e) be the probability density function for the universe (U) of all possible fire events (e) or situations. Therefore:

$$\int_U p(e)\, de = 1.$$

(c) Measure of Severity. Let s be a measure of severity, defined so that (i) the measure can be calculated for every element e of U and (ii) the measure is a monotonic indicator of better and worse outcomes. That is, in comparing two elements of U, if a higher value of s means a worse outcome (a more severe fire) for one pairwise comparison, then in any other pairwise comparison of elements of U, a higher value of s also will mean a worse outcome. This definition does not exclude the use of multiple measures of severity in a single analysis.

Some measures of severity include the following:

(i) Fire deaths
(ii) Fire injuries
(iii) Direct monetary damages to property
(iv) Damage to specific equipment involved in the productive operations of the property
(v) Damage to specific equipment involved in the protection of the property from some non-fire hazard, such as a core meltdown at a nuclear power plant
(vi) Area damaged by fire
(vii) Number of rooms damaged by fire or smoke
(viii) Whether or not fire extended beyond the designated compartmentation space for enclosing, confining, or isolating fires originating in that fire's initial location
(ix) Whether or not the structural integrity of the building was lost
(x) Time for room of fire origin to reach flashover
(xi) Time for first occupied room to reach untenable conditions for human occupation
(xii) Point score, based on assignment of points to various characteristics related to fire development and damage but for which the point scores have no direct physical interpretation

(d) Probability Distribution for a Measure of Severity. The severity function, s, and the probability density function of the universe of fire situations, p(e), jointly define a probability density function P(s) for the severity measure, s. Here, P(s=s') is given by:

$$P(s=s') = \int_U p(e|s(e) = s')\, de.$$

(e) Fire Hazard Analysis. A method for analysis of fire hazard is a method for calculating one or more severity measures, given a specified fire event, e, from the universe of fire situations. The purpose of a fire hazard analysis is to identify patterns in the changes in the severity measure(s) produced by changes in the specified fire event.

(f) Fire Risk Analysis. Analysis of fire risk involves the specification of one or more outcome measures, each of which is a well-defined statistic based on the probability density function of a specified severity measure. A method for analysis of fire risk must specify methods for calculating the outcome measure(s).

The purpose of a fire risk analysis is to measure changes in the outcome measure(s) produced by changes in the underlying probability density function of fire events. The mathematical modeling of these changes may represent the changes as either or both of the following: (a) the probabilities of some fire events are changed, or (b) the characteristics of some fire events, including their severities, are changed.

Some outcome measures that could be used include the following:

(i) Expected loss (that is, the expected value or arithmetic average), such as expected number of deaths or injuries or average monetary property damage.

(ii) Probability of failure (that is, cumulative probability that some qualitative outcome measure is satisfied), such as probability that structural integrity is lost or that fire extends beyond designated containment area or that essential equipment is damaged.

(iii) Expected utility (that is, the expected value of a function that reflects any nonlinear aspects in the evaluation of a particular value of the severity measure).

(iv) Perceived risk (similar to expected utility but incorporating nonlinear phenomena arising from the processing of risk information rather than the evaluation of it).

(v) Expected cost or benefit (or expected value). These are terms used for outcome measures that are expressed in monetary terms. Expected cost might be calculated from the three severity measures of fire deaths, fire injuries, and direct property damage in three steps: (a) Calculate expected loss separately in terms of fire deaths, fire injuries, and direct property damage. (b) Convert the expected loss values for fire deaths and fire injuries to monetary terms by using assumed values for value of a life saved and value of an injury averted. (c) Sum the three expected loss values, now all expressed in commensurable monetary terms.

4. DISCUSSION OF THE BASIC CONCEPTS

In both Japan and the U.S., some of the distinctions embodied in these general definitions are not yet universally employed and some of the possibilities cited are still rare or non-existent. In Japan, there are not yet different words to distinguish the concepts of risk and hazard; the word "kiken" is used for all such concepts. In the U.S., the use of "hazard" for a specific mathematical family of analyses is still rare. "Risk" is often used to refer to both concepts and to other, less precise concepts as well. As noted earlier, the conceptual framework described here is proposed as a means of clarifying discussion, but it is not merely a codification of generally accepted practices.

Major differences among fire risk models or methods typically involve either or both of these two aspects: (1) the choice of severity and outcome measures to be used and (2) the methods proposed for calculation of probabilities and severity measures. The latter tends to be a more traditional area of model differentiation, in which different models will reflect their designers' views on the most valid data sources, the most valid models, the most essential phenomena to be addressed, and the trade-off between the sophistication of the estimate and the cost or time required for calculation. The former choice, however, can reflect more than these technical differences. It may reflect the values and purposes of the users of the analysis.

For example, engineers are accustomed to problems in which events are either catastrophic (the building loses structural integrity and collapses, the dam breaks, the bridge collapses) or inconsequential (the building, dam, or bridge continues to stand). In such situations, appropriate severity measures are inevitably qualitative (whether or not a catastrophic failure occurs) and outcome measures are limited to the cumulative probability that such severe failures occur. Fault tree analysis is a classic example of the application of this view to the risks of fire. This model tends to underlie most of the fire risk analysis methods developed by or for engineers.

In fire, however, this approach is at best a simplification. Meaningful quantitative measures of fire effects do exist and show that fire severity is inherently a matter of degree. At the same time, there are some settings in which an approach using qualitative severity measures will provide a close approximation of the full richness of the real universe of fire situations. In some industrial settings, for example, the management controls may be sufficiently strict that the overall probability of fire is very low, while the likely severity of a catastrophic fire, if it occurred, would be orders of magnitude greater than the severity of even the worst non-catastrophic fire. (For example, in some industrial properties, the most costly fire of the decade involves more loss than all other fires combined in that type of property and that decade.) In such a situation, an analysis based on expected loss and an analysis based on the probability of a catastrophic fire would tend to produce the same results, and the latter might be preferable because it would be much less cumbersome and so would permit analysis of the details of the catastrophic fire situations in greater detail.

In contrast to engineers, economists are accustomed to problems in which all consequences can be reduced to expected monetary values so that changes to reduce fire risk can be evaluated simply by comparing costs saved to costs incurred to effect the changes. In such situations, severity measures should be quantitative and should involve consequences that have value to the owners and occupants of a property. Numbers of fire deaths would qualify, but area damaged by fire would not (unless it could be translated into estimated monetary damages). In the fields of statistics and operations research, such models are collectively referred to as decision analysis.

This approach is also a simplification, not because of the properties of fire but because of the concerns of individuals and organizations with risk. Individuals are concerned about expected loss, but they tend to be disproportionately concerned about the possibility of catastrophic events. Insurance companies are concerned about expected loss because it affects their costs of doing business, but they are unusually concerned about the possibility of catastrophic events that might overwhelm their reserves and drive them out of business. Building owners and property managers are concerned with the effects of expected risk on their costs, but they are even more concerned about the possibility of catastrophic events that will destroy their assets or businesses with no hope of recovery.

In addition to its being a simplification, this approach is also controversial to the extent that it involves the establishment of any equivalence between damage to people (deaths or injuries) and monetary values. Such equivalences are considered unacceptable by large segments of the population of potential users of fire risk analysis. In fact, parts of the U.S. risk analysis community (that is, those individuals whose jobs involve performing risk analyses for a wide diversity of users) and certain regulatory agencies are among the few groups who use such monetary equivalences. They are all but non-existent in Japan. It is therefore important to emphasize that expected loss is a useful approach even if no monetary equivalences for deaths or injuries are used and is particularly appropriate in any setting where overall fire loss tends to be dominated by the cumulative effect of large numbers of non-catastrophic events. This point is especially important in Japan, where fire risk models are much less likely to use any monetary loss severity measures of any kind, in part because the decision-makers (such as insurance companies) who find monetary loss measures in fire risk analysis most useful in the U.S. play a different role in Japan.

To summarize, most users of fire risk analysis will want two kinds of information - information on the expected quantity of loss by some measure and information on the relative likelihood of a catastrophic or unacceptably high level of loss. In some properties (such as tightly controlled industrial properties handling large quantities of hazardous materials), it may be sufficient to address only the relative likelihood of catastrophic loss. For some analyses of national programs, where large numbers of people or properties would be affected and a catastrophic event would have no more weight than many smaller losses, it may be sufficient to address only the expected loss.

5. REVIEW OF SELECTED MODELS

In the full paper, this framework is used to describe and compare the purposes and methods of these models:

(a) Fire Risk Assessment Method sponsored by the National Fire Protection Research Foundation (U.S.)

(b) Fire Safety Design Method of Buildings by the Ministry of Construction (Japan)

(c) Probabilistic Risk Analysis such as is used in the U.S. nuclear power industry (U.S.)

(d) Decision Analysis Method such as is used by U.S. decision analysts (U.S.)

(e) Estimation Method of Life Risk in Hospital Fires by Tsujimoto and Shida (Japan)

(f) Firesafety Concepts Tree by the National Fire Protection Association Technical Committee on Systems Concepts for Fire Protection in Structures (U.S.)

(g) Network Model for Quantitative Risk Analysis by Ling and Williamson (U.S.)

(h) Building Fire Simulation Model by Berlin, Swartz, Fahy, and others (U.S.)

(i) Fire Risk Evaluation Method for Multi-Occupancy Buildings by the Ministry of Home Affairs (Japan)

(j) Commercial Fire Rating Schedule by the Insurance Services Office (U.S.)

(k) Fire Brigade Fire Risk Assessment Method by Strickland (U.S.)

11th Joint Meeting of the
UJNR Panel on Fire Research and Safety

Radiation from Turbulent-Jet Flames and Wall Fires

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

We have made significant progress towards the development of models for predicting the radiation from buoyant turbulent diffusion flames for various fuels and oxidants in terms of tabulated "fundamental" composition properties. Two approaches have been taken: (1) development of a global algebraic model for the thermal radiation from buoyant turbulent-jet diffusion flames; and 2) development of scaling relationships for flame radiation through the use of three parameters: two parameters representing the overall buoyancy flux and the buoyancy due to individual flamelets; and a new radiation parameter relating the radiant losses to the convective heat flow rate. These models utilize experimental data obtained in this study and at other laboratories. Our greater understanding of the roles of gaseous radiant emission and soot radiant extinction provides a platform for describing wall-fire and turbulent-jet flame radiation in terms of fundamental properties and the fuel smoke point.

Our aim in developing a global algebraic model of flame radiation from buoyant, axisymmetric, turbulent-jets is to conserve mass, momentum, species and energy for the flame taken as a whole. The effects of soot production and extinction can be included in this model once we describe the gaseous radiation in the absence of soot. Low sooting fuels such as H_2, CH_4, C_2H_6, etc. have smaller radiant fractions ($0.15 < \chi_r < 0.25$) since most of their flame radiation originates from gaseous products of combustion (H_2O and CO_2). More sooty fuels, such as C_2H_2, C_2H_4, etc. have larger χ_R ($0.35 < \chi_R$) due to their copious generation of soot. This increase in radiant loss fraction with increasing soot causes a strong decrease in the effective flame radiation temperature and consequent radiant emission from the gaseous species. Hence, it takes a many-fold increase in the soot volume fraction to increase radiant fraction from 0.2 to 0.4. Our model for gaseous radiation (see Figure 1) requires the following empirical inputs: 1) McCaffrey's[1] correlations of his centerline thermocouple measurements and observed flame tip heights; 2) the entrainment constant for buoyant axisymmetric turbulent flows; 3) a radiation temperature correction factor based on Markstein's[2] measured effective flame radiation temperature; and 4) thermophysical, chemical and radiant properties of the flame configuration. Predicted radiant fractions for typical hydrocarbon fuels with no incomplete products of combustion and no soot radiant emission are around 12%, which is close to the 15% suggested by the literature. We are currently setting up instrumentation to measure the incompleteness of combustion, which is required by all our models.

In a parallel analysis we have developed a scaling relationship for χ_r and for flame heights. This analysis shows that in addition to the usual hydrodynamic mixing-combustion length-scale, one has a radiative cooling length-scale which results in radiative flame heights being proportional to either $\dot{Q}'^{1/2}$ for planar flames or $\dot{Q}^{1/3}$ for axisymmetric flames in agreement with the recent measurements described below. An empirical correlation for luminous flames based on the fuel smoke-point, ℓ_s, but neglecting gas radiation effects, suggests that $\chi_R \sim \ell_s^{-1/4}$ and explains much of the observed dependence on ambient vitiation and oxygen enrichment, as shown in Figures 2 and 3. This empirical relationship was derived by arguing that χ_R is a function of the ratio of the hydrodynamic to the radiative cooling length-scale. The same scaling concepts have been extended to momentum controlled flame jets and are consistent with our previous measurements of these fires. One should observe that the dependence of the radiant fraction on the "smokiness" of the fuel is weak (i.e. $\chi_{R,T} \sim \dot{Q}_{sp}^{-1/4}$) relative to the dependence of the soot concentration on "smokiness" ($Y_s \sim 1/\dot{Q}_{sp}$). This weak dependence is attributed to the cooling of the flames owing to the radiant losses. The present scaling analysis will be incorporated in turbulence models for predicting soot concentrations, flame radiation and soot yields in turbulent jet flames.

Much of our information on the distribution of thermal radiation for the preceding models has come from detailed studies of axisymmetric and planar turbulent-jet flames as well as wall flames. In experiments with axisymmetric turbulent buoyant-jet flames in a controlled environment enclosure: 1) we have measured the radiant fraction for several hydrocarbon fuels over broad ranges of ambient O_2/N_2 environments and fuel jet dilutions with N_2; 2) we have correlated the measured radiant fractions (see Figure 4) in terms of (i) the fuel mixture/oxidant adiabatic stoichiometric flame temperature, T_{ad}; (ii) the mass of oxidant required to stoichiometrically react with unit mass of fuel, S, (the correlation in Figure 4 is for $S \geq 12$) and (iii) the observed radiant fraction, χ_R^* of the fuel under "standard conditions" (e.g. $T_{ad}^* = 2200K$ and $S^* = 12$), and finally 3) successfully correlated (see Figure 2) the values of χ_R^* under standard conditions against the laminar smoke-point values also under standard conditions. By making the turbulent to laminar flame comparison at standard conditions, the correlation is improved because one eliminates the effects of non-standard T_{ad} and S which have quantitatively different influences on smoke-point and turbulent flame radiation. This empirical result represents a significant milestone because it allows one to predict the turbulent flame radiation from burning fuel jets by knowing only T_{ad}, S and the fuel's smoke point.

We have simulated wall fires of solid fuels in a separate study by burning gaseous hydrocarbon fuels on a water-cooled vertical porous metal surface under steady-state conditions. The burner of 380 mm width is subdivided into a number of panels of equal height (132 mm), so that the simulated pyrolysis height can be varied by the choice of the number of fuel-supplying panels. Currently, five panels topped by a water-cooled heat transfer plate are used, providing an overall height of 2.2 m. Water-cooled sidewalls provide two-dimensional flame structure. In addition to porous-wall fires, a slot burner, placed either adjacent to a heat transfer plate or free burning between sidewalls, produces planar turbulent-jet flames while a nozzle produces axisymmetric jet flames. Instrumentation used in this second study includes a wide-view-angle radiometer for measuring the total radiant emission from the flames, and a scanning slit radiometer for obtaining the vertical distribution (see Figure 5) of radiant power per unit height emitted by narrow horizontal slices across the flames. The scan is obtained by an electromagnetically deflected plane front surface mirror operated in a linear ramp mode. Both instruments employ spectrally flat sensors.

Four fuels of varying sooting tendency, methane, ethane, ethylene and propylene were selected for this study. One of the important results of the work concerns the radiative fraction χ_r of total heat-release rate for the various flame configurations and fuels. Values of χ_r averaged over the range of heat-release rates of about 10 to 60 kW are presented in Table 1.

Table 1. Average Radiative Fractions

Fuel	Jet Flame	Slot Burner Free-Burning	Slot Burner Against Wall
CH_4	.200	.182	.143
C_2H_6	.240	.239	.168
C_2H_4	.372	.371	.240
C_3H_6	.445	.440	.313

The values for free-burning slot-burner flames are only slightly reduced with respect to those for jet flames, but placing the slot burner adjacent to the wall is seen to cause substantial reductions of χ_r. However, all three flame configurations show the same trend with fuel sooting tendency and thus the quantitative relationship between χ_r and fuel smoke point established previously for jet flames can certainly be applied also to free-burning slot-burner flames, and presumably can be generalized for application to wall flames. Power-law exponents relating χ_r to total heat-release rate $\dot{Q}_{tot}$, averaged over the four fuels, were 0.04 ± 0.07 for jet flames, 0.08 ± 0.04 for free-burning slot-burner flames, and 0.18 ± 0.02 for slot-burner flames adjacent to the wall. Results of current work with the porous-metal burner are still incomplete, but indicate further reductions of χ_r relative to those obtained with the slot burner adjacent to the wall, as well as further increases of the power-law exponents.

The vertical distributions of radiant emission per unit height differed significantly for the various flame configurations, as shown in Figure 5. Free-burning slot-burner flames show steeper rise and decay of radiant emission than jet flames; placing the slot burner against the wall reduces the peak radiant emission drastically and nearly doubles the height required for burnout.

The vertical distributions for jet and slot-burner flames exhibit similarity with respect to heat-release rate. For each flame configuration and fuel, the distributions for various heat-release rates can be collapsed into a single dimensionless plot, as seen in Figure 6, by introducing a normalizing length parameter proportional to the variance of the individual distribution. The power-law exponents of this flame-length parameter with respect to heat-release rate are, as noted above in connection with model development, about 1/3 for jet flames and about 1/2 for slot-burner flames, in contrast to the flame-height exponents of 2/5 for jet flames and 2/3 for slot-burner flames derived from fluid-dynamic similarity. Again, results obtained with the porous-metal wall burner are incomplete, but are being evaluated to see whether similarity relationships can be formulated for the distributions of radiant emission from these actual wall fires.

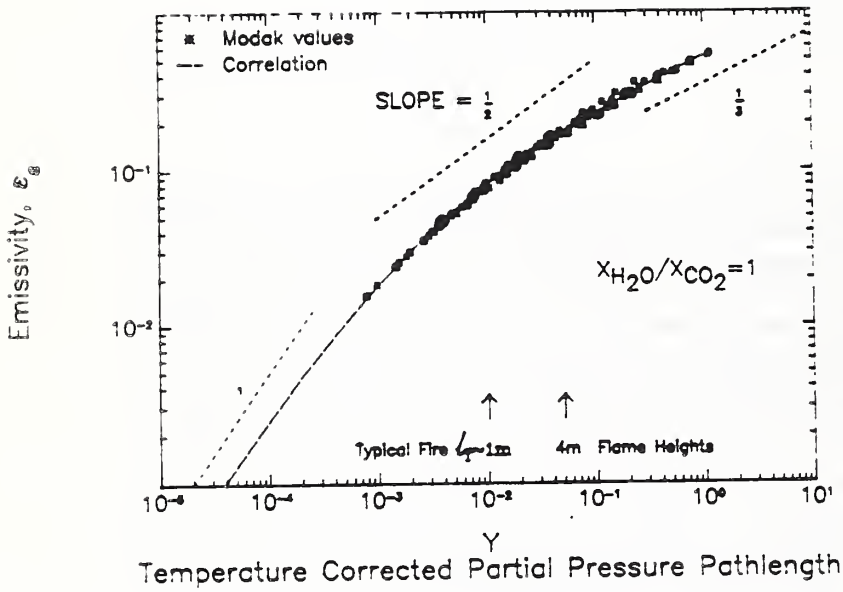


Fig. 1: A general correlation of homogeneous gas emissivity including parameter values of interest for typical fires. ("Modak values" come from curve fits which match and extend experimental values from Hottel.)

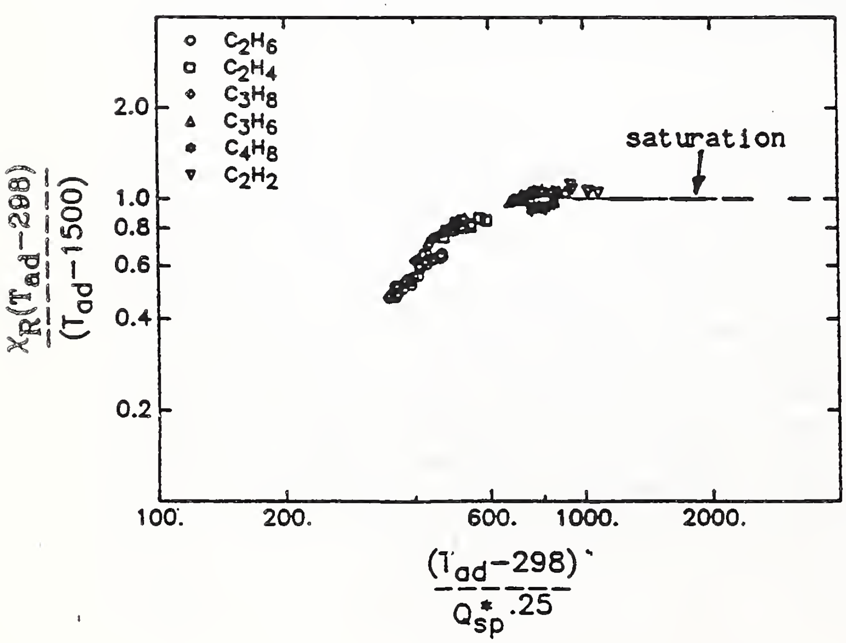


Fig. 2: Radiant fraction for varying adiabatic temperature and stoichiometric ratio $S \geq 12$ (the chemical system is Fuel - N_2/O_2 - N_2)

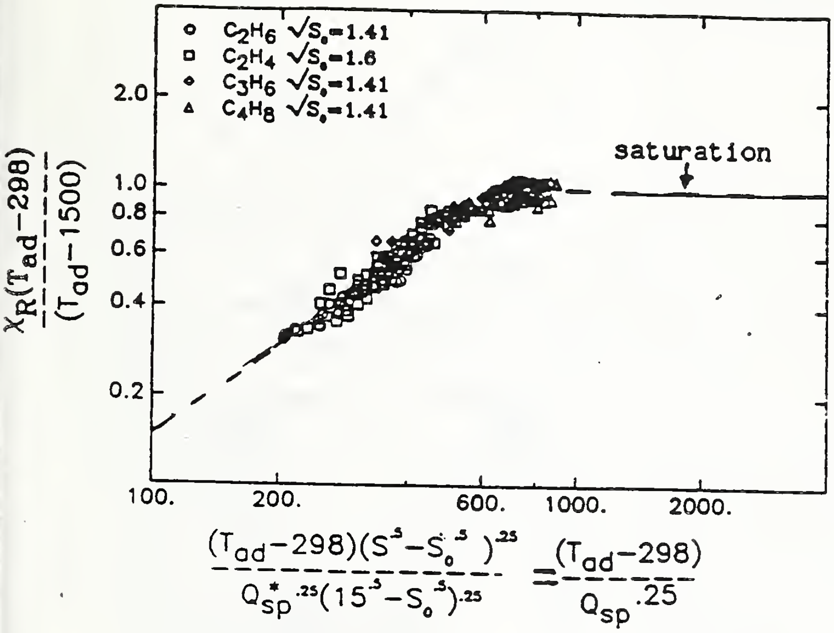


Fig. 3: Radiant fraction for varying adiabatic temperature and all S (the chemical system is Fuel - N_2/O_2 - N_2). S_o is a characteristic cut-off stoichiometric ratio.

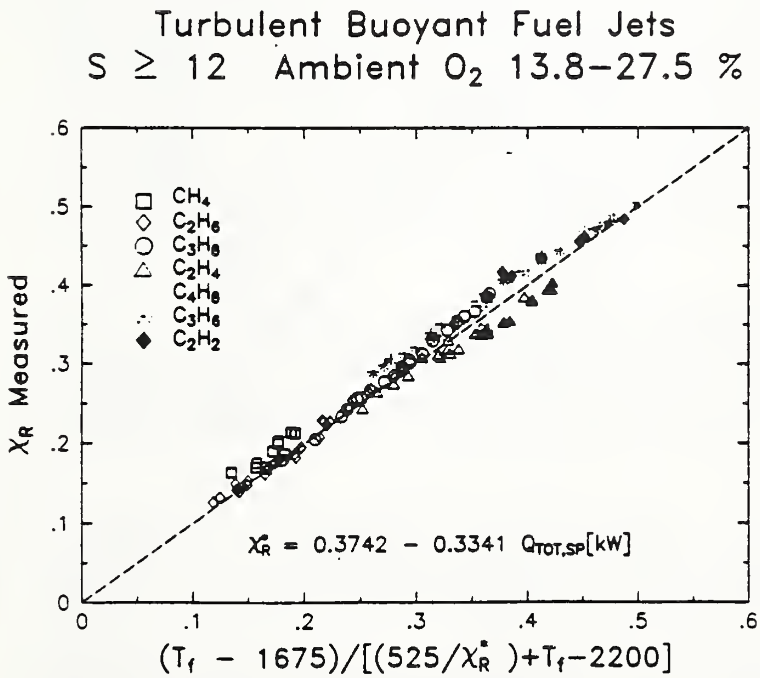


Fig. 4: General correlation of radiant fraction based on χ_R obtained from laminar smoke point.

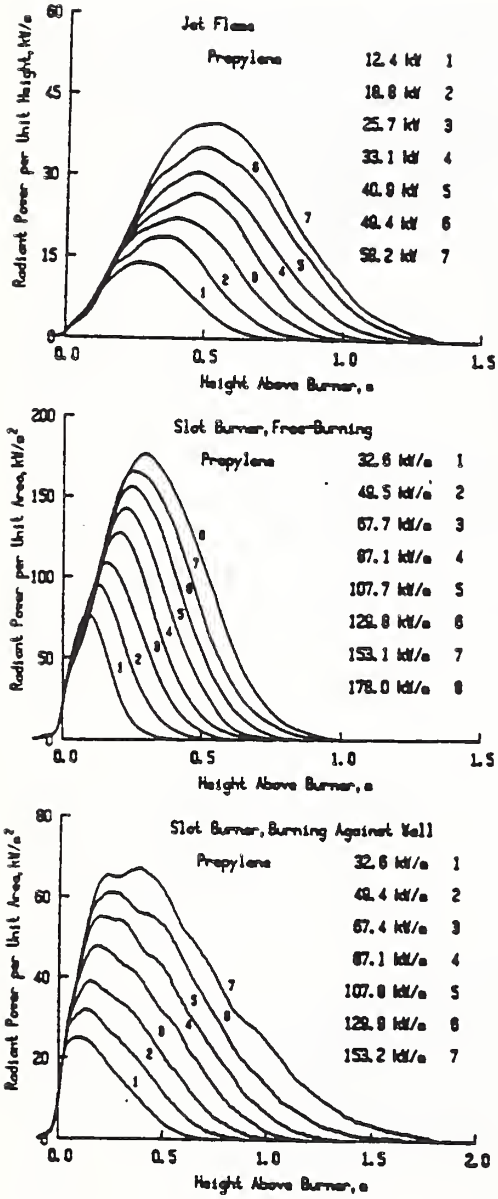


Fig. 5: Vertical Distributions of Radiant Emission

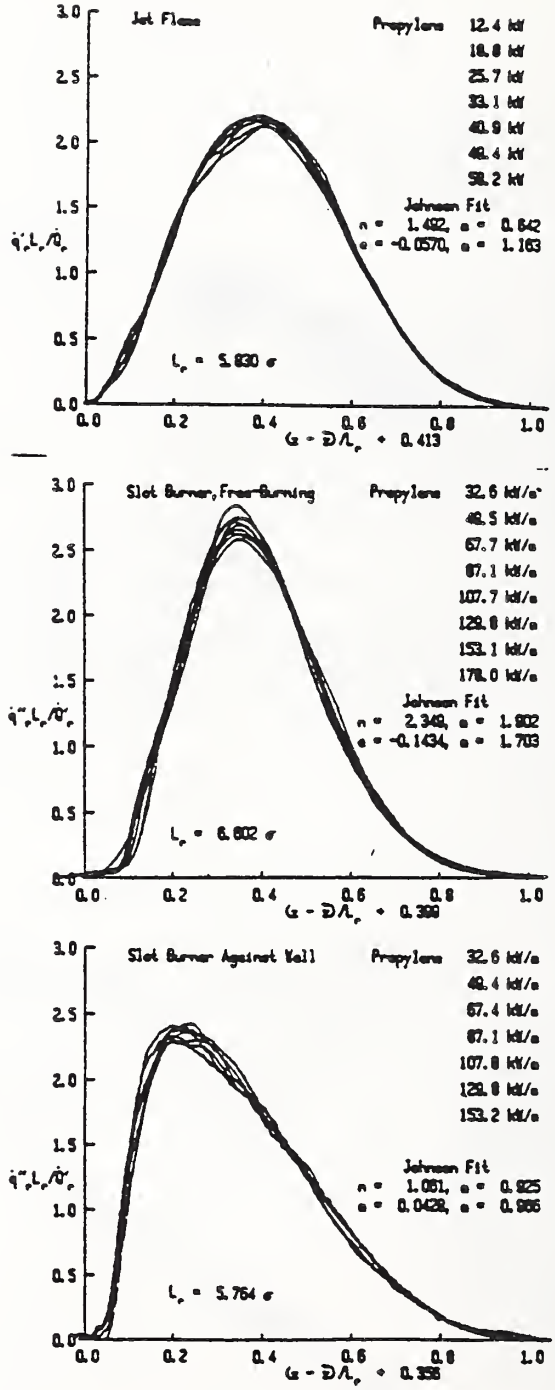


Fig. 6: Normalized Plots of the Data Shown in Fig. 1.

INFLOW OF AIR REQUIRED AT WALL AND CEILING APERTURES TO PREVENT ESCAPE OF FIRE SMOKE

GUNNAR HESKESTAD
ROBERT D. SPAULDING
Factory Mutual Research Corporation
1151 Boston-Providence Turnpike
Norwood, MA 02062, USA

ABSTRACT

Experiments have been conducted to determine critical Froude numbers associated with required inflow of air to a fire space through wall and ceiling apertures to prevent escape of smoke. The experiments were conducted mostly on reduced, model scale, with verification in a 2.4 m high test room. Critical Froude numbers, as formulated, were insensitive to aperture geometry. Those for wall apertures varied slowly and predictably with the vertical temperature distribution in the room, consistent with a discharge coefficient of 0.64 for the inflow. Those for ceiling apertures exhibited a dependence on an aperture Grashof number, with both a high-Grashof number asymptote and an apparent low-Grashof number asymptote. While discharge coefficients for wall apertures can be considered constant near 0.64 for aperture Froude numbers larger than critical, the discharge coefficient for ceiling apertures increased from 0.19 near the critical Froude number, toward the familiar isothermal value for sharp-edged orifices of 0.61 near a Froude number seven times larger than the critical.

1. INTRODUCTION

Smoke control may be practiced according to two different objectives. One objective might be to limit smoke to a fire zone, which always includes the compartment on fire, but may also include contiguous space on the same floor, even an entire floor or several floors of a building. The other objective might be to limit smoke to a fraction of the space of the fire compartment. Accordingly, one may speak of "zoned smoke control" and "compartment smoke control." The present investigation was undertaken to provide data for the design of zoned smoke control systems, addressing specifically the minimum flow rates needed at openings in a boundary to a fire zone from the surrounding space to prevent escape of smoke, i.e., contamination of the surrounding space.

The most relevant previous work is the investigation by Thomas[1] on the minimum air velocity necessary to prevent smoke flowing upstream in a horizontal passage. The critical average velocity in the passage, $\bar{u}_c$ can be expressed in terms of a critical Froude number (assuming 80 percent of the heat generated by the fire source was transferred to the air in the experiments):

$$\dot{u}_c/[2gH\Delta T_{ave}/T_{ave}]^{1/2} = 0.79 \ . \qquad (1)$$

Epstein[2] studied buoyancy induced exchange flows through openings in a horizontal partition of a constant-volume liquid system, with brine initially on top and fresh water initially below the partition. From experiments with two simultaneous circular openings, it was possible to determine a critical volumetric flow rate and associated Froude number for transition between unidirectional flow and bidirectional flow in a 0.045m diameter opening. An analogue critical Froude number exists for escape of smoke from an opening in the roof of a fire compartment:

$$\bar{u}_c/[2gD\Delta T/T]^{1/2} = 0.29 \qquad (2)$$

This result pertains to the specific Grashof number of the experiment, which was:

$$(\Delta\rho/\bar{\rho})gD^3/\nu^2 = 7.0 \cdot 10^5 \qquad (3)$$

2. THEORETICAL CONCEPTS

For an aperture in a vertical wall, a simple theory leads to a prediction for the critical inflow at the aperture which just prevents hot gases from escaping the fire space. The theory is most appropriate for the case where the aperture extends from the floor to the ceiling, Figure 1. Cold air from the surrounding space flows through the aperture of width W into the fire ("hot") space, forming a jet into the fire space which has a vena contracta considerably narrower than the width of the aperture. Since pressures increase more rapidly with depth in the cold space than in the hot space, the critical condition of zero, local velocity in the aperture is first reached at the top of the aperture as the overall throughflow is gradually reduced. Any further reduction in throughflow causes hot gases to back up into the cold space. Bernoulli's equation can be written for any elevation, y, between the quiescent cold space and the vena contracta, where the horizontal velocity profile is considered uniform, which provides an expression for u(y/H) in the vena contracta. At the critical condition, u(1) = 0, which fixes the vertical velocity profile in the vena contracta in terms of the temperature distribution in the hot space. The average (cold) velocity through the aperture at the critical condition, $\bar{u}_c$, can be defined from the total volumetric flow rate and the aperture area, whose nondimentional form,

$$Fr_c = \bar{u}_c/(2gH\Theta_H)^{1/2}, \qquad (4)$$

is the critical Froude number. The following prediction is established for the critical Froude number:

$$Fr_c = CP. \qquad (5)$$

Here, C is the discharge coefficient or coefficient of contraction, often found to be near 0.6 for isothermal flows through sharp-edged circular and slot orifices. The quantity, P, is a temperature distibution parameter for the hot space, defined:

$$P = \int_o^1 \left[\int_{y/H}^1 (\Theta/\Theta_H)\, d(y'/H)\right]^{1/2} d(y/H)\ . \qquad (6)$$

For a uniform vertical temperature profile, P = 2/3 .

If the aperture does not extend from floor to ceiling, there are difficulties with the simple theory since it cannot be assumed that there is no contraction of the cold jet into the hot space in the vertical direction. One might still expect Eq. (5) to be applicable, with H (in definition of Fr_c and P) taken as the height of the aperture, but possibly with a different value for the coefficient, C.

Viscous effects on the aperture flow, if they exist, are expected to depend on the Grashof number:

$$Gr = g\rho_c^2\ \Theta_H\ (HW^2)/\mu^2, \qquad (7)$$

where μ is evaluated at the mean of the hot and cold temperatures.

Transitions between bidirectional and unidirectional flows, of the kind included in Epstein's studies[2] and the issue of concern in connection with ceiling apertures, are extremely complex and no theory is attempted for this case. In general, the state of the flow at a horizontal aperture, with a hot fire space below and cold ambient space above, will be governed by Froude and Grashof numbers akin to those defined for vertical openings in Eqs. (4) and (7), except H is replaced by the aperture width, W. The critical Froude number for ambient air flowing into the fire space, just sufficient to prevent escape of smoke, will be a function of the Grashof number, where the two nondimensional groups are defined:

$$\text{Critical Froude Number: } Fr_c = \bar{u}_c/(2gW\Theta_{c\ell})^{1/2} \qquad (8)$$

$$\text{Grashof Number: } Gr = g\rho_c^2\ \Theta_{c\ell}W^3/\mu^2\ . \qquad (9)$$

Here, $\Theta_{c\ell}$ is $\Delta T/T$ evaluated at the ceiling level (away from the thermal boundary layer).

3. EXPERIMENTAL ARRANGEMENT

Most of the experiments were conducted in a reduced scale facility having a ceiling height of 0.61 m. The facility consisted of a square fire compartment measuring 2.44 m on the side, with an air supply plenum attached to one side of the compartment, in which various wall apertures were mounted, and with two floor-to-ceiling ventilation openings for the fire in the opposite side. As fire source was used a 0.31 m diameter "sandbox" gas burner flush with the floor near the ventilation wall, burning propylene or propane at rates from 8 to 165 kW (corresponding to 270-5600 kW in a 2.5 m high room). Temperatures were measured at several elevations in the fire compartment and the air plenum, and the pressure differential between the plenum and fire compartment was monitored at midheight of the facility. Following ignition, temperatures in the fire compartment were allowed to approach a steady state. Then the flow rate of conditioned air from the plenum was decreased in 10 percent steps until the first indication of smoke by a photometer in the plenum. The critical flow rate was taken as the average of the first flow rate indicating presence of smoke and the immediately preceding flow rate. Figure 2 illustrates the wall apertures investigated, formed by 2.7 or 1.7 mm thick steel plating.

For investigation of ceiling apertures, the air plenum was positioned over apertures in the ceiling of the fire compartment near the wall of the compartment opposite the burner. Figure 3 shows the various ceiling apertures, cut in 1.7 mm steel plates.

A fire test room was available from a previous program to investigate door-size apertures (0.92 m x 2.03 m) in wall and ceiling. The fire test room, measuring 3.7 x 7.3 x 2.4 m high, was exhausted by a blower via 0.61 m diameter ducting attached to one of the walls of the test room and provided with flow metering. Vertical thermocouple traverses were provided in the room. As fire source was used heptane floated on water in a 0.5 m diameter container (approximate heat-release rate of 150 kW). The critical flow conditions for escape of smoke were determined by visual observation of the aperture flows, which were illuminated by flood light. Observations began after temperatures in the room had stabilized.

In analogy with the reduced-scale tests, the exhaust flow was reduced in small steps until smoke puffs were first observed to escape into the laboratory (at the top of the door, or above central regions of the ceiling aperture). It was possible to determine rather narrow flow brackets, no smoke versus smoke into the laboratory, for both apertures.

4. CRITICAL FROUDE NUMBERS

Figure 4 presents critical Froude numbers for the wall apertures, defined in Eq. (4), as a function of the temperature distribution parameter, P, defined in Eq. (6). (Some of the tests had to be discarded, because unacceptable density variations built up in the air plenum due to heat transfer from the fire compartment to the plenum through the common wall.) The straight, dashed line is a fair representation of the data, drawn to satisfy Eq. (5). This line corresponds to a discharge coefficient, $C = 0.64$. Note that most of the data are well represented by this line, i.e., the floor-to-ceiling apertures, high rectangular apertures, low rectangular apertures, central rectangular apertures, central circular aperture, and the normal-size doorway. The range in P from 0.53 to 0.67 may cover most practical cases, from highly non-uniform vertical temperature profiles at low heat release rates to nearly uniform profiles at high heat release rates. The accompanying variation in Fr_c is seen to be 0.32 to 0.43. No effect of the Grashof number (Eq.(7)) has been seen in the data of Figure 4.

Critical Froude numbers for ceiling apertures, defined in Eq. (8), are presented in Figure 5 as a function of the Grashof number, defined in Eq. (9). Here there is a definite effect of the Grashof number, with a high-Grashof number asymptote near $Fr_c = 0.23$ and an apparent low Grashof number asymptote near $Fr_c = 0.38$, separated by a transition range. There is no apparent effect of aspect ratio. Nor is there an effect of the orientation of a rectangular aperture. This latter finding, together with the small effect observed of a partial partition for Aperture I (partial wall between aperture and fire source), imply that gas motion in the ceiling gas layer had little effect on the critical conditions for escape of smoke.

5. PRESSURE DIFFERENTIALS AND DISCHARGE COEFFICIENTS

Pressure differentials measured across the floor-to-ceiling wall aperture at the critical Froude numbers, adjusted to the top of the aperture by hydrostatic corrections using the vertical temperature profiles, were verified to be close to zero, as assumed in the theory. The discharge coefficient best fitting the theory to the experiments for critical conditions in apertures of vertical walls, $C = 0.64$, is close to the value 0.61 often found to represent isothermal forced flows through sharp-edged orifices and slots. Consequently, it appears safe to assume a discharge coefficient of comparable magnitude for calculation of all supercritical flows through wall apertures.

For the ceiling apertures, the measured pressure differentials were converted, using hydro-static corrections, to pressure differentials across the ceiling, at the level of the ceiling. Most of the data pertained to the critical Froude numbers and slightly larger, but limited data were also obtained at considerably larger Froude numbers. Discharge coefficients, C, were calculated from:

$$\dot{m} = CA\,(2\rho_c \Delta p)^{1/2}\,, \tag{10}$$

where $\dot{m}$ is the mass flow rate through the aperture for a given pressure differential across the ceiling, Δp. The discharge coefficients are plotted as a function of Froude number in Figure 6. For the high asymptotic range ($Gr \geq 2 \cdot 10^7$), the familiar isothermal flow limit, 0.61, appears to be approached at a Froude number of 1.5. The pressure differential across the ceiling can be calculated from:

$$\Delta p = (Fr/C)^2 \rho_c g W \Theta_{c\ell} \quad (11)$$

6. COMPARISON WITH PREVIOUS WORK

The critical Froude number derived from Thomas' work to prevent smoke from backing up in a horizontal passage[1], Eq.(2), can be converted to the form adopted in the present study:

$$Fr_c = 0.79 \left[(\Delta T_{ave}/T_{ave})/(\Delta T_H/T_H)\right]^{1/2} \quad (12)$$

The vertical temperature distributions in Thomas' experiments are not known. It will be assumed they were rather steep, with a representative value of 0.5 for the temperature ratio within brackets in Eq. (12), as for the lowest heat release rate experiments in the current study. Then Thomas' result corresponds to $Fr_c = 0.56$. For a flow passage, having a discharge coefficient of 1, the present results correspond to (cfr. Eq. (5)):

$$Fr_c = P \quad (13)$$

The experiments indicated a close correlation between P and the temperature ratio in Eq. (12); for a temperature ratio of 0.5, the value P = 0.55 was indicated. Hence the present experiments imply the value $Fr_c = 0.55$ for a horizontal passage, in good agreement with the value deduced from Thomas' experiments, $Fr_c = 0.56$.

Eq. (2) was inferred from Epstein's work for the critical Froude nmber to prevent escape of smoke from a ceiling vent, i.e., $Fr_c = 0.29$, associated with a Grashof number of $7 \cdot 10^5$. According to Figure 5, the present study indicates $Fr_c = 0.38$ at the same Grashof number, a somewhat higher value.

7. CONCLUSIONS

1. Critical Froude numbers of air inflow to prevent escape of smoke from wall apertures, Fr_c (Eq. (4)), were found to be insensitive to aperture geometry, consistent with simple theory and an experimental discharge coefficient of 0.64. Values of Fr_c varied from 0.32 to 0.43 in the tested range of vertical room temperature distributions (Figure 4).

2. Critical Froude numbers of air inflow to prevent escape of smoke from ceiling apertures, Fr_c (Eq. (8)), were also insensitive to aperture geometry and approached an asymptotic value $Fr_c = 0.23$ at Grashof numbers (Eq. (9)) greater than $2 \cdot 10^7$. An apparent asymptote was also reached at Grashof numbers smaller than $5 \cdot 10^6$, $Fr_c = 0.38$.

3. Discharge coefficients for ceiling apertures were found to increase with the Froude number (Figure 6), starting near 0.19 at $Fr = Fr_c = 0.23$ and approaching 0.61, the familiar isothermal value for sharp-edge orifice flows, near Fr = 1.5 (high Grashof number range). Discharge coefficients for wall apertures can be assumed to remain near 0.64 (Conclusion 1) as Froude numbers increase above Fr_c.

SYMBOLS

A	area of aperture
C	discharge coefficient
D	diameter
Fr	Froude number, $\bar{u}/2gH\Theta_H)^{1/2}$ for wall apertures and $\bar{u}/(2gW\Theta_{c\ell})^{1/2}$ for ceiling apertures
Fr_c	critical value of Fr to prevent escape of smoke from aperture
Gr	Grashof number, Eq. (7) for wall apertures and Eq. (9) for ceiling apertures
g	acceleration of gravity
H	height of aperture or passage
$\dot{m}$	mass flow rate
P	temperature distribution parameter, Eq. (6)
Δp	pressure differential across aperture
T	compartment temperature
T_{ave}	average dowmstream temperature in passage
T_c	temperature in quiescent cold space
T_H	temperature at top level of aperture
T_∞	ambient temperature
ΔT	$T-T_c$
ΔT_{ave}	$T_{ave}-T_\infty$
ΔT_H	T_H-T_c
u	velocity
$\bar{u}$	average velocity in aperture or passage (volumetric flow rate in ratio to flow area)
$\bar{u}_c$	critical $\bar{u}$ to prevent escape of smoke from aperture
W	aperture width (being smaller dimension of a recentangular ceiling aperture)
y	height above bottom of aperture
Θ	$\Delta T/T$
$\Theta_{c\ell}$	Θ just under ceiling
Θ_H	Θ at top level of aperture
μ	dynamic viscosity
ν	kinematic viscosity
ρ	density in quiescent hot space
ρ_c	density in quiescent cold space
$\bar{\rho}$	mean density of two liquids
$\Delta\rho$	density difference between heavier and lighter fluid ($(\rho_c-\rho)$ in fire applications)

REFERENCES

1. Thomas, P.H., "The Movement of Smoke in Horizontal Passages Against an Air Flow," Fire Research Note No. 723, Fire Research Station, Boreham Wood, Herts, England, September 1968.

2. Epstein, M., "Buoyancy-Driven Exchange Flow Through Small Openings in Horizontal Partitions," ASME Journal of Heat Transfer, Vol. 110, 1988, pp. 885-893.

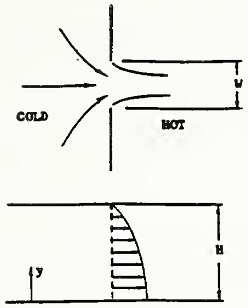


Figure 1 Critical flow conditions at a wall aperture extending from floor to ceiling.

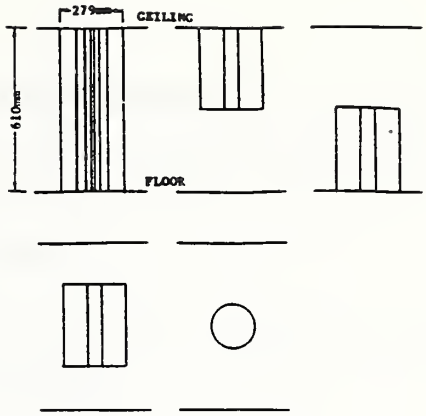


Figure 2 Wall apertures

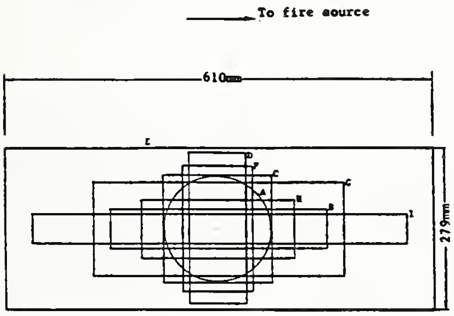


Figure 3 Ceiling apertures

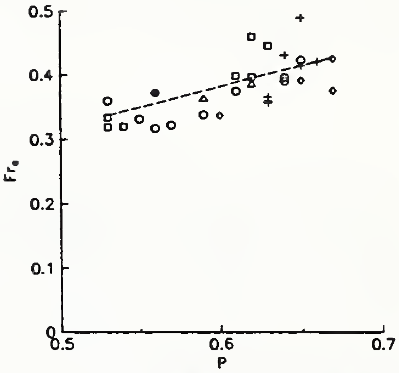


Figure 4 Critical Froude number for wall apertures; ○ floor-to-ceiling apertures; + high apertures; △ low apertures; □ central apertures; ◇ central circular aperture; ● doorway, larger-scale.

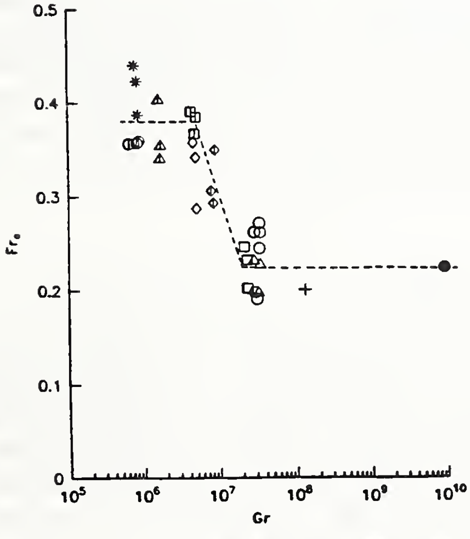


Figure 5 Critical Froude numbers for ceiling apertures: Except for ● (normal doorway), the symbols represent apertures identified with corresponding letters in Figure 3 according to ○(A), ▲(B), △(C), ⊞(D), +(E), ⦶(F), □(G), ◇(H), ✱(I), ⦶(I with partition).

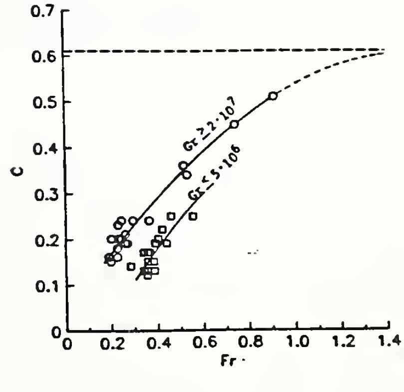


Figure 6 Discharge coefficients for ceiling apertures.

Estimation of Thermal Radiation from Large Pool Fires

Hiroshi Hayasaka
Faculty of Engineering
Hokkaido University
Kita-ku, N13, W8, 060 Sapporo, JAPAN

Hiroshi Koseki
Fire Research Institute
Nakahara 3-14, Mitaka, 181 Tokyo, JAPAN

ABSTRACT

The one mesh model[1], which has been developing by one of authors recently, is employed to estimate thermal radiation from large pool fires having diameters over 10m. The predicted results are compared with the experimental results.

1. INTRODUCTION

Thermal radiation plays a very important role in pool fires, because the burning rate of large pool fires is greatly influenced by radiative heat transfer. The problem of thermal radiation hazards also depends on the characteristics of radiative heat transfer. In an attempt to estimate thermal radiation from pool fires, the authors have been devising a new and simple simulation model which is called the one mesh model. The analytical results of the one mesh model were compared with the experimental results and values in the literatures[2-7].

2. EXPERIMENT

Kerosene pool fire tests were conducted under a quiescent atmosphere of a large indoor test space of FRI(24mx24m,20mhigh). The size of pool fires were 1m round and 2.7m square tanks. Radiative heat from flames was measured with wide angle radiometer located at a distance 5D (D is the tank diameter) from the center of the tank. Kerosene was fed above water which was filled into the tank before experiment. Burning rate was measured by electrical float level meter. These experimental setup is shown in Fig.1.

3. ANALYTICAL MODEL

3.1 FLAME MODEL FOR POOL FIRES AND HEAT BALANCE EQUATION A simple analytical model which is called one mesh model is introduced to estimate thermal radiation from large pool fires. The one mesh model has been recently developing by one of the authors. The flame shape of pool fires is assumed to be a cylindrical one for simplicity as shown in Fig.2. Properties such as temperature, T_f and absorption coefficient, k are considered to be uniform within the flame model. Heat generation due to the combustion of fuel is assumed to take place within the flame model. Therefore, the heat balance equation for this flame model are made up of heat generated by combustion of fuel, $Q_{f,i}$, heat carried with entrained air, $Q_{a,i}$, radiative heat from the surrounding air, $Q_{r,i}$, heat of fuel vaporization, $Q_{f,o}$, heat carried away from the top of the flame by flown, $Q_{g,o}$ and heat loss by radiation to the surroundings, $Q_{r,o}$. These heat terms are shown in Fig.2 with arrow. Then the heat balance equation is:

$$Q_{f,i}+Q_{a,i}+Q_{r,i}=Q_{f,o}+Q_{g,o}+Q_{r,o} \quad (1)$$

where $Q_{f,i}$ is:

$$Q_{f,i}=\eta m_f \Delta H_c \quad (2)$$

where η is the combustion efficiency, m_f is the fuel burning rate(kg/s), ΔH_c is the heat of combustion(Ws/kg).

$Q_{a,i}$ is:

$$Q_{a,i}=m_a c_{pa} T_a \quad (3)$$

where m_a is the mass velocity of entrained air(kg/s), c_{pa} is the specific heat of air(Ws/(kgK)), T_a is air temperature(K).

$Q_{f,o}$ is:

$$Q_{f,o}=m_f(\Delta H_f+(T_b-T_a)c_f) \quad (4)$$

where ΔH_f is the heat of vaporization(Ws/kg), T_b is the boiling point of fuel(K), c_f is the specific heat of fuel(Ws/(kgK)).

$Q_{g,o}$ is:

$$Q_{g,o}=(m_a+m_f)c_{pg}T_m \quad (5)$$

where c_{pg} is the specific heat of combustion gas(Ws/(kgK)), T_m is mean temperature of of the flame model.

Other terms of $Q_{r,o}$ and $Q_{r,i}$ are described in the following section.

3.2 RADIATION MODEL FOR POOL FIRES Total heat loss by radiation to the surroundings of the flame model, $Q_{r,o}$ is:

$$Q_{r,o}=4(1-\alpha_s)\sigma k_m T_m{}^4 V \quad (6)$$

where σ is Stefan-Boltzmann constant($5.67\times10^{-8}W/(m^2K^4)$), V is flame volume and α_s is a self-absorption factor. Approximate value of α_s for various shapes of gas mass can be calculated easily using the following equation cosisting of k_m, V and a surface area of the flame model, S.

$$\alpha_s=1-(1-\exp(-ck_mL))/(k_mL) \quad (7)$$

where c is a factor, which is given in the reference[8], for various gas shapes. L is the mean beam path length and can be expressed as:

$$L=4V/S \quad (8)$$

Radiation from the entire flame model is assumed to be emitted uniformly to the surroundings from the point which located on the center line of flame of height D above the tank. Therefore the radiative energy per unit area q_x at the distance L=5D is:

$$q_x=(1-\alpha_s)Q_{r,o}/(4\pi(L^2+D^2)) \quad (9)$$

Measured and calculated irradiance are compared at a dimensionless distance of 5(=L/D) in this paper.

$Q_{r,i}$ is radiative heat from the surrounding air:

$$Q_{r,i}=\sigma\varepsilon_a S T_a{}^4 \quad (10)$$

ε_a is an emissivity of air and set to unity.

$Q_{f,o}$ of eq.(4) is also expressed as:

$$Q_{f,o}=\sigma\varepsilon_{base}A_sT_{base}^4+A_sh_s(T_m-T_b) \quad (11)$$

where ε_{base} is an emissivity at the bottom of the flame model:

$$\varepsilon_{base}=1-\exp(-0.814*0.85kD) \quad (12)$$

T_{base} are the temperature at the flame model bottom and h_s is a convective heat transfer coefficient between flame and fuel surface.

3.3 ANALYTICAL MODEL FOR AIR ENTRAINMENT AND FLAME HEIGHT To obtain $Q_{r,o}$, $Q_{r,i}$ and m_a, the following mathematical model is introduced to the one mesh model. According to Fang[9] and Ndubizu[10], the rate of air entrainment into the flame model can be obtained if we know the flame height above the tank H_f, Froude number Fr, heat generation in the fire and properties of the ambient atmosphere. The flame height H_f is given by

$$H_f=y_0 1.49\theta_1^{1/5}Z^{2/5} \quad (13)$$

where y_0 is radius of the tank, θ_1 is given by

$$\theta_1=\omega(\omega/\rho_o'+\gamma/X_{o2})^2/\alpha_f^4/(1-\omega) \quad (14)$$

where γ is the stoichiometric oxygen/fuel ratio, X_{o2} is the oxygen mass fraction in the air, α_f is the entrainment coefficient, ω is given by

$$\omega=M/M_a/(1+(\Delta H_c X_{o2})/(\gamma c_{pa}T_a)) \quad (15)$$

where M is average molecular weight of species in the fire,
M_a is molecular weight of environmental air. Z is the modified Froude number and given by

$$Z=\rho_o'Fr^{1/2} \quad (16)$$

where Fr is the Froude number and given by

$$Fr=(m_f/\rho_v/A_s)^2/(gy_0) \quad (17)$$

where ρ_v is the density of vapor , A_s is the area of fuel surface, g is acceleration due to gravity. ρ_o' is the normalized density at the fuel surface and is given by

$$\rho_o'=M_fT_a/(29T_s) \quad (18)$$

where M_f is the molecular weight of fuel, T_s is fuel surface temperature. Finally, the rate of air entrainment into the flame model m_f is

$$m_a=m_f\rho_o'^{-1}\omega((0.4\alpha_fX_iH_f/y_0+1)^{5/2}-1) \quad (19)$$

where X_i is

$$X_i=((1-\omega)/(\alpha_f\omega Fr))^{1/5} \quad (20)$$

3.4 ANALYSIS PROCEDURE The calculation procedure of the one mesh model is shown in Fig.3. If a tank diameter D, absorption coefficient k and fuel properties are given, m_f, m_a, H_f and q_x can be obtained usually after several times of iteration.

4.RESULTS AND DISCUSSION

The one mesh model has been tested on kerosene pool fires of tanks with diameters of 0.1m to 100m. The predicted and measured fuel burning rate are shown in Fig.4. The solid line represents the calculated results by the one mesh model.The one mesh model does well in predicting the burning rate of large diameter fires (D > 2m). The predicted and measured irradiance at L/D=5 are shown in Fig.5. The solid and broken lines represent the calculated results by the one mesh model. The one mesh model does well in predicting the burning rate of large diameter fires (D < 2m). Unfortunately, the one mesh model can not predict large diameter fires (D > 3m) at present. This is because the combustion model which can predict the efficiency of combustion has not been completed. However broken lines in Fig.5 express the effect of the efficiency of combustion on irradiance and we can notice the efficiency of combustion may decreases rapidly when tank diameter exceeds 10m.

5.CONCLUSION

A simple analytical model which is called the one mesh model has been developing to predict the characteristics of pool fires. The predicted and measured fuel burning rate and irradiance of kerosene pool fires show good agreement but further work to make the combustion model which can predict the efficiency of combustion is needed.

REFERENCES

1. Hayasaka, H. and Koseki, H., Joint Conf. of WS-JS, the Combustion Institute., p.250, 1987.
2. Blinov, V.I. and Khudyakov, G.N., Izv. Akad., Nauk,SSSR 1961.
3. Uehara, Y., Yumoto, T. and Nakagawa, S., FRI Report No.37, 1973.(in Japanese)
4. Japan Society of Safety Engineering, 1979.(in Japanese)
5. Yumoto, T., Sato, K. and Koseki, H., J. of Fire Research Institute, p.30, 1981.
6. Yumoto, T. and Koseki, H., Unpublished data.
7. Mizner, G.A. and Eyre, J.A., I. Chem. E. Symposium Series, No.71, p.147,1982.
8. Hottel, H.C. and Sarofim A.F., Radiative Transfer, McGraw-Hill, 1967.
9. Fang, J.B., NBSIR-73-115, NBS(U.S.A.), 1973.
10. Ndubizu, C.C., Ramaker, D.E., Tatem, P.A. and Williams, F.W., Combustion Science and Technology, Vol.31, p.233, 1983.

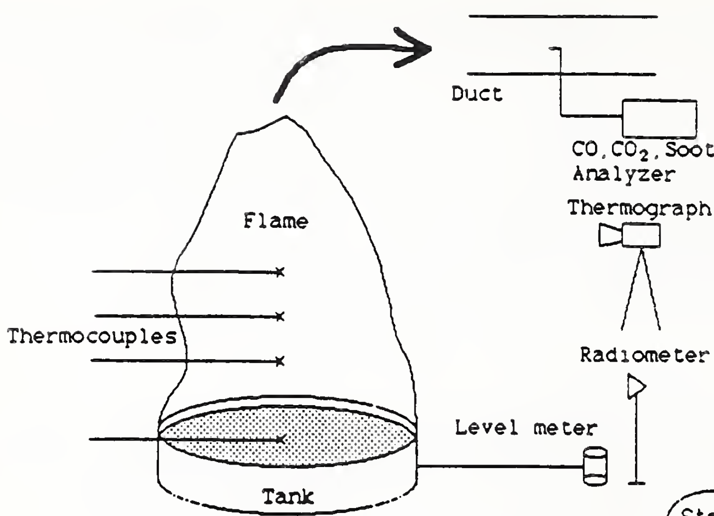


Fig.1 Schematic of experimental set up

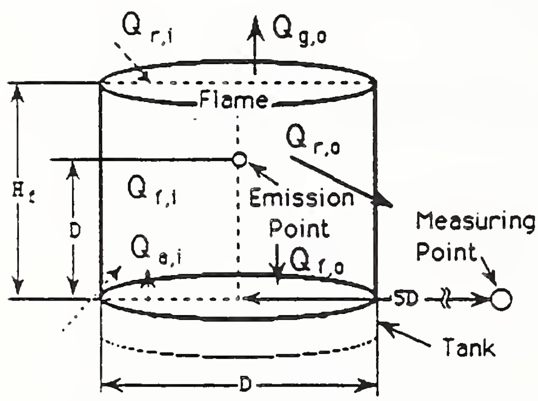


Fig.2 Flame model of the one mesh model

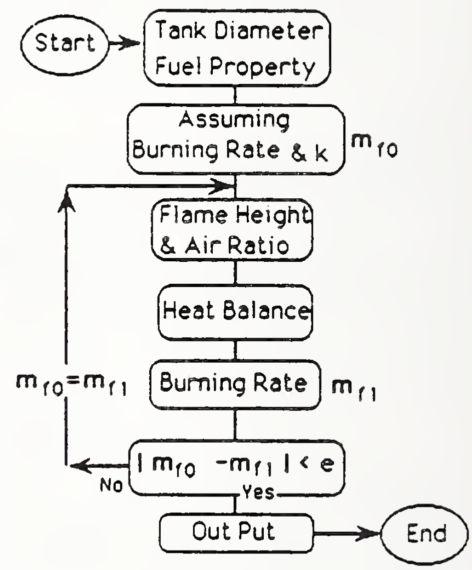


Fig.3 Computational procedure

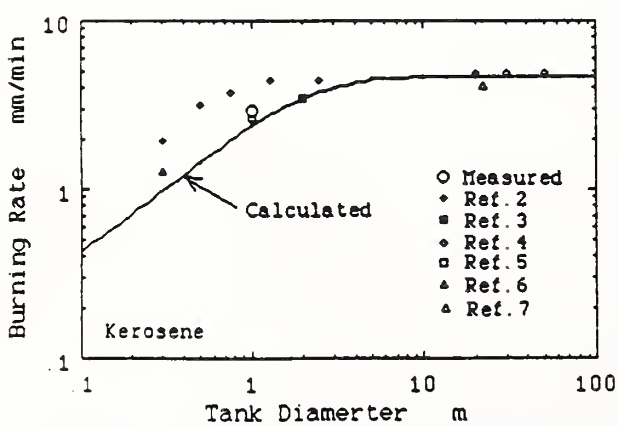


Fig.4 Burning rate

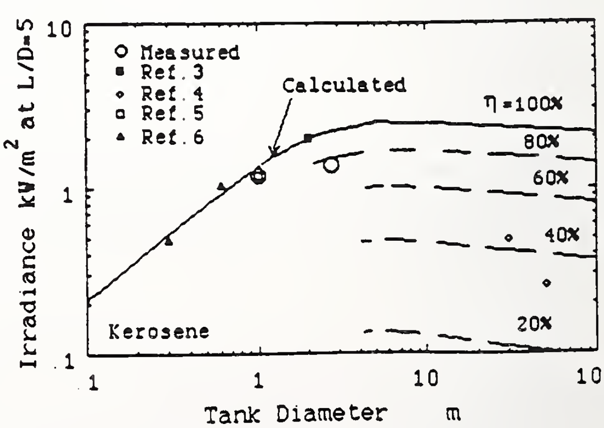


Fig.5 Irradiance

Burning Behavior in a Poorly-ventilated Compartment Fire
-- Ghosting Fire --

Osami Sugawa, Kunio Kawagoe, and Yasushi Oka

Center for Fire Science and Technology
Science University of Tokyo
2641 Yamasaki, Noda-shi, Chiba 278, Japan

Abstract
We have investigated fire behavior in a poorly ventilated compartment using a methyl alcohol pool fire as a source in a box of 2m(W) x 3m(L) x 0.6m(H). Temperatures, gas concentrations of CO, CO_2, and O_2, fuel consumption rate were measured simultaneously. The level of the fuel surface was kept constant during the tests by means of automatic fuel supply system. The flame began to detach from the fuel surface as the oxygen concentration decreased to about 16 vol.%, it color then becoming pale blue. The flame later detached completely from the fuel and a blue "ghosting flame" was observed just under the ceiling like an aurora. The oxygen concentration measured under the ceiling in the ghosting period under the ceiling was 9 - 10 vol.%, and the CO_2 was 4.5 vol.% so that the oxygen acted as an inert gas. The CO_2 gas concentration was almost uniform with a gradient in the upper part in the ghosting period. Temperatures in the same layer decreased after ghosting occurred also with a gradient. For these fires, the air exchange rate as 1.6 - 2.4 times/hr was estimated, and the burning rate decreased finally to about 1/6 of that of the fuel controlled fire.

key words : ghosting, poor ventilation, compartment fire, detached flame

1. Introduction

We have conducted about 40 fire tests in an enclosure with low ventilation, exploring fire behavior for fuel rich conditions. These tests were carried out to improve a model compartment fires to accommodate better the condition of very low natural ventilation which obtains in some recently designed residential buildings and energy power plants. To avoid the leakage and diffusion of radiative particles from atomic power plants, small air exchange openings are provided in the plant building. It is plausible that in such a power plant a fire would become a ghosting fire in the energy rich and poor-ventilation condition [2] that obtain. It has been tacitly assumed in the past that flame (reaction zone) and pyrolyzing material (fuel) leave the compartment together, but for the ghosting fire this is not necessarily so. Therefore, for the extinction of ghosting fires in a poorly ventilated enclosure with excess fuel and energy rich as in a power plant may be extremely difficult.

2. Experiment

A model compartment 2 m width x 3 m long x 0.6 m height was made with calcium silicate boards used as outer walls and ceramic boards inside. (see in Figure 1). Two adjustable slit panels were provided on the upper area of the front wall which was 60 cm x 60 cm with a observation window. A detachable opening door was also provided in it. The door was closed and sealed during tests.

Methyl alcohol in a stainless steel pan of 30 cm diameter set 40 cm above the floor at the center of the box was used as a fire source. The fuel was supplied from a reservoir through a copper tube to keep the fuel level constant during the burning, and the consumption measured.

Temperatures were measured by 0.3mmϕ chromel-alumel thermocouples with stainless steel sheath cover on a vertical rake so that a vertical temperature profile could be obtained.

Concentrations of CO and CO_2 were measured by gas analyzers of non-disperse Infra-red detecting type, and oxygen was measured simultaneously by a galvanic battery type detector.

In order to find the experimental condition to obtain the ghosting fire [1], we took an unexpectedly long time to improve the sealing of the joints between the boards, and is find a suitable arrangement of its small opening and the vertical position of the fuel pan. The final procedure was; the fire source was ignited by a pilot flame and then the door was closed and sealed. After 4 min from the ignition, the total opening area of the both slits was adjusted to 150 - 160 cm^2 to avoid choking and to limit the ventilation.

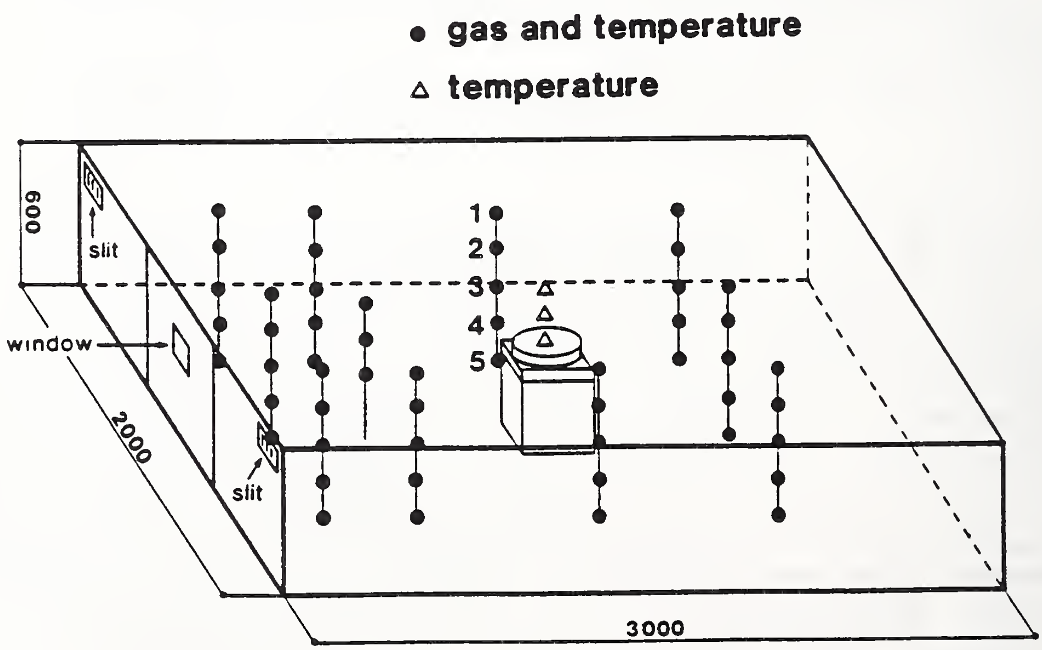


Figure 1-(a) Outline of the experimental box for the ghosting. Numbers correspond to the height from the floor, as 1:600mm, 2:450mm, 3:300mm, 4:150mm, and 5:5mm.

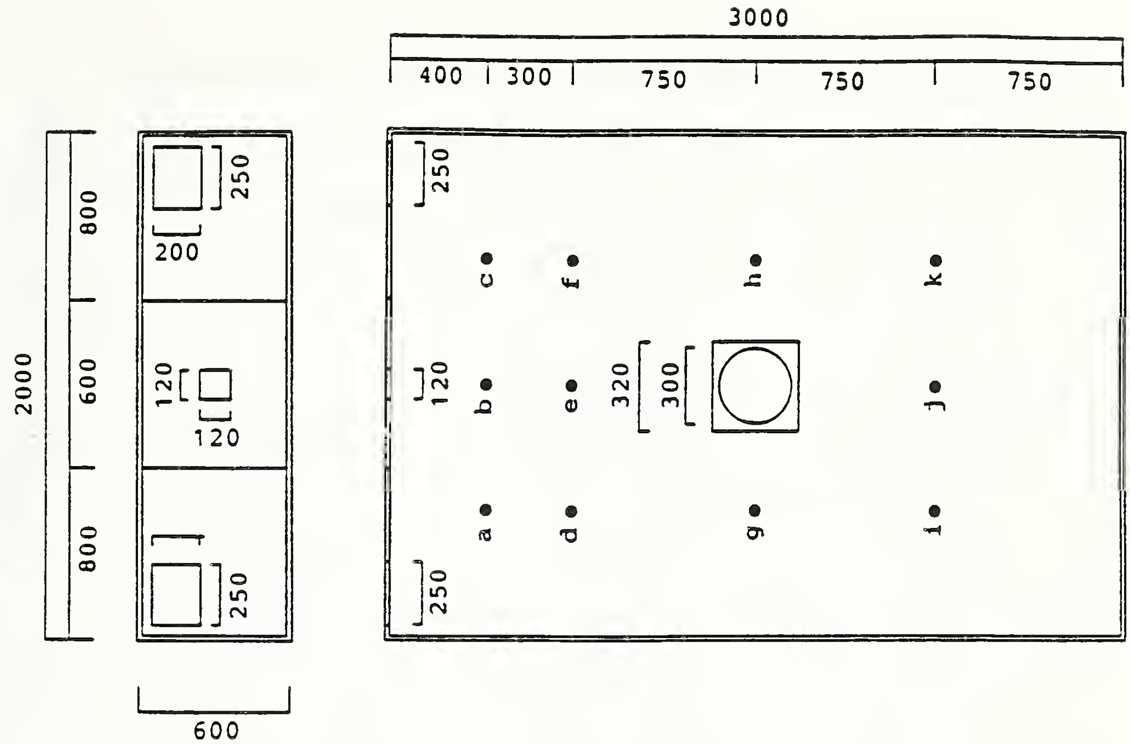


Figure 1-(b) Measuring positions in the enclosure. Length unit is mm.

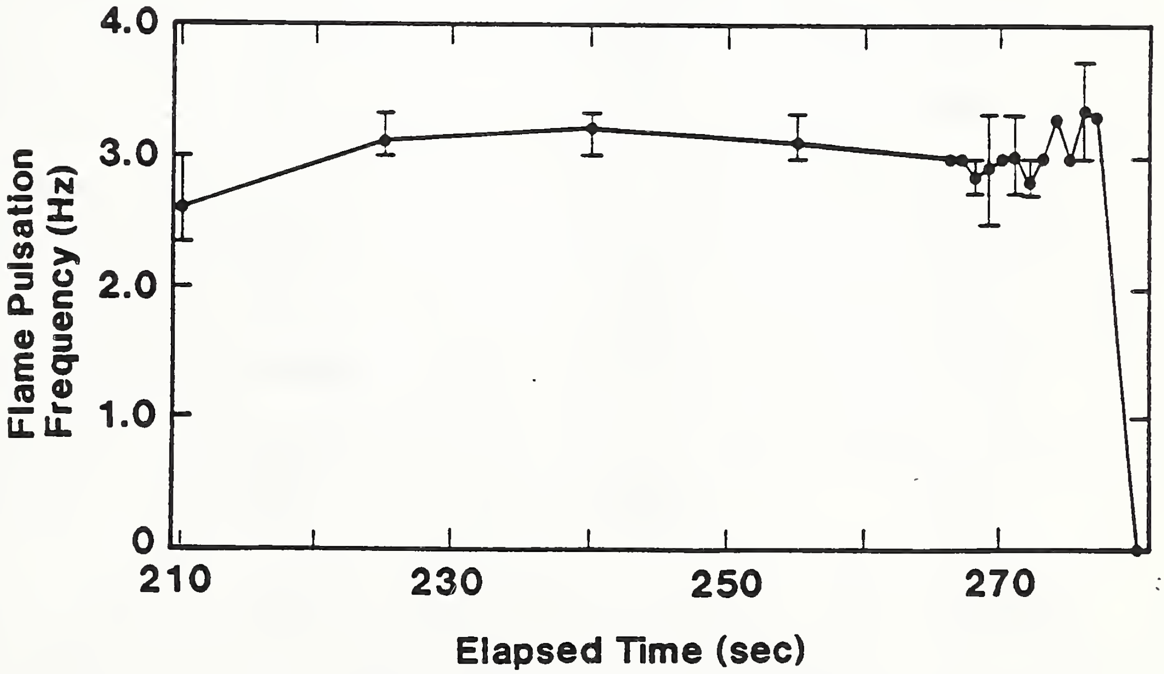


Figure 2 Time history of flame pulsation frequency of the methyl alcohol pool fire under poor ventilation.

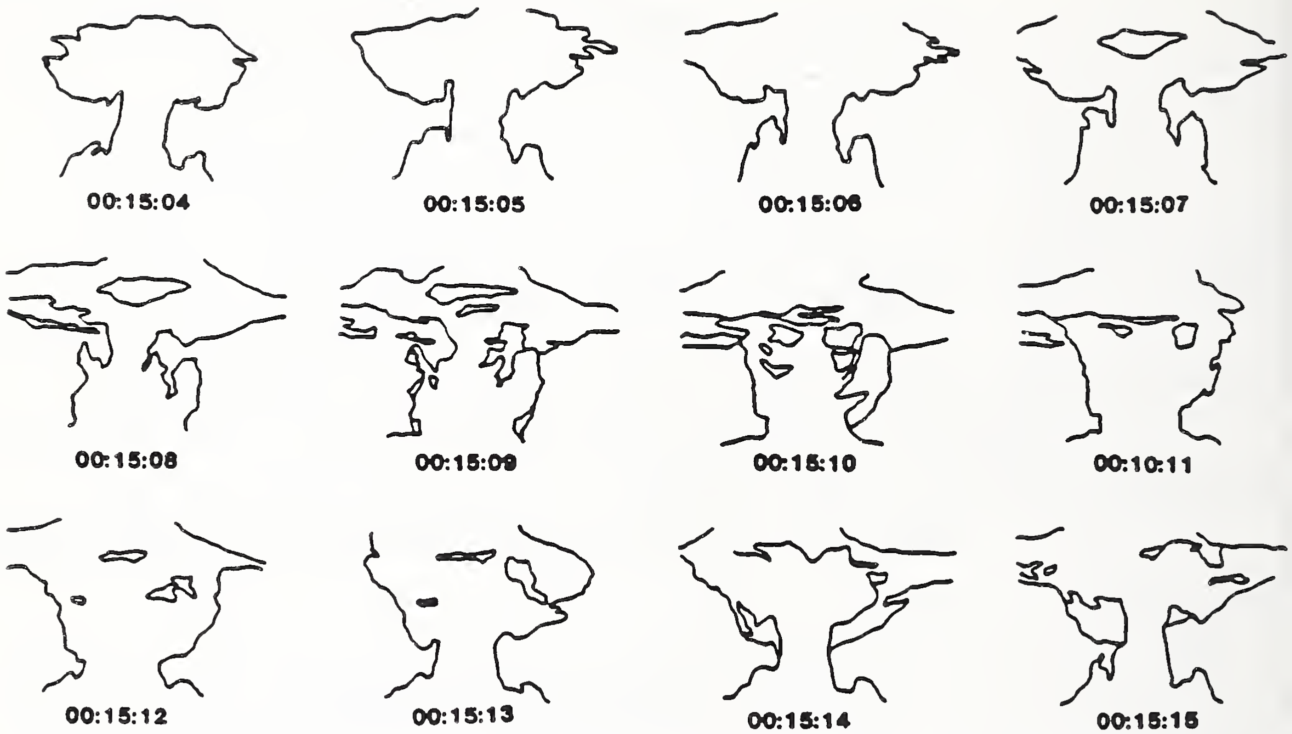


Figure 3 Typical one cycle of flame pulsation before ghosting.

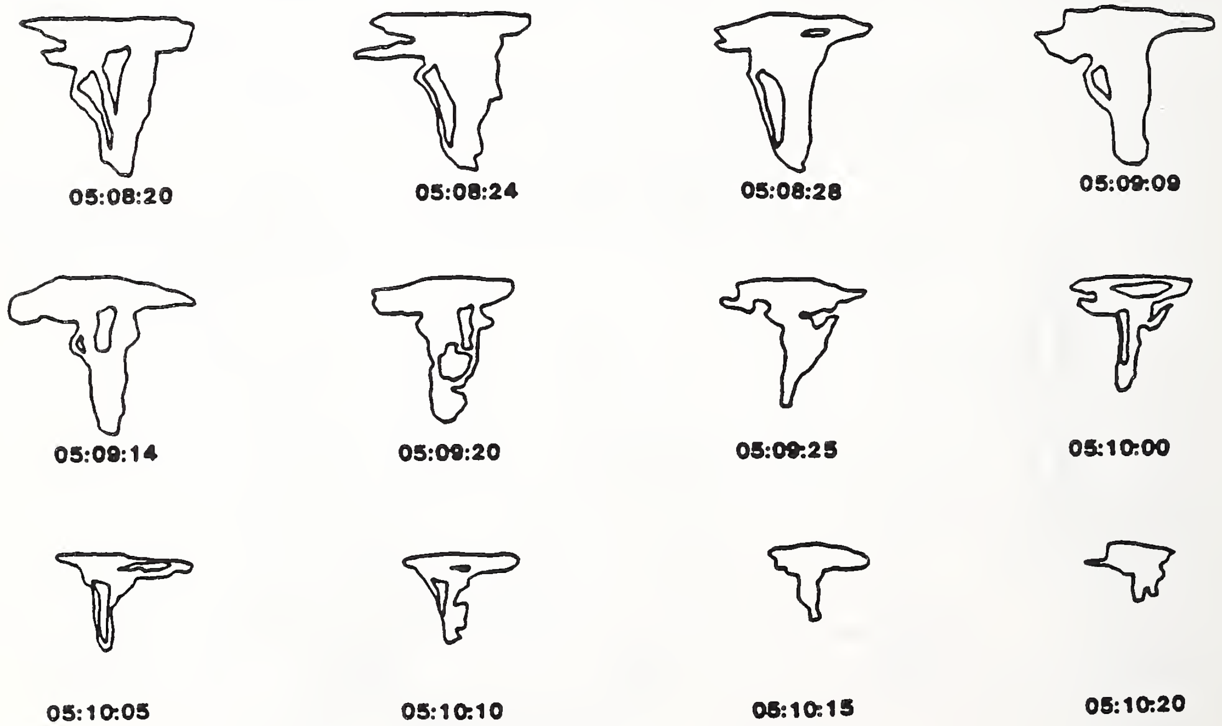


Figure 4 Flame shapes in the transition period to ghosting flame.

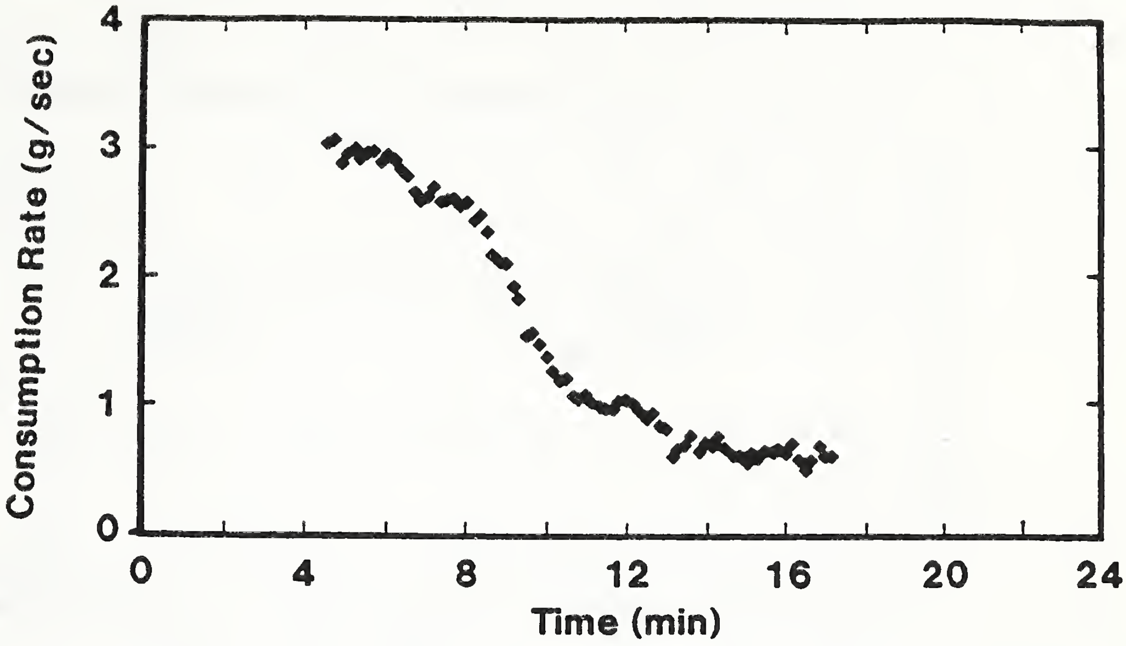


Figure 5 Time history of the consumption rate of the fuel including transition to ghosting.

3. Results and Discussion

(a) Observation

The diffusion flame from the fuel impinged on the ceiling for the first 6 - 7 min, and then flame began to detach from partly of the circular pan edge. The flame color, initially bright orange became pale blue. About 10 min after the ignition, the flame detached completely from the fuel surface and the "ghosting flame" started. It floated just under the ceiling with a thickness of about 5 cm and a diameter of about 40 cm. The thin pale blue ghosting flame looked like an aurora. This ghosting flame continued for times varying from 7 to 20 minutes in the different tests, sometimes coming down to the fuel surface forming an attached flame again. During the burning, a flame pulsation frequency of about 3 Hz was observed and it continued until just before the ghosting as shown in Figure 2. The pulsation frequency decreased abruptly about 3 sec before the ghosting began. Figure 3 shows one cycle of the pulsating flame, and Figure 4 the outline flame shapes in the transition to ghosting. Photo 1 shows the ghosting flame which appeared under the ceiling just above the pool. The last two frames show the beginning of the ghosting flame.

(b) Consumption rate of the fuel

Figure 5 shows the variation in time of the consumption rate of the fuel. In the first period of burning, the consumption rate was about 3 g/sec. The flame behavior changed as the consumption rate decreased and flame began to detach from the pan in this transition period. The consumption rate in the ghosting stage decreased finally to about 0.5 g/sec as an average value, 1/6 of that of the fuel controlled fire.

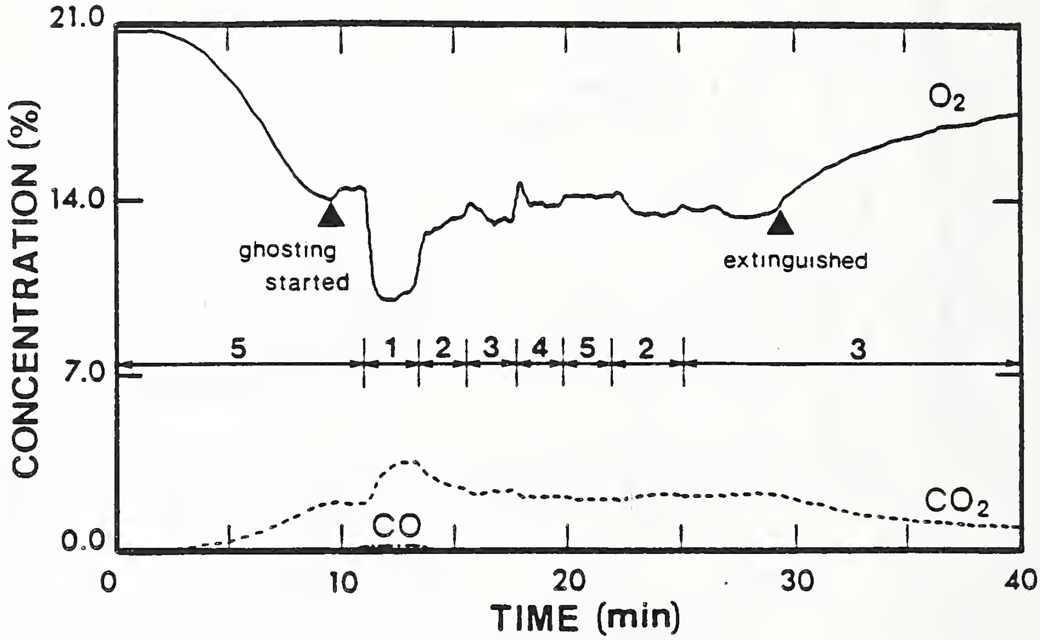


Figure 6 Time histories of typical gas concentrations for Test 46

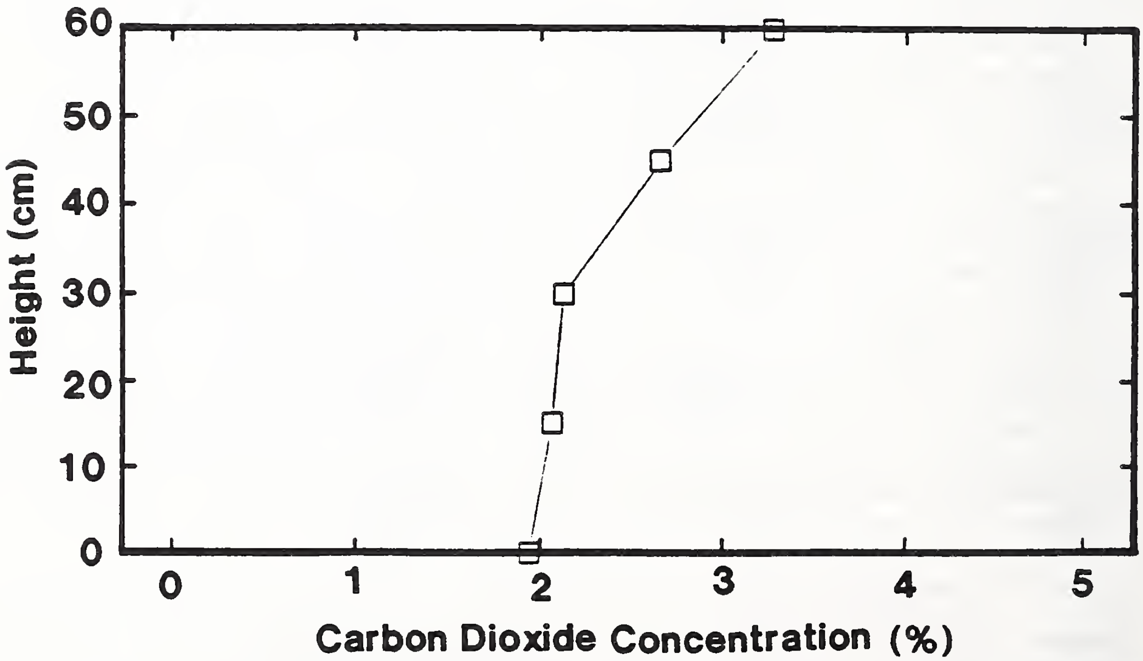


Figure 7 Vertical distribution of CO_2 gas concentration in the ghosting period. Data from Test 46.

(c) Gas Concentrations

Sample gas was sucked from the various positions a - k in the box, as shown in Figure 1, at 600 mm (corresponding to the ceiling height), 450 mm, 300 mm, 150 mm, and 5 mm from the floor. Figure 6 shows the typical variation in time of the gas concentrations and a triangle in the figure shows the start of the ghosting fire. Numbers in the figure 4 refer to the sampling positions of the rake. It is very clear that the measured carbon monoxide concentration was very low. 13 - 14 % oxygen concentration was measured in the ghosting period. The concentration of carbon dioxide varied with height and its vertical profile was almost uniform with some gradient in the upper part. Figure 7 shows the CO_2 gas concentration profile in the ghosting period. In the upper part of the layer the concentration was 2.7 - 3.5 % and it was 2 % below the mid height.

(d) Temperature

The temperature of the fuel was measured every 10 sec at the mid height for this tests and Figure 8 shows the variation in time of fuel temperatures. For both tests, the fuel temperature increased for 3 - 5 min after the ignition and then the rate of rise decreased with decrease of oxygen concentration. In test 21, the ghosting continued for only about 30 sec and then extinguished when the oxygen concentration (measured at point b) reached about 4 - 4.8 %. The experimental conditions of test 24 was the same as the test 21, however ghosting continued for about 20 min. The oxygen concentration decreased to a minimum of 5.5 % about 2 min before the ghosting started, and then increased to about 14 % in the ghosting period. Ghosting stopped when the fuel temperature reached about 45 ^{o}C. The quenching of ghosting may be associated both with the high fuel concentration or temperature within 10 - 15 ^{o}C of the

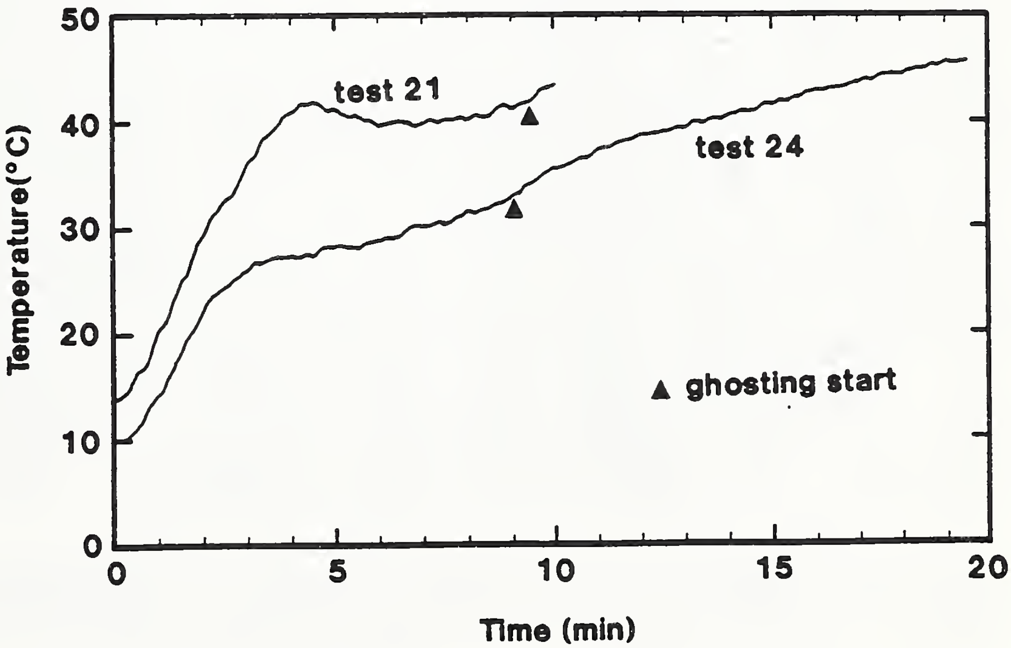


Figure 8 Time histories of fuel temperature.

boiling point and the low concentration of oxygen. In the ghosting period, the temperature just under the ceiling decreased about 100 ^{o}C as shown in Figure 9. This decrease of temperature produced less thermal radiation feedback to the fuel surface and reduced the rate of rise of the fuel temperature.

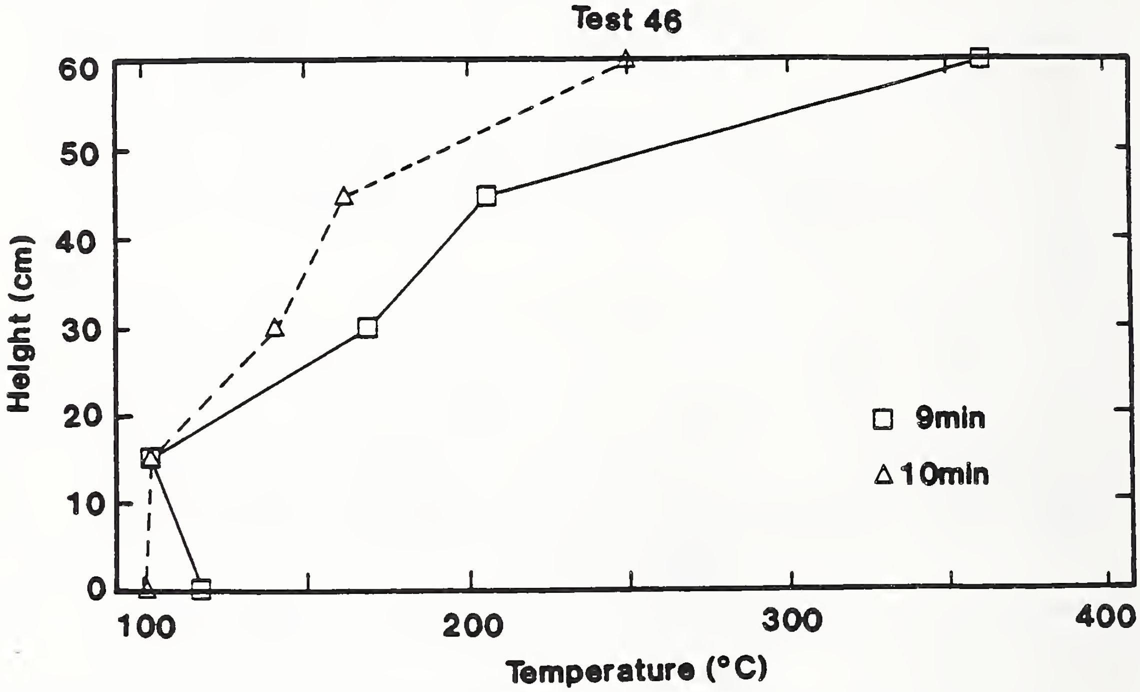


Figure 9 Typical temperature distribution for vertical direction before and in the ghosting period. Data from Test 46.

(e) Air Exchange Rate

In order to estimate the air change rate for the enclosure and the influence on it if the total leak area including the two slits, oxygen gas concentration was employed as a tracer gas after the extinction of burning. Figure 10 shows the variation in time of the oxygen gas concentration both with 160 cm^2 slit opening area (test 18 : point b) and another the slit closed (test 46 : point d): the air exchange rate was about 2.4/hr in the former case and 1.1/hr in the later. The air exchange rate condition required to start the ghosting fire was 1.1/hr and to sustain the ghosting was 2.4/hr. In the ghosting fire period, an oxygen concentration of about 14% was estimated as shown in Figure 6. Numbers in the Figure correspond to the measuring positions as shown in Figure 1-(b). Foote [1] found the "ghosting fire" using a methane diffusion burner in a full scale compartment under mechanical ventilation applying more than 5 times of air volume of the room per hour. As to be referred he found that the appearance of ghosting depended on the positions of the fire source and of the air inlet and outlet.

In the fully developed compartment fire in the ventilation controlled regime, the oxygen in the air (21% oxygen) which flows into a compartment is consumed almost completely by chemical reaction and in the out flow oxygen concentration is nearly zero.

But in the ghosting condition, 13 - 14% oxygen was observed so that it seems that it behaves like an inert gas. When the oxygen concentration decreased under this critical value, spontaneous extinguishment was obtained.

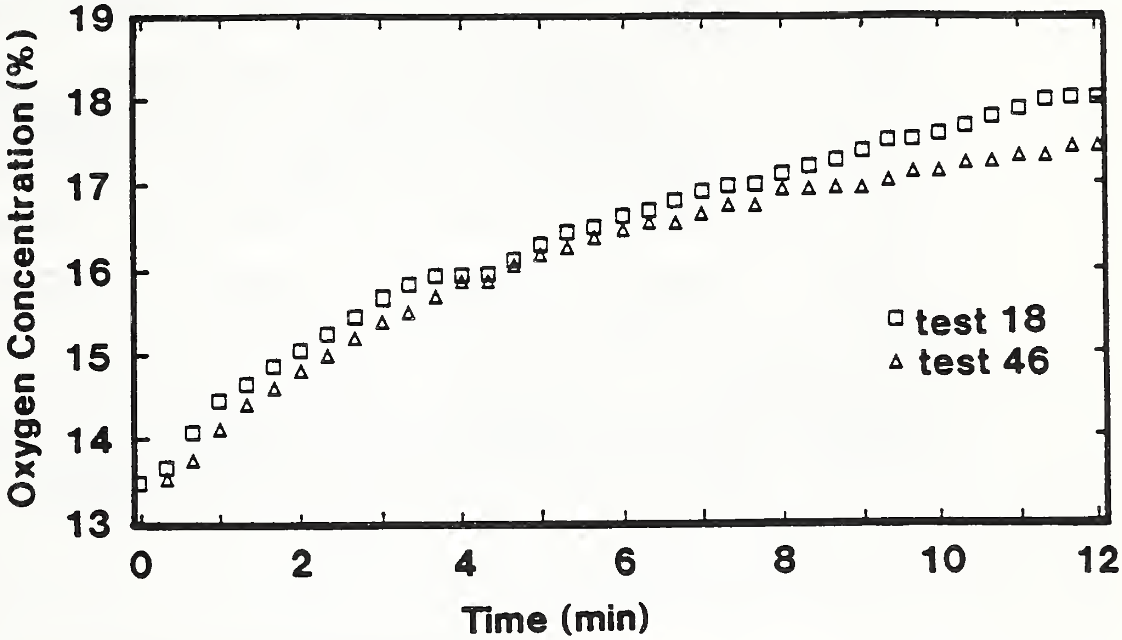


Figure 10 Time histories of oxygen concentration after extinction.

4. Conclusion

Many researchers are now interested in the pre-flashover phenomenon under the condition of enough oxygen. The computer fire codes for a two-layer zone model [3] can simulate the fire propagation from a small fire source up to flashover in a compartment. The assume that the cool lower zone is always supplied with enough air having 21% oxygen all of which could be available for consumption. But under the ghosting condition, the air in the lower zone having 13 - 14% of oxygen behaves as an inert gas. Thus the zone model seems suitable for predicting fire phenomena under the condition of oxygen starvation. It is necessary to apply a field model to predict such ghosting fire, although the mechanism of ghosting is not yet clear. Oxygen starvation may be obtained in an actual fire, some cases have been reported by the fire brigades.[4] We believe that the further study of the fire phenomenon under the oxygen starvation condition of in a compartment is essential in order to advance fire protection and fire fighting tactics for multi-story buildings.

5. Acknowledgment

The authors sincere thanks to Professor Iichi Ogahara and Mr. Ikuo Takahashi for the kind support of this work.

6. References

1) Foote, K.L., "1986 LLNL Enclosure Fire Tests Data Report", UCID-21236, Lawrence Livermore National Laboratory, August 5,(1987)
2) Backovsky,J., Foote,K.L., and Alvares,N.J. "Temperature Profiles in Forced-Ventilation Enclosure Fires", p315-324, Proc. of the Second Int. Symp. on Fire Safety Science, ed., by T.Wakamatsu et al., Hemisphere Publishing Corp. (1988)
3) There are several two-layer Zone Models and Codes, typical ones are;
"FIRST", "HAZARD I", "ASET A", "ASET B", Center for Fire Research, National Institute of Standards and Technology, Department of Commerce, USA
"Tanaka-Model", Building research Institute, Ministry of Construction of Japan
"ASKFRS", Building Research Establishment, UK (1988)
4) Private communication from Tokyo Fire Department

Photo 1 Ghosting flame located under the ceiling and above the fire source pool. The photo was taken by IR film with 1 sec exposure and opened iris.

Smoke Control Tests at the Plaza Hotel in Washington DC

JOHN H. KLOTE
Center for Fire Research
National Institute
of Standards and Technology
Gaithersburg, MD 20899, USA

1. INTRODUCTION

In the spring of 1989, a series of full scale fire experiments of zoned smoke control were conducted at the seven story Plaza Hotel in Washington, DC. A zoned smoke control system is a system that uses pressurization produced by fans to restrict smoke flow to the zone of fire origin. The benefit of these systems is that other zones in the building remain essentially "smoke free" reducing property loss and hazard to life. No zoned smoke control system has been tested under real fire conditions either by a research effort or an accidental fire. However, fire experiments of smoke control systems for stairwells and elevators have been conducted.

This project was sponsored by the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE); Bell Atlantic Telephone Company; New Jersey Bell Telephone Company; U.S. Fire Administration; U.S. Veterans Administration, and US West Incorporated. Member companies of the Air Movement and Control Association (AMCA) donated fans for this project. The Architect of the Capitol obtained approval of the U.S. Senate Committee on Rules and Administration for NIST to use the Plaza Hotel building for this project.

The objective of this effort is to evaluate the current approach to zoned smoke control systems. Accordingly, the smoke control system was designed using the calculational methods of the ASHRAE Smoke Control Manual (Klote and Fothergill 1983) and it was designed to produce the levels of pressurization recommended by the National Fire Protection Association (NFPA 1988). This zoned smoke control system was designed to operate along with a stairwell pressurization system. The design analysis of both of these systems are discussed in detail by Klote (1988). Data analysis is ongoing for this project, and a detailed report will be published in the near future. This paper is an initial discussion of the tests.

2. DESCRIPTIONS OF TESTS

The Plaza Hotel building is a masonry structure consisting of two wings, one three stories and the other seven stories tall. Fires were set on the second floor of the seven story wing. The areas of the second floor indicated on figure 1 were fire hardened by covering the walls, floor and ceiling with calcium silicate board to minimize structural damage to the building. Other floors of the seven story wing are of similar size and layout to that shown in figure 1.

The building had no central forced air heating system, so a dedicated system of fans and ducts was installed for zoned smoke control and stairwell pressurization. The zoned smoke control system consisted of three 0.94 m^3/s (2000 cfm) centrifugal fans: one for pressurization of the first floor, one for exhaust of the fire floor (second floor), and one for pressurization of the third floor. Another centrifugal fan, located outside, supplied 3.3 m^3/s (7000 cfm) of pressurization air to the stairwell at the first floor. The exterior basement door of the stairwell was open during operation of the stair pressurization fan. This was done to simulate a system for which the exterior door opens upon system activation to eliminate the pressure fluctuations due to opening and closing the exterior door.

The test series consisted of chemical smoke tests and wood fires, and the test schedule is listed in table 1. Two of the wood fires (tests 10 and 11) were sprinklered. The chemical smoke was produced by three smoke bombs rated by the manufacturer for a three minute duration. The smoke bomb tests were included to evaluate the extent to which smoke bombs are appropriate for acceptance testing of smoke control systems.

Wood was selected for these urban area experiments because it produces relatively light smoke. Wood sticks were arranged in geometric piles called cribs, because these crib fires are repeatable and fairly well understood (Gross 1962, Block 1971). The cribs, illustrated in figure 2, were constructed of fir sticks 38 mm (1.5 in) by 38 mm (1.5 in) by 0.61 mm (2 ft) long. The sticks were fastened together with 8d common nails. The crib illustrated in figure 2 consisted of 24 layers and weighted approximately 68 kg (150 lbs), and these cribs were used for most of the tests. The exception was test 3 for which a smaller crib of 18 layers weighing about 45 kg (100 lb) was used because of concern about possible damage to the buildings structural system. Each fire used two cribs located in the corridor as illustrated in figure 1. By extrapolation of data (Walton 1988) for similar cribs, it is estimated that two 24 layer cribs would have a peak energy release rate of 1.5 MW, and two 18 layer cribs would have a peak energy release rate of 1.0 MW. A 0.13 m (5.0 in) diameter metal pan with 100 ml of heptane was centered under each crib as an ignition source. The cribs were stored in a room in the Plaza Hotel without humidity control, however, all the cribs had a moisture content less than 6 percent.

3. DISCUSSION OF WOOD FIRE TESTS

During test 5 which was without zoned smoke control and stair pressurization, significant amounts of smoke infiltrated the seventh floor and lesser amounts reached the third floor as illustrated by figure 3. For this test the second floor door was cracked ½ inch open simulating the gap of a door warped due to high differential temperatures. Video recordings also showed smoke flowing through the door gap and into the stairwell. Smoke was also observed on floors 4 and 7 of the stairwell. Test 1 was similar except that the stairwell doors were closed. As expected the smoke obscuration away from the fire was considerably lower for test 1.

For the tests with smoke control, the spaces away from the fire floor were essentially smoke free. This was observed on the video for floors 3 through 7 and for the stairwell. Figure shows that essentially no smoke reached the third and seventh floors during test 9, which was the same as test 5, except that zoned smoke control and stair pressurization were operating.

To obtain an idea of the relative effect of sprinklers, tests 10 and 11 were sprinklered. Test 10 was with a conventional sprinkler and test 11 was with an on-off head. In both tests, the sprinkler was located just below the ceiling and directly over the fire. During test 10, the sprinkler extinguished the fire shortly after it activated, and the smoke levels were very low on the fire floor. Other floors were essentially smoke free. This indicates that when a fire is rapidly extinguished, smoke spread away from the fire is slight. The sprinkler was ideally located for test 10, and for less ideal location considerably more smoke might have been generated. The on-off sprinkler used in test 11 failed to extinguish the fire, but it resulted in a cycling of the water spray with fire growth when the spray was off. This resulted in considerable smoke as can be seen from figure 5. Further study is needed concerning the effect of sprinklers on smoke generation.

Figure 6 shows the concentrations of carbon monoxide (CO) on the second floor during the wood fires. For the fires without smoke control (tests 1 and 5), CO on the fire floor approached 2 percent. For these tests, the oxygen levels decreased to about 10 percent and remained a that level until the end of the test. For the non-sprinklered fires with smoke control (tests 3, 7 and 9), CO concentrations were much lower. Possibly the lower CO levels are because the smoke control system pulled air into the fire floor. The lower CO levels with smoke might appear to be a possible benefit of smoke control. However, caution should be exercised in this regard, because greater fuel loads could also result in the high levels of CO for non-sprinklered fires.

4. DISCUSSION OF CHEMICAL SMOKE TESTS

As with the wood fires, some smoke moved beyond the fire floor for the non-sprinklered fire (test 4) without smoke control. During this fire, the video showed smoke in the stairwell as it did for the wood fire (test 5) with similar conditions. For tests 2, 6 and 8 with smoke control, the spaces away from the fire floor were essentially smoke free as is illustrated for test 6 in figure 8. However, the smoke concentrations due to smoke bombs tests are considerably different from those due to the wood fires. The chemical smoke is produced over a short time (3 minutes according to the smoke bomb manufacturer). However, the fire burns for nearly a half an hour. The chemical smoke results in lower obscuration. With smoke control, obscuration due to chemical smoke decreases rapidly at about 5 minutes after ignition. This is believed to be the result of the smoke control system purging the chemical smoke. Further, this chemical smoke does not develop the buoyancy pressures of the hot fire gases from the wood fires. It is possible that persons only observing the chemical smoke in an acceptance test could develop unrealistic expectations about improvements in smoke conditions on the fire floor.

5. SUMMARY

During the fires for which the smoke control system was not operating, there was significant smoke movement into the stairwell and to other floors especially the seventh floor. When the smoke control system was operating, the stairwell and floors away from the fire remained essentially smoke free. These results demonstrated that zoned smoke control systems can achieve the objective of preventing smoke infiltration beyond the smoke zone. The experimental data is being analyzed to evaluate the underlying assumptions of zoned smoke control, and a detailed report will be published in the near future.

6. REFERENCES

Block, J.A. 1971. A Theoretical and Experimental Study of Nonpropagating Free-Burning Fires, Thirteenth Symposium (International) on Combustion, 1970 August 23-29, Salt Lake City, UT, Combustion Institute, pp 971-978.

Gross, D. 1962. Experiments on the Burning of Cross Piles of Wood, Journal of Research of NBS, Vol 66C, No. 2, pp 99-105.

Klote, J.H. and Fothergill, J.W., 1983. Design of Smoke Control Systems for Buildings, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA.

Klote, J.H., 1988. Project Plan for Full Scale Smoke Movement and Smoke Control Tests, Nat. Bur. Stand. (U. S.), NBSIR 88-3800.

NFPA 92A, 1988. Recommended Practice for Smoke Control Systems, National Fire Protection Association, Batterymarch Park, MA.

Walton, W.D. 1988. Suppression of Wood Crib Fires With Sprinkler Sprays: Test Results, Nat. Bur. Stand. (U. S.), NBSIR 88-3696.

Table 1. Test Schedule

Test	Test Type	Fire Load[1] lb (kg)	Zoned Smoke Control[2]	Stairwell Pressurization[3]	Activation Time[4] (min)	Condition of Stairwell Doors at: Basement to Outside	2nd Floor[5]	7th Floor
1	Wood Fire	300 (136)	off	off	-	closed	closed	closed
2	Smoke Bomb	-	on	off	0	closed	closed	closed
3	Wood Fire	200 (91)	on	off	0	closed	closed	closed
4	Smoke Bomb	-	off	off	-	closed	½ inch	open
5	Wood Fire	300 (136)	off	off	-	closed	½ inch	open
6	Smoke Bomb	-	on	on	0	open	½ inch	open
7	Wood Fire	300 (136)	on	on	0	open	½ inch	open
8	Smoke Bomb	-	on	on	4	open	½ inch	open
9	Wood Fire	300 (136)	on	on	4	open	½ inch	open
10	Sprinklered	300 (136)	off	off	-	closed	½ inch	open
11	Sprinklered	300 (136)	off	off	-	closed	½ inch	open

[1] Fire load is approximate.
[2] Zoned smoke control consisted of pressurization of first and third floors at 2000 cfm (0.94 m^3/s) each, and exhaust of the second floor at the same rate.
[3] Stairwell pressurization consisted of supplying 7000 cfm (3.3 m^3/s) into the stairwell at the first floor with the exterior basement door open.
[4] Activation time is the time after ignition that the smoke control system and stairwell pressurization system are turned on.
[5] Second floor door designation ½ inch indicates that the door was cracked open ½ inch.

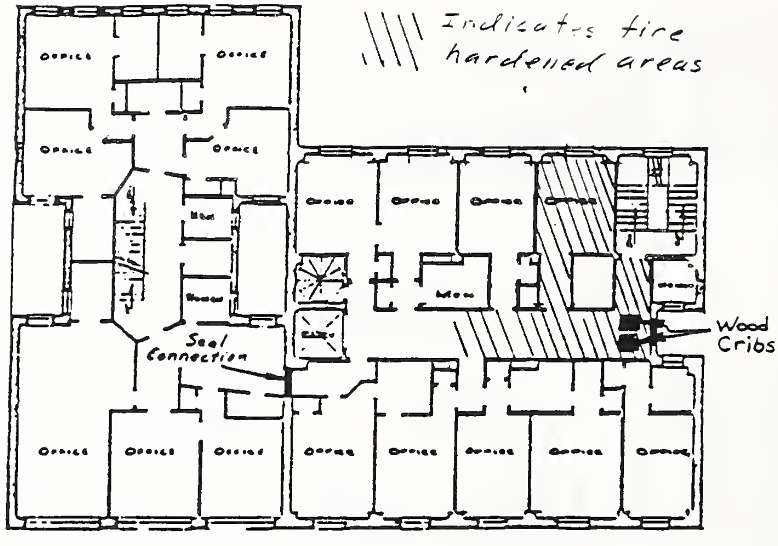


Figure 1. Second floor plan of Plaza Hotel

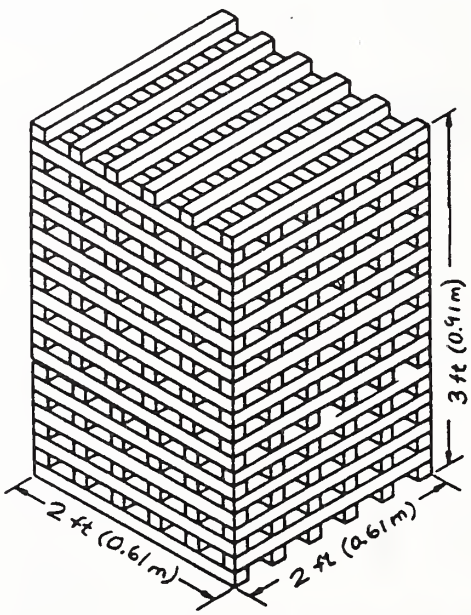


Figure 2. Crib configuration

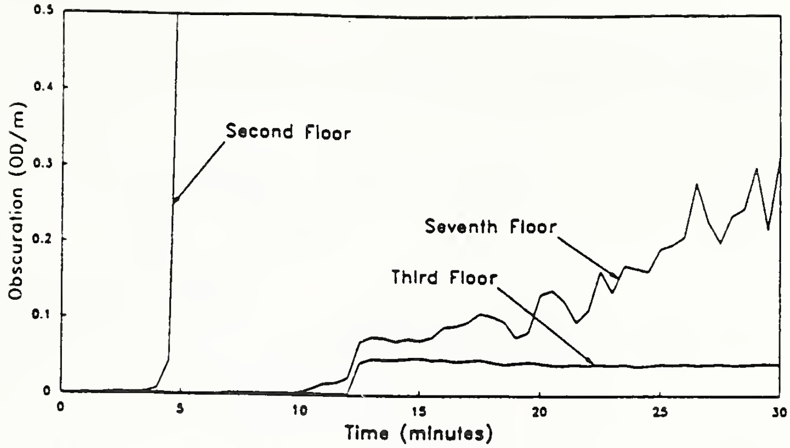


Figure 3. Smoke obscuration for wood fire without smoke control (test 5)

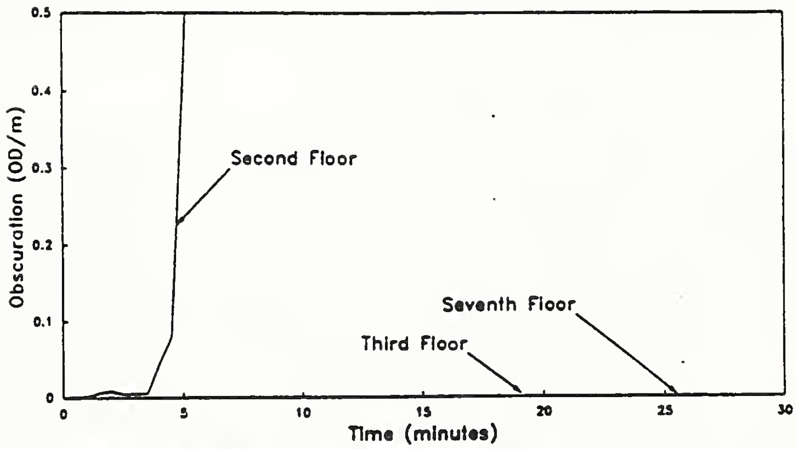


Figure 4. Smoke obscuration for wood fire with smoke control (test 9)

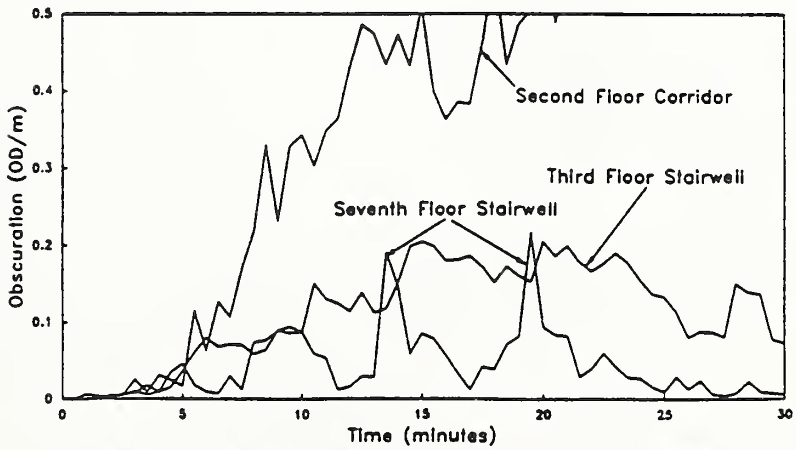


Figure 5. Smoke obscuration for wood fire without smoke control and sprinklered by on-off sprinkler (test 11)

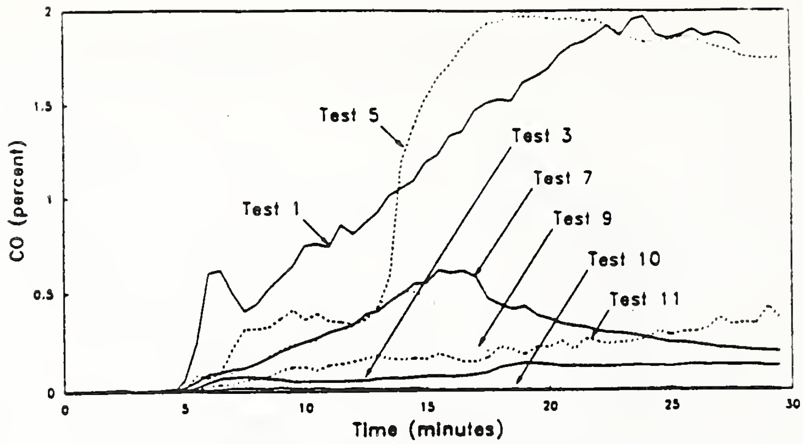


Figure 6. Second floor CO concentrations for wood fires

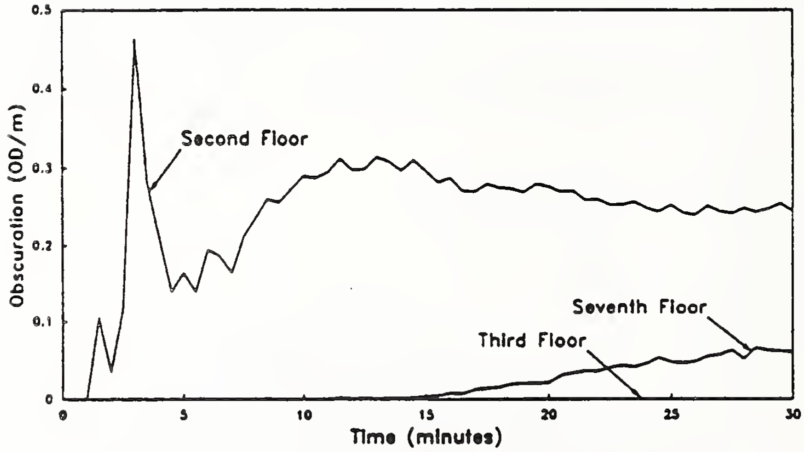


Figure 7. Smoke obscuration for smoke bomb test without smoke control (test 4)

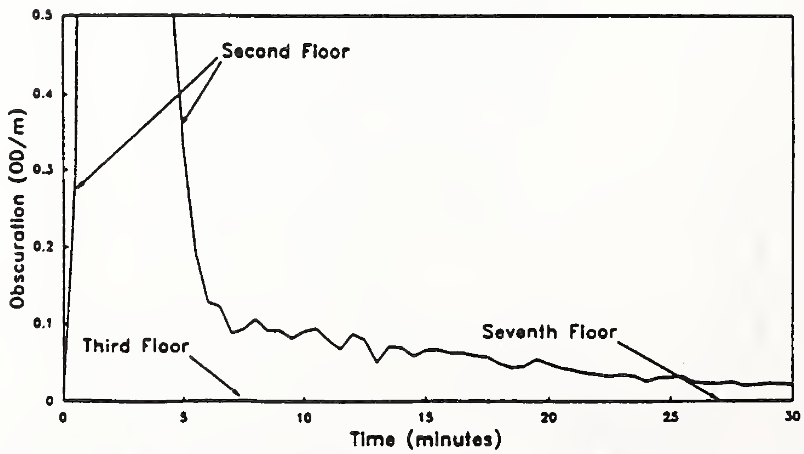


Figure 8. Smoke obscuration for smoke bomb test with smoke control (test 6)

A SCALING LAW OF SMOKE MOVEMENT IN ATRIUM

Makoto Tsujimoto, Tetsuji Takenouchi
Faculty of Engineering
Nagoya University
Furo-cho, Chikusa-ku, Nagoya, Japan
Shigeo Uehara
Building Design Department, Tokyo Main Office
Takenaka Corporation
8-21-1, Ginza, Chuo-ku, Tokyo, Japan

ABSTRACT

An experimental verification on a scaling law of smoke movement in an atrium was performed using the models of 1/25 and 1/10 scale. In accordance with the scaling law , which requires that heat release rate and time are proportional to 5/2th power and 1/2th power of representative length, respectively, the movement and the temperature profile of smoke layer became similar.

1. INTRODUCTION

These days the number of buildings which have a large atrium space is growing in Japan. And some of them are designed without barriers between atrium space and its surrounding area. So, from a standpoint of fire safety engineering, it is necessary to develop a method to estimate the unsteady smoke movement in the atrium.

One of the methods is to confirm the scaling law governing the smoke movement in the compartment, and to make small scale experiments according to the scaling law. If the smoke movement in the atrium is considered to be governed primarily by the fire plume, the scaling law can be selected from the study by Quintiere[1)]. Because the phenomenon is unsteady, however, only a few experiments, for example, Emori's[2)], show the validity of the scaling law.

In this study, two different scale model, 1/10 and 1/25 were used to investigate it. Although, according to the scaling law, the heat release rate of these two models differs about 10 times, the pictures of the smoke movement visualised by lazer light sheet proved the validity.

2. SCALING LAW

The atrium which we deal with in this study is five stories height, and its plan and sketch are shown in Fig.1 and Fig.2. And the ultimate purpose of this study is to estimate the smoke movement by small scale experiments under the various condition of openings, for example, changing the position and the size of the openings between the atrium and the outside air, the ones of elevator shafts between each atrium etc., to avoid the condition in which people in evacuation become in danger. Because the present object of this study is to confirm the scaling law, the condition of the openings of the model was simplified.

As the smoke movement in an atrium is considered to be a phenomenon of heat convection governed by the fire plume, using the classical dimensional analysis, we can derive the dimension of length $[L]$ and time $[t]$ as a function of the variables (Q, C_p, T_0, ρ_0 and g), the combination of which explains the velocity or temperature of the free boundary fire plume.

$$[L] = \left(\frac{Q^2}{g\rho_0^2 C_p^2 T_0^2}\right)^{\frac{1}{5}} \qquad [t] = \left(\frac{Q}{g^3 \rho_0 C_p T_0}\right)^{\frac{1}{5}} \qquad (1)$$

where Q:heat release rate, C_p, T_0, ρ_0:specific heat, absolute temperature, and density of ambient air, respectively, g:gravity acceleration

If the heat release rate in real scale and reduced scale are given, these equations are rewritten as follows;

$$\frac{Q_M}{Q_R} = (\frac{L_M}{L_R})^{\frac{5}{2}}$$

$$\frac{t_M}{t_R} = (\frac{L_M}{L_R})^{\frac{1}{2}} \tag{2}$$

where subscripts M and R mean model and real scale, respectively.

The same relation was derived by Quintiere[1)] using the Froude modeling and the Boussinesq assumption. If the heat transfer by radiation and between smoke layer and the wall of atrium is neglected, the temperature rise of smoke($\Delta\theta$) becomes independent of scale as follows;

$$\frac{\Delta\theta_M}{\Delta\theta_R} \simeq \frac{Q_M t_M / L_M^3}{Q_R t_R / L_R^3} = 1 \tag{3}$$

3. EXPERIMENT

A series of experiments was performed under following conditions.

1) length scale

   Two scale models, 1/25, 1/10, were used in the experiments. Fig.5 shows the plan and cross-section of the models.

2) material of wall

   If the materials of the wall were selected in such condition that heat transfer from smoke layer to the wall is propotional to $Q{\cdot}t$ in equation(3), $\Delta\theta$ becomes independent of scale.

   Simplifying the mechanism of surface heat transfer, the surface temperature of the wall is considered to be equal to the smoke layer. The condition that the heat absorbed to the wall is proportional to $Q{\cdot}t$ gives following equation ;

$$\frac{(\lambda_s \rho_s C_s)_M}{(\lambda_s \rho_s C_s)_R} = (\frac{L_M}{L_R})^{\frac{3}{2}} \tag{4}$$

   λ_s, ρ_s, C_s : thermal conductivity, density, specific heat of the wall

   It suggests that a concrete wall in real scale corresponds to cork in 1/25 scale, and cedar in 1/10 scale. So the walls of the models were made of cork and hard board, respectively.

3) heat source

   The diameter of fire in real scale was assumed to be 1.5m, and the glass funnel stuffed with small stones was used as a burner. Propane was used as fuel.

4) smoke generator

   As combustion product gas of propane is too clear to visualize, a smoke ball made of gun-powder and small chips of wood was used. The position of the smoke ball was selected for generated smoke to mix into the upward flow of plume.

5) variables

The experiments were performed, by changing the size of openings, heat release rate, and the position of the burner. The conditions of standard experiments are listed in Table.1. The values of Table.1 showes real scale ones, and in Series A (scale 1/25) and Series B(scale 1/10), the values were determined according to equations(2).

6) measurement

The temperatures in the compartment and at the openings were measured by 0.65ϕ CC thermo-couples every 10 seconds (Series A) or every 16 seconds (series B). The smoke layer visualized by the argon lazer light sheet (4W) was recorded by photographs and a video system.

4. RESULTS

To confirm the scaling law, the results of experiments in Series A and B are compared with in regard to the following two characteristics.

1) transient change of temperature profile; for example, the vertical temperature profiles in experiment 1-5, 2-5, 5-2 are shown in Fig.5-1 $\sim$ 5-3.

2) transient change of visualized smoke layer; video pictures of experiments in Series A which are played back slowly in 63% ($1/\sqrt{2.5}$) speed are compared with the corresponding ones in Series B using two CRTs at the same time. And the comparison of the photos shown in Fig.6, as an example, is performed.

After these comparisons, it is concluded that both the profile of temperature and the movement of smoke layer are similar among Series A and B, except that the temperature of smoke layer in Series B is higher than that in Series A when the atrium has no opening (No.1-4 $\sim$ 1-6).

In this series of experiments, unexpected phenomena were observed. Before starting the experiments, the position of the burner was planned to be placed in center of the atrium such as No.3-1 $\sim$ 3-3 in Table.1. But the fire in that condition generated a fire whirl, and the smoke layer was too disturbed to be compared with as was shown in Fig.7. The fire whirl was observed in both series. So the position of the burner was changed to the corner where the fire whirl was not generated.

Another phnomenon observed is that the depth of smoke layer at the openings differs like Fig.5-3 because geometrical relations between the burner and the two openings are different.

One should note that these two phenomena cannot be explained by the two-zone model.

ACKNOWLEDGEMENT

We would like to express our thanks to Dr.Y.Hasemi, Dr.O.Sugawa and Dr.T.Yamada for their helpful advice.

A part of this rescarch, a series of experiments, was made under control of T-50 Comittee found from Takenaka Corporation and Nippon Steel Corporation in the Building Center of Japan.

REFERENCES

1) Quintiere, J.G., "Scaling Application in Fire Research", Proc. of the International Symposium on Scale Modeling, 1988

2) Emori, R.I., Saito, K., "A Study of Scaling Law in Pool and Crib Fires", Combustion Science and Technology, Vol.31, pp.217–231, 1983

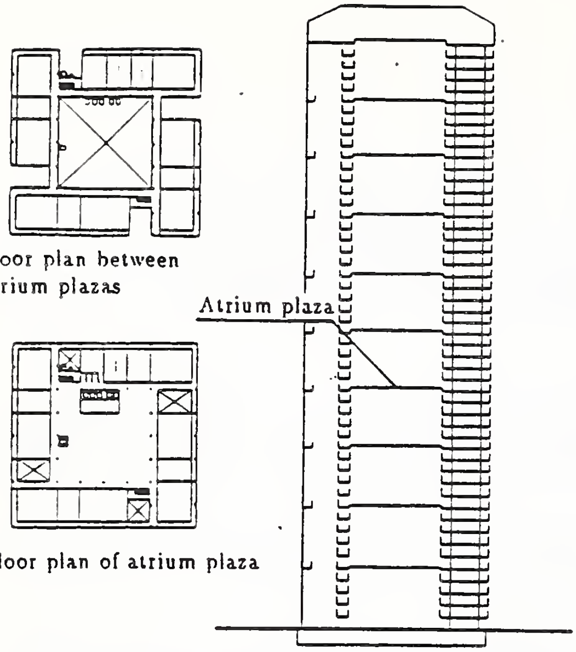


Fig.1 Plans and section of a high-rise apartment which has atriums every five stories

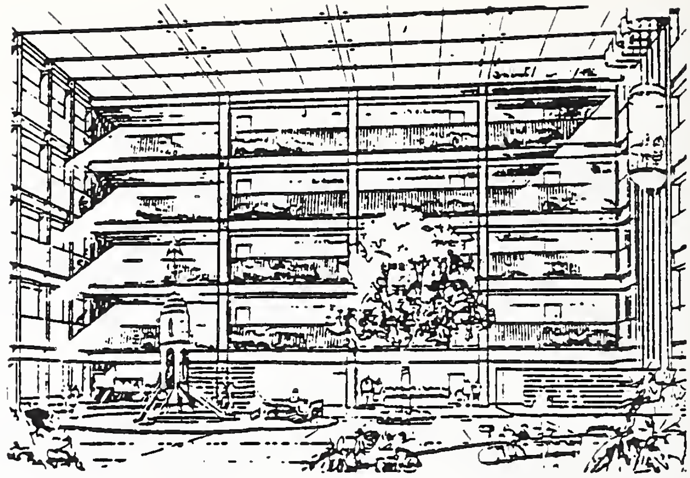


Fig.2 A perspective drawing of an atrium space

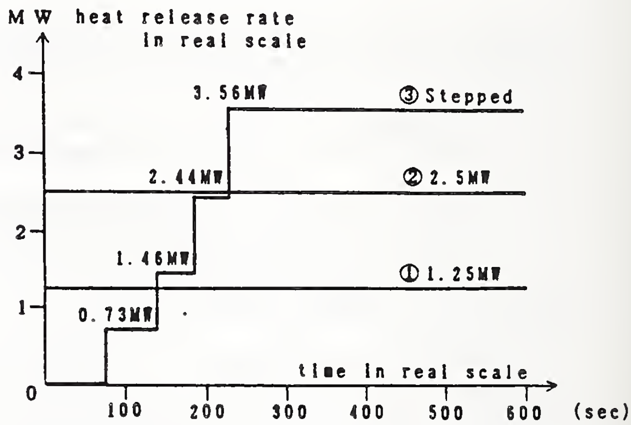


Fig.3 Experimental conditions of heat release rate

Table.1 Experimental conditions

No.	Opening (see Fig.4)	Position of burner (see Fig.4)	Heat release rate (see Fig.3)
1-4	No opening	Corner	1.25MW
1-5	〃	〃	2.5 MW
1-6	〃	〃	Stepped
2-4	W=2250,H=0	Corner	1.25MW
2-5	〃	〃	2.5 MW
2-6	〃	〃	Stepped
3-1	W=2250,H=0	Center	1.25MW
3-2	〃	〃	2.5 MW
3-3	〃	〃	Stepped
5-1	W=2250,H=1000	Corner	1.25MW
5-2	〃	〃	2.5 MW
5-3	〃	〃	Stepped

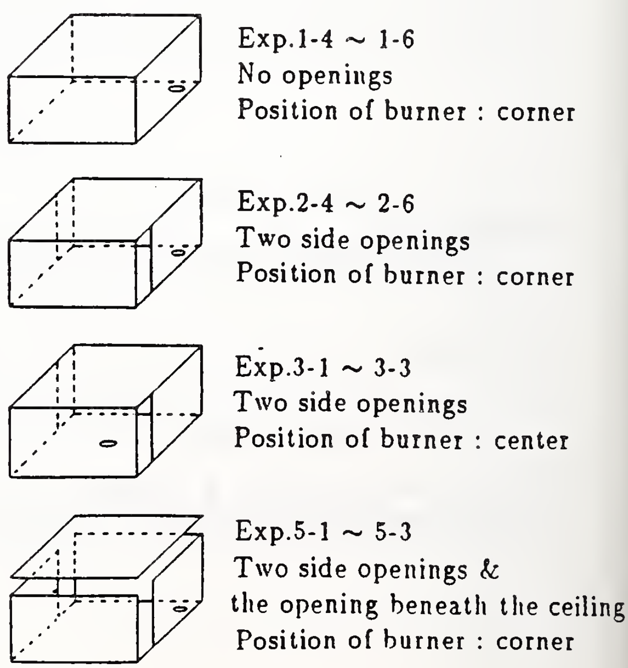


Fig.4 Schematics of Experimental conditions

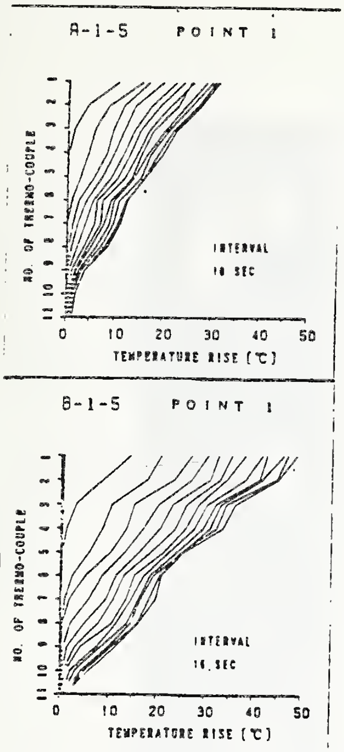


Fig.6-1 Vertical temperature profiles at 12 different time periods in Experiment 1-5

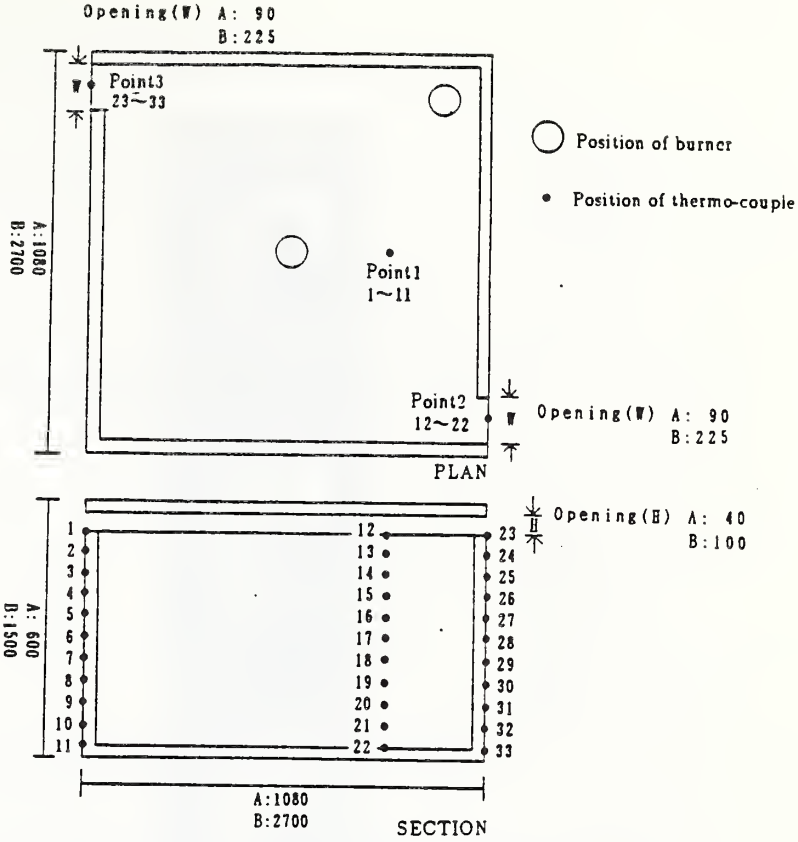


Fig.5 Plan and Section of Models (A:1/25, B:1/10)

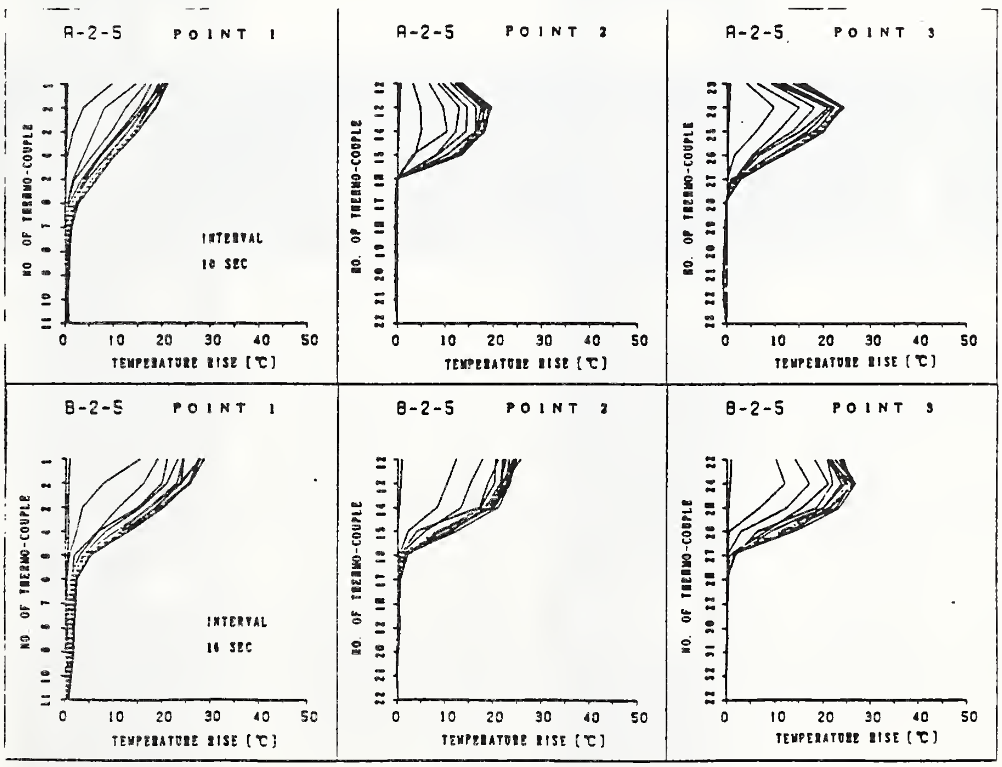


Fig.6-2 Vertical temperature profiles at 12 different time periods in Experiment 2-5

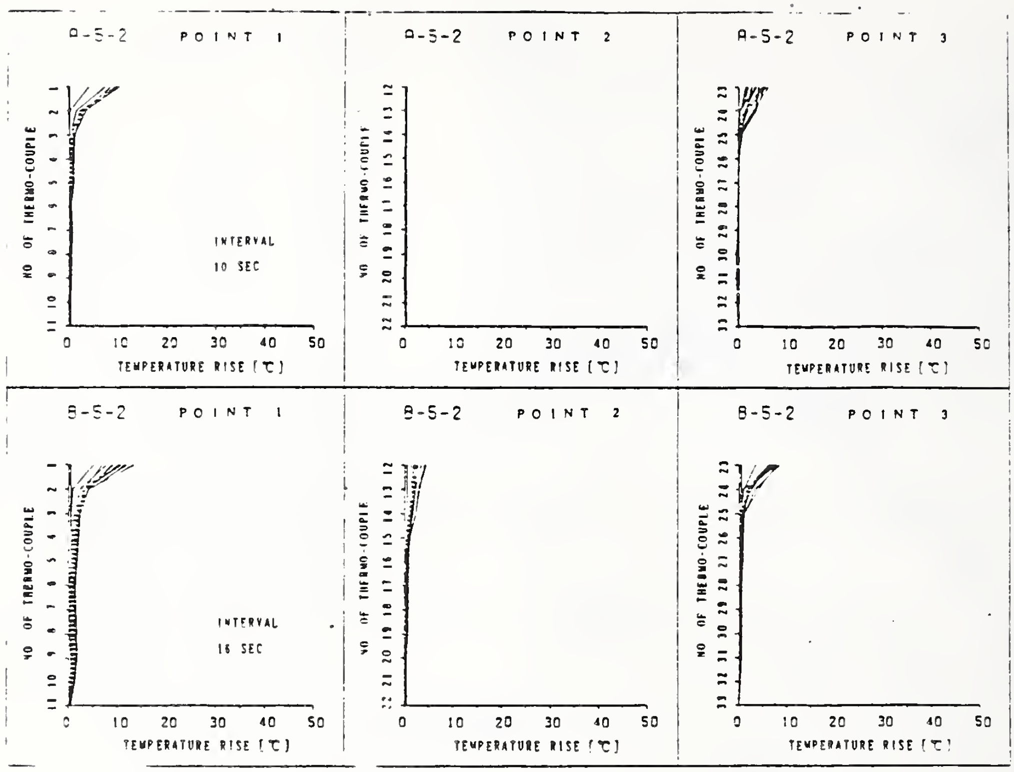


Fig.6-3 Vertical temperatature profiles at 12 different time periods in Experiment 5-2

Experiment B-3-2 (Scale 1/10)

71"1 79"0 86"9 94"8

height of atrium space ; 1500mm
heat release rate ; 7.9kw
diameter of burner ; 150mm

(the only difference between Experiment B-2-5(Fig.7) and this is the position of the burner)

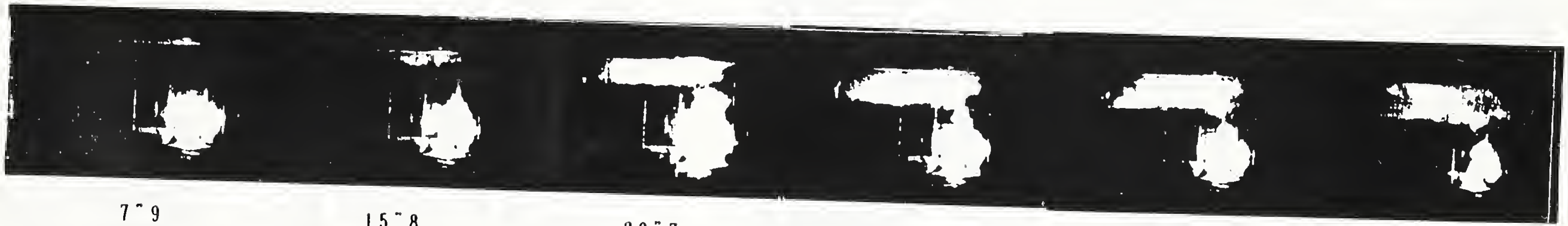
Fig.8 An example of fire whirl generated in Experiment B-3-2

Experiment A-2-5 (Scale 1/25)

5" 10" 15" 20" 25" 30"

height of atrium space ; 600mm
heat release rate ; 0.80kw
diameter of burner ; 60mm

Experiment B-2-5 (Scale 1/10)



7"9 15"8 23"7 31"6 39"5 47"4

height of atrium space ; 1500mm
heat release rate ; 7.9kw
diameter of burner : 150mm

Fig.7 Visualized smoke layer in 1/25 and 1/10 scale

A SMOKE CONTROL CALCULATION FOR PRESSURIZED ELEVATOR SHAFT

Takayuki MATSUSHITA
Building Research Institute
Ministry of Construction
1 Tatehara,Tsukuba-shi,Ibaraki-ken
Japan

1.INTRODUCTION

The possibility of using pressurized elevator for the evacuation of the handicapped is being explored by Klote,Tamura and others[1]. In this paper, it is shown that the computer smoke transport model developed by the author et al.[4] is successfully applicable for the case where a building has a shaft with a moving cage, and the effects of multiple air supply inlets on the smoke control of pressurized elevator shaft are investigated.

2.MATHEMATICAL FORMULATION

Klote and Tamura made the experiments and theoretical analyses on the air flow in a pressurized elevator shaft with a moving cage[2,3], however, it will be difficult to apply their analytical method to the conditions which change as a fire develops in a building. The advantage of using a computer model is that it can be flexibly applied to such transient conditions. Unlike usual one zone models for smoke transport in buildings, the change of node(space) volume with respect to time cannot be ignored when a cage moves in a shaft. Accordingly, the basic equations for the smoke transport in a building are given as follows:

(1) Mass conservation

$$\{V\frac{d\rho}{dt}\}+\{\rho\frac{dV}{dt}\}+[I]\{w\}=\{W\} \qquad (1)$$

where V,ρ,w and W stand for node volume[m^3], gas density[kg/m^3], net flow rate at opening[kg/s] and mass generation rate[kg/s], respectively. Symbols {} stand for vector of nodes and {} stand for vector of openings, and [I] is the incidence matrix[4]. Note that $dV/dt\neq0$ at a node in the elevator shaft when the cage is moving in the node.

(2) Energy conservation

$$\{C\frac{\rho TV}{P}\frac{dP}{dt}\}+\{C_p\rho T\frac{dV}{dt}\}+[I]\{E\}=\{Q\} \qquad (2)$$

where C_p,P,T,E and Q stand for specific heat of gas [kJ/kgK], absolute pressure[Pa], temperature [K], net energy flow at an opening[kJ/s] and heat release rate[kW], respectively. When temperature is the same at all the nodes, Equation (2) becomes as follows:

$$\{C_p\rho T\frac{dV}{dt}\}+C_pT[I]\{w\}=\{Q\} \qquad (2')$$

(3) Equation of state of ideal gas

$$P=\rho RT \qquad (3)$$

(4) Flow rate through an opening

Flow rate through an opening is calculated using Bernoulli's equation for orifice flow as a function of pressure difference, temperature and opening conditions.

(5) Change of node volume

The difference of this system of equations from that of existing one is that dV/dt term is added in the equations for mass and energy conservations. The change of the volume with time of a node in which an elevator cage is passing is given as

$$\frac{dV}{dt}=A_c v \qquad (4)$$

where A_c and v stand for the horizontal section area [m^2] and the velocity of the cage [m], respectively.

3.CALCULATION OF SMOKE CONTROL IN THE ELEVATOR SHAFT

The experiments by Klote et al.[3] were conducted under room temperature condition. For the smoke transport calculation at constant temperatures, Eqns. (2'),(3) and (4) are the only equations to be used.

The test building is modeled as shown by the graph in Figure 1. The input property data are given in Table 1. The velocity of the elevator cage is modeled as shown in Figure 2.

In this calculation method, the elevator shaft is divided at each floor height so that each segment space is taken as a node. The pressure loss ΔP due to flow friction of the elevator shaft can be calculated by the following equation, which has been established for circular ducts.

$$\Delta P= \lambda(L/D)\ v^2/2 \qquad (5)$$

where λ,L,D stand for friction coefficient, length [m] and diameter of the duct [m], respectively. Substituting the real dimensions of the shaft in the experiment by Klote and Tamura into D and L, and an established data for concrete duct into λ, we have the value corresponding to the flow coefficient for the length of a floor height as follows:

$$(D/\lambda L)^{1/2}=5.0 \qquad (6)$$

As for the flow coefficient α' for the space between the cage and the shaft wall, Klote et al. obtained the value of 0.83. The value of α' was calculated using the following equation assuming that the volume flow rate through the space is equal to the shaft section area multiplied by the cage velocity.

$$A_s v= \alpha' A_f(\rho \Delta P/2)^{1/2} \qquad (7)$$

where A_s and A_f stand for the section area of the shaft and the space between the shaft wall and the cage, respectively.

On the other hand, in this calculation method, it is considered to be more appropriate to use the cage section area A_c instead of A_s in Eq.(7) for defining the flow coefficient α, then using the data of Klote's experiment, α becomes as follows.

$$\alpha = \alpha' A_c/A_s=0.6 \qquad (8)$$

In Figure 3, comparisons of the pressure between the analysis by Klote et al. and this computing method are shown. A good agreement is seen between the two in case of α=0.6.

The comparison of the pressure between the experiments by Klote and Tamura for a pressurized elevator shaft with a moving cage and the results of the calculations by the computer smoke transport model are shown in Figure 4 and 5 respectively for the cases, when the cage ascends and in Figure 5 when the cage descends. These results show a good agreement between the experiments and the calculations.

4.EFFECT OF AIR SUPPLY PATTERNS ON SHAFT PRESSURE

In order to investigate the effects of different air supply patterns on the smoke control efficacy of a pressurized elevator shaft, the calculations were made for the following three typical supply patterns.

(1) air supply at two positions; on the 1st and the 15th floors
(2) air supply at three positions; on the 1st,8th and 15th floors
(3) uniform air supply; on each of the floors

The total air supply rate is fixed at the same value which is uniformly distributed to the air supply positions in each case.

The calculation results of pressure at the levels of 1st, 8th and 15th floors in each of the above mentioned cases are shown in Figs.6-8. Although these results are given only for the cases when the cage ascends, the results for the cases when the cage descends can be obtained just by exchanging the pressures of 1st and 15th floors.

In these figures, it can be seen that the pressure drop at the 1st floor due to the cage passing is the smallest when air supply is given to 1st and 15th floors and the shaft pressure is stable. In case of uniform air supply, the pressure change at the 1st floor is large, although the pressure difference between above and below the cage is kept constant.

5.CONCLUDING REMARKS

(1) In case of a pressurized elevator shaft with a moving cage, the computer model of smoke transport developed earlier by the author et al. can be used by a slight modification that $dV/dt \neq 0$ at a divided node in the elevator shaft.
(2) In this calculation method, the value of 0.6 which is modified from experimental data of Klote and Tamura to the flow coefficient for the space between the cage and the shaft wall gives an acceptable agreement with the experiment .
(3) The effects of different air supply patterns in a pressurized elevator shaft is investigated by using the computer model of smoke transport. Such flexibility of the computer model will be useful when we need close consideration on the availability of pressurized elevator shafts for the evacuation of the handicapped.

REFERENCE

[1] Klote;NBSIR82-2507,1982.5
[2] Klote,Tamura;ASHRAE Transactions,Vol.93,2217-2228,1987
[3] Klote,Tamura;Fire Safety Journal,Vol.11,227-233,1986
[4] Matsushita,Fukai,Terai;1st Fire Safety Science,1123-1132,1986

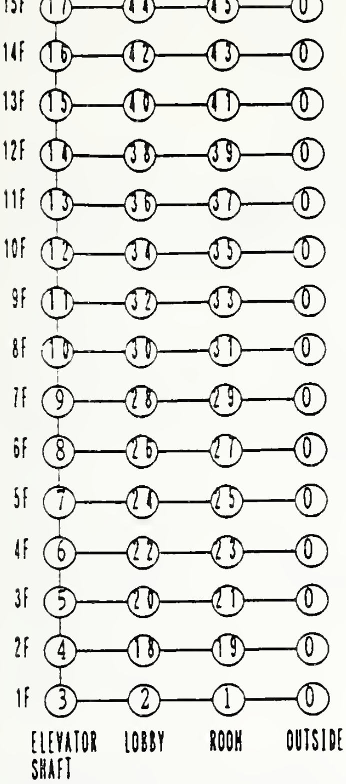


Figure-1. Graph of building for analysis

	Values	Comments
Supply rate of air	8.05[kg/s]	Exp. condition by KLOTE
Cross-sectional shaft area	5.515 [m²]	ditto
Area around elevator car	1.947 [m²]	ditto
Area between shaft and lobby	0.131 [m²]	Used value by KLOTE
Area between lobby and building	0.0901[m²]	ditto
Area between building and outside	0.450 [m²]	ditto
Flow coefficient for opening	0.65	ditto(estimated)
Flow coefficient for flow around elevator car	0.83 0.60	ditto modified value
Flow coefficient for shaft	5.0	Friction loss(estimated)

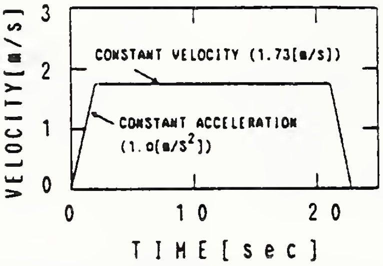


Figure-2. Time schedule of a moving cage in a elevator

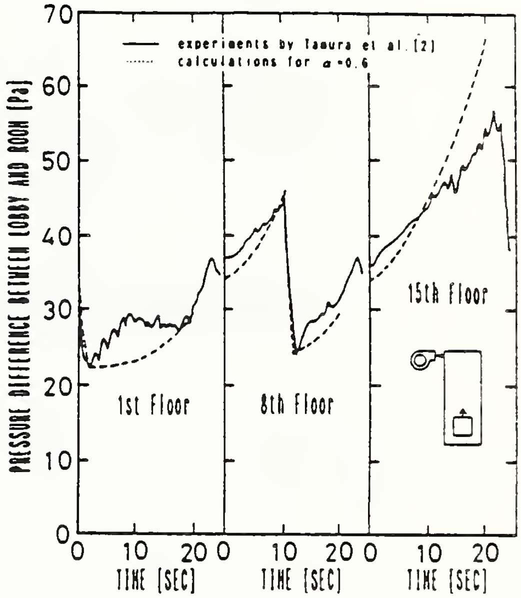


Figure-4. Comparison between the experiments by Klote and Tamura and the calculation by the computing method when a cage ascends in a pressurized elevator shaft

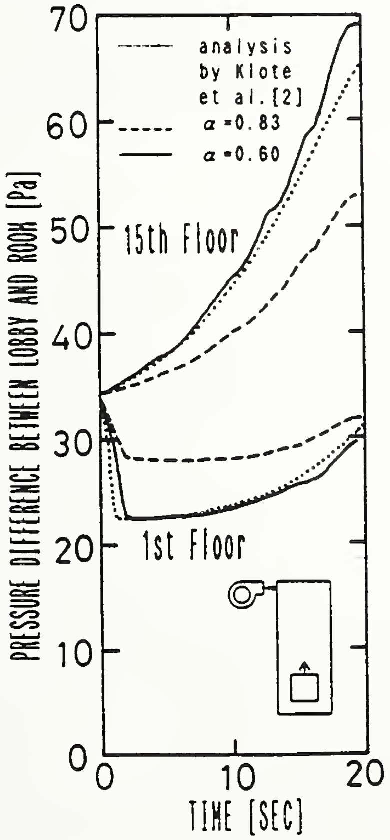


Figure-3. Comparison between the analytical results by Klote and Tamura and the calculation by the computing method when a cage ascends in a pressurized elevator shaft

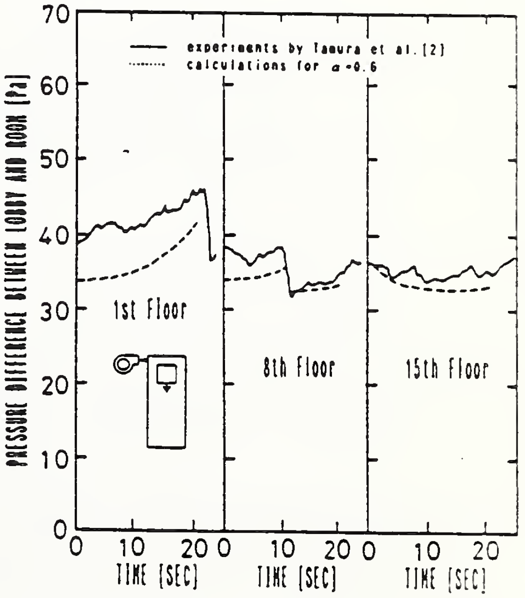


Figure-5. Comparison between the experiments by Klote and Tamura and the calculation by the computing method when a cage descends in a pressurized elevator shaft

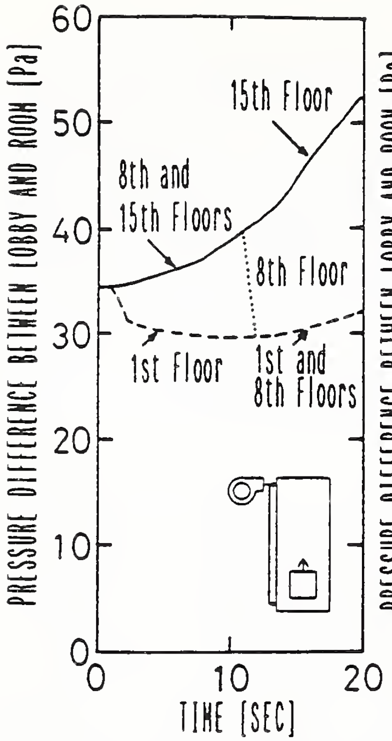


Figure-6. Calculation results when air supply on 1st and 15th floors and a cage ascends

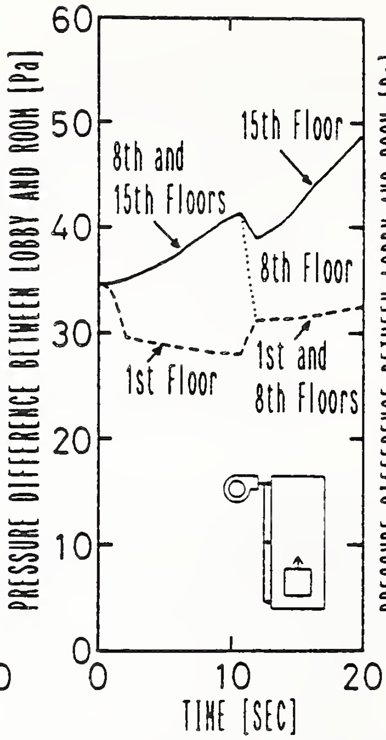


Figure-7. Calculation results when air supply on 1st,8th and 15th floors and a cage ascends

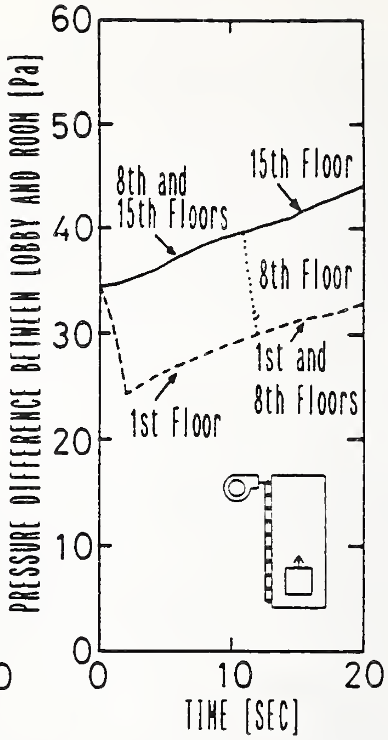


Figure-8. Calculation results when air supply on each of the floors and a cage ascends

Method for Estimating Smoke Leakage through Small Openings Using Tracer Gas

Tokiyoshi YAMADA

Fire Research Institute
Fire Defence Agency,
Ministry of Home Affairs

ABSTRACT

Smoke leakage through openings concealed behind ceilings and/or walls can create confusion and therefore a hazard which threatens occupants in case of a building fire. This kind of small opening, which is the result of defective construction work and/or aging, can not be found easily after the completion of the building.

This paper presents a method for estimating the effective areas of these openings as well as smoke leakage rates trough application of methods for measuring air infiltration rates of buildings with SF_6 tracer gas.

Two test series consisting of a total of eleven full-scale experiments were conducted to determine the degree of accuracy of this prediction method. Smoke leakage rates estimated from tracer gas concentrations and ventilation rates agree well with experimental data measured by an orifice flow meter. The maximum error is about 20%. However, rapid concentration change and its unhomogeneousness in the fire room immediately after purging tracer gas increases the degree of error.

1. INTRODUCTION

In building fires in Japan, a little less than half of the deaths are reported to be the result of smoke inhalation [1]. However, many victims seem to be trapped by thinner smoke in the early stage of a fire, spend much time struggling to escape before dying. As Dr.Jin has pointed out [2], evacuees lost visibility and mobility in relatively thin smoke ($Cs<=1.0$) before CO concentration reached a dangerous level.

Many smoke problems are the result of smoke infiltration through unexpected openings, unused air ducts, unplugged piping shaft etc, as well as stair cases in Japan. Small openings, which are consequences of defective construction work and/or aging, can not be found easily after the completion of the building. Unanticipated smoke leakage through these openings creates confusion among evacuees. In addition these openings constitute an even greater danger when they permit the spread fire into other parts in a building.

Many efforts to predict fire smoke movement have been made in the past and are now continuing. However, no mathematical model can predict smoke spread without knowing the size and locations of such openings. Mathematical models--

zone models for example--- are powerful prediction tools for designers and engineers involved in the planning of new buildings, but they do not always adequately address the problem of smoke propagation in existing buildings. For this reason we need some other experimental methods to get the boundary conditions for predicting smoke propagation in more practical situations.

One Study concerned with this problem was conducted by Fung C.W. and R.H.Zile [3] in '75. They tried to predict the possibility of smoke propagation in an existing building using SF_6 tracer gas. However the results are limited to the qualitative character of the building they studied, and are not expandable to a general prediction method. This paper presents an method for estimating such smoke leakage rates and opening areas which applies a method for measuring the rate of air infiltration of building using SF_6 tracer gas and provides a basis for the practical inspection of existing buildings now and in the future.

2.ESTIMATION METHOD OF SMOKE LEAKAGE AND OPENING AREA.

Estimation of infiltration through openings has been investigated within the research field of building physics [4][5][6]. The principle interest of those studies was the ventilation rate between the inside and outside of the building from the view point of energy saving. However, nearly the same method is applicable to smoke leakage between rooms inside a building .

When effective areas of openings are known between rooms, the smoke leakage rate can be obtained by the next simple equation. For simplification, locations of openings, especially their heights, are not considered.

$$\dot{Q} = \alpha A \left[\frac{2\Delta P}{\rho} \right]^{1/n} \text{------------------------------} (1)$$

where $\dot{Q}$: Volumetric leak rate [m^3/sec]
n : nondimensional value varies from 1.6 to 2.0 depending upon the opening character and passing flow rate. 2.0 is commonly used when the pressure difference is relatively large (≥45 pa [6]) and/or the opening area is large.
α : opening coefficient.
A : area of opening [m^2]
ΔP : pressure difference across the opening (between rooms) [pa].

The difference between normal ventilation and smoke leakage is the magnitude of the pressure difference. Compared with normal ventilation, the pressure difference in the case of fire is larger, so even a small opening can not be neglected.

To obtain the αA value, the values of both Q and ΔP are required. Once the αA is known, the smoke leakage rate through the opening under certain fire conditions can be predicted with mathematical models. To get the smaller αA, we had to produce more pressure difference or take much time to measure Q under a lower pressure difference condition. However, the latter is not practical, since the surrounding conditions vary, especially wind, and long time exclusive possession for testing is inconvenient for the tenants of the building.

To simplify the situation, we consider the case shown in **Fig.1**. Smoke leaks through openings from the lower fire room to room directly above and gradually contaminates the air in the upper room. (Here we express these rooms as FIRE-room and UPPER-room.) The smoke leakage can be estimated easily with the mass conservation equation (2) given the concentration of smoke and ventilation rate, provided that the following quasi-steady conditions are satisfied:

(1) Smoke concentration distribution in the upper room is uniform.
(2) Change of density due to temperature rise is negligible.
(3) Smoke leaks only from assumed FIRE room to UPPER room, and does not turn back and/or and comes from other routes,i.e. corridor, stair well, etc.

and as a preferable condition for accessing the experimental prediction method

(4) Leak and ventilation rate are in quasi-steady.

The conditions mentioned above are not the same as occur in a real fire, even in the early stage. However it is not necessary to duplicate the fire condition to determine αA for the opening.

(Mass conservation equation in the UPPER-room.)

$$\bar{g}_1(t) = \frac{\{ Co(t) - Co(t_0)\} V_o + \int_{t_0}^{t} Co(t)\, Go(t)\, dt}{\int_{t_0}^{t} Co(t)\, dt} \text{ ------------- (2)}$$

where $\bar{g}_1(t)$: mean leak rate during time t_0 to t. [m^3/min.]
C (t) : smoke or tracer gas conch. at time t. [volumetric conch.]
G (t) : ventilation rate at time t. [m^3/min.]
V : room volume [m^3]
(*cf. weight unit is also available for above g_1,C,G instead of volumetric unit.)

subscript o : observation UPPER-room (2FL)
f : FIRE-room (1FL)
0 : basic time point

In practical estimation methods for leakage, certain tracer gases (SF_6 in this study) can be used instead of smoke and the αA can be obtained from Eqs.(1) and (2) when the pressure difference between rooms is measured. In this paper the first priority is to assess the degree of accuracy of smoke leakage rate estimated with Eq.(2). However, αA is also estimated in one series of experiments.

There are two methods for producing the required pressure difference between rooms. One utilizes the buoyant effect,i.e. warm the FIRE-room to an adequate temperature level, and the other uses mechanical venting, i.e. pressurize the FIRE-room and/or exhaust from the UPPER-room. The latter is a useful and powerful method when a VHA system and other ventilation fan are available.

3.EXPERIMENTS

3.1.INSTALLATION

Two series of experiments are conducted to assess the degree of accuracy of the estimation method for the leak rate from a small opening and its effective area.

Each experiment has one FIRE-room, and one upper observation room directly above as shown in **Fig.2** and **Fig.3**. An orifice flow meter (ID.50-40 mmϕ) is installed at a slab between two rooms and serves as an "unknown" small opening. The leakage through this opening is measured directly with this orifice flow meter, and also estimated by tracer gas concentration and ventilation rate as indicated by **Eq.(2)**. Thus comparisons between estimations and experiments are possible.

The difference between the two series of experiments is the method used to produce the pressure difference. Natural ventilation force due to buoyancy effect is adopted in the six runs in the first series of experiments, and mechanical exhausting with a ventilation fan is used to produce the pressure difference in the five runs of the second series of experiments.

3.2. Producing Pressure Difference

3.2.1. Series-I

In this experimental series, the electrical fan heater is used to warm the FIRE-room. Two operating conditions of the fan are examined ; Run-No.1 to 3 the condition is higher temperature and more wind volume (12 kW, 7.3 m^3/min.) and the other is a lower condition (8 kW, 10.2 m^3/min.). About ten minutes prior to releasing the SF_6 tracer gas, warm wind is blown into the FIRE-room. The FIRE-room temperature rises to a level from 8 to 20 deg.C above ambient temperature, and a steady state temperature is achieved and maintained in each run. Under such conditions, the estimated maximum pressure difference due to buoyant effects is about 2.8 pa. Some difference of temperature rise between runs is caused by changes in the opening condition of the FIRE-room.

3.2.2. Series-II

Two levels of pressure difference are produced by mechanical exhausting with the ventilation fan in the UPPER-room with all windows and a door of the room is closed, values of about 3 pa. and 2.3 pa. pressure differences are obtained. In this series of experiments, the ventilation rate is directly measured with an orifice flow meter connected to the fan.

3.3.Description of Measurements

3.3.1.Tracer Gas

To estimate the leak rate, the gas concentration in each room and the ventilation rate of the UPPER-room are required. SF_6 gas, which is ordinarily used for measurement of building ventilation or investigation of atmospheric dispersion mechanism, was selected as the tracer gas for these experiments.

Charging Gas ; 99.9 vol.% pure SF_6 gas is charged into the FIRE-room at a constant rate of 400 cm^3/min. in series-I and about 80 cm^3/min. in series-II to reach some ten ppm after 20 min. In these experiments, time=0 occurs at the initiation of charging.

SAMPLING & ANALYSIS ; In each series of experiments, air is sampled with automated gas sampling equipment as shown in **Fig.4** on the time schedules indicated in **Fig.5** and **Fig.6**. In both series the sampling rate is one sample/4 minutes. Differences between the series are the time interval during which the sample is accumulated (sampling time), sample volume, and sampling location. In series-I, the sampling time is two minutes and the samples are taken at three different levels at the center of the UPPER-room using three independent sampling lines. In series-II, the sampling time is one minutes and samples are drawn through two independent lines; one line is connected to eight sampling ports and the other to two sampling ports as shown in **Fig.4**

The air in the FIRE-room is sampled from a line having four sampling ports located 50cm below the ceiling. These test specimens are accumulated in a 5000 cm^3 teflon sampling bag at a rate of 1000 cm^3/min. in series-I and 4000 cm^3/min.in series-II.
The specimen are quantitatively analyzed by a gas chromatograph with a Flame Photometric Detector within 24 hours after each experiment. Details of the gas chromatograph and its operating conditions are shown in **Tab.1**. With this method, the analysis error is found empirically to be within five percent.

Tab.1. Condition of Chromatographic Analysis

Column	porapack Q, SUS.col. , I.D. 3ϕ x 2 m
Temperature	Col.230 °C, Inj.240 °C, Det.230 °C
Detector	FPD (Flame Photometric Detector)
	H_2 flow rate 0.4 cm^3/min., applied Voltage 800 V O_2 flow rate 0.2 cm^3/min. N_2 flow rate 0.2 cm^3/min.
Carrier gas	N_2 flow rate 70 cm^3/min.
Working Curve	concentration $\propto$ ln(peak height)

3.3.2. Ventilation Rate

The ventilation rate is measured with a CO^2 decay method. Prior to each run, CO_2 gas is released to attain some thousands ppm level in the UPPER-room. The depletion of the CO_2 concentration is then measured during the experiment. Since the ventilation rate seems to be quasi-steady, an average ventilation rate (number of exchanges) is obtained from a tangent of the regression line of $-\ln\{Cco_2(t_i)/Cco_2(t_0)\}$ against time lapse $t_i - t_0$, where t_i is the i-th time increment. In these experiments, data obtained every one minute with the infrared analyzer are used to get a mean average between t_i and t_0. In series-II, the ventilation rate is measured directly by an orifice flow meter as mentioned above as well as the decay method.

3.3.3. Leak Rate & Pressure Difference.

The leak rate through an orifice ($\alpha A = 11.3\ cm^2$) is measured with a pressure transducer. In series-II, the pressure difference between the rooms --- i.e., between the ceiling level of FIRE-room and floor level of the UPPER-floor --- is measured at the center of the room as shown in **Fig.3** with a high resolution pressure transducer. These data are recorded with a pen recorder (in series-I and-II) and digital recorder of one second interval in series-II.

3.3.4. Other Equipments

Gas temperatures in each room and ambient temperature are measured with CA-thermocouples. The room temperature profiles are measured at 15 points in a vertical line at every 15 seconds. With the above mentioned equipments, the experimental runs are conducted on the time schedules shown in **Fig.5** and **Fig.6**.

4. RESULTS AND CONSIDERATIONS

4.1. Experimental Conditions and Results.

Six runs in experimental series I and five in series II were conducted under quasi steady state conditions. The experimental conditions (ventilation rate in UPPER-room, SF_6 concentration level in FIRE-room and temperature), and the results consisting of the leakage rate from the orifice, SF_6 concentration in the UPPER-room and the pressure difference are indicated in **Tab.2** and **Tab.3**.

In spite of efforts to establish the same experimental conditions in some runs, the experimental conditions and leakage rates are slightly different between those runs. For example, the conditions of the outer wind appears to effect the ventilation rate and leak rate.

In series-I, a principle parameter of the experimental condition is the temperature rise in the FIRE-room. For example, runs No.1 to 3 show more heat and mass flow to the FIRE-room than the other three runs as explained in 3.2.1. The SF_6 concentrations in FIRE room were intentionally changed slightly to determine the effect on estimation accuracy.

In series-II, runs No.1 to 3 were conducted under almost the same conditions, however No.4 was conducted with two orifice opening, and No.5 was done under smaller pressure difference. Other conditions were the same.

The dilution listed in **Tab.2** and **Tab.3** is the ratio of SF_6 concentration in the UPPER-room to that in the FIRE-room. These results indicate how easily the air in the UPPER-room is contaminated through relatively small openings even under lesser pressure-difference conditions than occur in a real fire.

4.2. Comparisons between Estimation and Experiment.

4.2.1. Estimation of Leak Rate.

The leak rate is estimated with a numerical approximation of Eq.(2); that is,

Tab.2. **Conditions, Leak Rate & SF_6 Conc.** ; (Series I)

Exp. Run No.	Temperature [deg.C] Ra. temp.rise 2FL	1FL	Ambient temp.	Vent. rate [turn /hour]	Leak rate [$x10^{-3}$ $m^3/m.$]	SF_6 CONC. [ppm] 2FL. (UPPER)	1FL (FIRE)	dilution [%]
1	+5.9	18.9	19.8 C	1.9	100.1	0.931	38.3	2.4
2	0.9	18.2	17.8	2.7	79.0	0.477	20.7	2.3
3	0.1	14.4	26.6	2.1	82.3	0.485	17.0	2.9
4	2.4	11.1	20.4	1.9	80.1	0.597	27.5	2.2
5	2.3	9.2	21.5	3.1	87.9	0.781	47.7	1.6
6	0.6	7.9	25.3	2.4	61.9	0.471	24.5	1.9

cf. *1) temp. rise of 1FL:2FL is an average temperature difference of 15 vertical measuring points from ambient temperature.

*2) Vent. rate is presented here as number of room air exchange between five to 20 min.

*3) SF6 conc.is the average of three vertical sample points at 20 to 22 min. period.(exp.5, 18 to 20). dilution is the diluted conc.of 2FL. against the 1FL.Conc.

Tab.3. **Conditions, Leak Rate & SF_6 Conc.**; (Series II)

Exp. Run No.	Vent rate [T/H] by orifice (SD/M)	by CO_2 decay	Leak rate [$m^3/m.$] (SD/M)	pressure differ. ΔP [pa] (SD/M)	SF6 CONC. [ppm] 2FL. UPPER	1FL. FIRE	dilution [%]
1	4.58 (.01)	4.6	0.173 (.04)	2.99 (.08)	1.07	35.5	3.0
2	4.57 (.05)	4.7	0.181 (.05)	2.84 (.11)	1.22	38.2	3.2
3	4.45 (.11)	4.6	0.175 (.11)	3.21 (.29)	0.59	26.2	2.2
4	4.43 (.07)	4.6	0.340 (.07)	2.89 (.17)	1.87	39.0	4.8
5	3.22 (.16)	3.6	0.158 (.16)	2.32 (.47)	0.82	28.2	2.9

cf. *1) Vent. rate is presented here as a number of room air exchange during 29 min. after starting of SF6 injection.

*2) vent rate ,leak rate and pressure are mean value during 29 min. the value in parenthesis is standard deviation/mean.

*3) SF6 conc.is the average of 8 sample points at 23 to 24 one min. period.(exp.1, 24 to 25, exp.2, 20 to 21). dilution is the diluted conc.of 2FL. against the 1FL.conc.

*4) exp.1 to 3 are almost the same exp.condition except SF6 purge rate and weather, mainly wind conditions.

$$g_{1\,i_0 \to i} = \frac{(Co_i - Co_{i_0})\,Vo + G_{i_0 \to i} \sum_{i=i_0}^{i-1} (Co_i + Co_{i+1})/2\ \Delta T}{\sum_{i=i_0}^{i-1} (C_{f\,i} + C_{f\,i+1})/2\ \Delta T} \quad \text{-------(2')}$$

where $g_1\ i_0 \to i$: mean estimation of leak rate during Ti_0 and Ti time duration.
$G\ \ i_0 \to i$: mean ventilation rate during Ti_0 and Ti time duration.
C i : mean SF_6 conch. of the i-th sampling duration.
Ti : mid time of the i-th sampling duration.
ΔT : $T_{i+1} - T_i$
i0 : basic time point

Thus the mean leak rate through a small opening (orifice in this experiments) are obtained by the above simple procedure. In this analysis, a base point Ti_0 and accumulated time duration ($i_0 \to i$) are varied to determine their effects on the accuracy of this prediction method.

4.2.2. Comparisons between Estimation and Experiment.

Tab.4 and **Tab.5** show the ratio of estimation against to experiment.

Basic Time and Sampling Interval; As shown in **Tab.4**, the error is larger when the starting time of the SF_6 charge is chosen as the basic time (Ti_0) and an averaging time duration($Ti_0 \to i$) is shorter. These results show that the rapid concentration change immediately after starting the SF_6 charge is not desirable for this prediction method for the reason as mentioned in section.2 condition (1).

When the basic time is set to be seven or nine minutes and the averaging time duration is longer than eight min. the prediction agrees with experimental results fairy well. (see **Tab.4** and **Tab.5**) The averaging procedure is required for this method and shorter time interval for sampling can be used when the basic time is set to be later from the beginning of SF_6 purging.

In these experiments, the errors are found to be within 20 %. For example, an average value of error is about 8 %, when the Ti_0 = 9 min. and Ti = 17 min. are chosen in series-I. More accurate estimations are obtained in Series-II within a few percent when later basic time is adopted.

Ventilation Term ; Compared with the series-II experimental results, a tendency of depletion of accuracy at the longer durations is found in series-I. This difference appears to be caused by the ventilation term in Eq.(2'). In series-II , the mechanically ventilated rate was stable and the measurement error was less than that for the natural vent in series-I. In this estimation methods, the effect of the ventilation term becomes larger when the SF_6 conc.level is higher as time goes by. So although the averaging effect improves the estimation, the error of ventilation measurements seems to offset this improvement.

Tab.4. Comparison of Experiment and Estimation Leak Rate under Different Basic Time(Ti_0) and Duration($Ti_0 \rightarrow i$) ; (series I)

[ratio = estimation/experiment]

Exp. Run No.	Basic Time (Ti_0) = beginning of SF_6 inj.: to 5 min.	9.	13.	17.	21.	Ti_0 = 9 min.: to 13 min.	17.	21.
1	1.57	1.21	1.10	1.17	1.17	0.85	1.08	1.07
2	1.89	1.32	1.22	1.25	1.31	1.05	1.16	1.27
3	1.51	1.30	1.25	1.23	1.22	1.16	1.16	1.19
4	1.65	1.21	1.16	1.22	1.18	0.92	1.04	1.02
5	0.76	0.61	0.65	0.77	0.84	0.69	0.87	0.91
6	1.16	1.02	1.07	1.09	1.23	1.17	1.15	1.30

cf. *1) the values in table are estimation/experiment of leak rate calculated through the each duration from basic time Ti_0 a certain time.)

*2) estimation value are calculated with eq.(3). Steady state of ventilation rate is assumed as shown in Tab.1.

*3) the SF6 conc. of two minutes sampling time is assumed to be the conc. of mid time in each sampling period, and linear approximation between each data is assumed.

*4) the time shown in Tab. is a mid time of each two minute sampling period. (in Run No.5, deduct two minutes from each time including basic time = 9 in right side)

Tab.5. Comparison of Experiment and Estimation Leak Rate under Different Basic Time(Ti_0) and Duration($Ti_0 \rightarrow i$) ; (series II)

[ratio = estimation/experiment]

Exp. Run No.	Basic Time (Ti_0)=8.5 min. after SF_6 inj.: to 12.5	16.5	20.5	24.5	28.5	Ti_0 = 16.5 min.: to 20.5	24.5	28.5
1	0.90	0.90	0.90	0.98	1.09	0.88	1.01	1.13
2	0.95	0.98	0.97	1.00	1.05	0.94	1.00	1.03
3	0.98	0.91	0.92	0.94	0.98	0.91	0.95	1.00
4	0.82	0.84	0.85	0.89	0.96	0.87	0.92	1.01
5	0.70	0.91	0.95	0.97	1.07	0.99	0.99	1.15

cf. *1) the values in table are estimation/experiment of leak rate calculated through the each duration from basic time Ti_0 a certain time.)

*2) estimation value are calculated with eq.(3). Steady state of ventilation rate is assumed as shown in Tab.1.

*3) the SF6 conc. of one minutes sampling time is assumed to be the conc. of mid time in each sampling period, and linear approximation between each data is assumed.

*4) the time shown in Tab. is a mid time of each one minute sampling period. (in Run No.1, deduct two minutes from each time point, and add one minute for Run No.4 & 5)

Tab.6. **Comparison of estimated effective area with orifice opening;** (series II)

Exp. Run No.	Leak rate estimation [m^3/min]	Pressure difference [pa]	Estimated effective area [cm2]	Description of orifice opening.
1	0.174	2.97	12.9 (1.14)	effective area of
2	0.173	2.83	13.2 (1.17)	40-50 mmϕ orifice
3	0.167	3.22	11.9 (1.05)	is 11.3cm^2
4	0.312	2.82	23.6 (1.04)	(α=0.89,
5	0.167	2.74	12.9 (1.14)	A=12.6 cm^2)

cf *1) the value inside the parenthesis indicates the ratio against the effective area of orifice. run No.4 is two orifice of the same area are used.
*2) The values are obtained from measured data of Ti_0=16.5 to Ti=24.5.

4.2.3. Estimation of Effective Opening Area (αA).

The effective area of the opening can be estimated from Eq.(1). **Tab.6.** shows the estimated effective area for each run in series-II. The estimation error is about 20 % and is sufficiently accurate for estimating these area for practical use. The measured pressure difference is under estimated in the experiments and more improvement is needed for the measurement of pressure difference between rooms of different floor.

5. CONCLUSIONS and FUTURE DIRECTIONS

A simple experimental method for estimating the smoke leakage through small openings and the effective areas of the openings is presented. Two series of experiments were conducted to determine the degree of accuracy of the method by measuring tracer gas density, ventilation rate and the pressure difference. Comparisons of estimation and experimental leak rates show agreement within 20 %. When the exhaust system is used to produce the pressure difference between rooms, the accuracy is fairly well within a few percent. These results indicate that this estimation method is favorable as a practical estimation method.

However this experimental study was limited to only one type of opening between relatively small volume rooms. Uniformity inside the room and quasi-steady state are very important for this method. Further experimental studies are desirable for verifying its appropriateness in larger volume rooms. The size of opening that can be distinguished with this method is determined by room volume, charged tracer gas concentration, produced pressure difference, and mostly depends on the resolution of the tracer-gas analyzer. Future work will formulate relationships between distinguishable opening size and these other parameters for practical building configurations.

REFERENCES

[1] Fire Defence Agency : "Fire Defence White Paper", '88

[2] Jin T. Yamada.T.: "Experimental Study of Human Behavior in Smoke Filled Corridors", the 2nd IAFSS Symposium proceedings, pp.511-519,(1988).

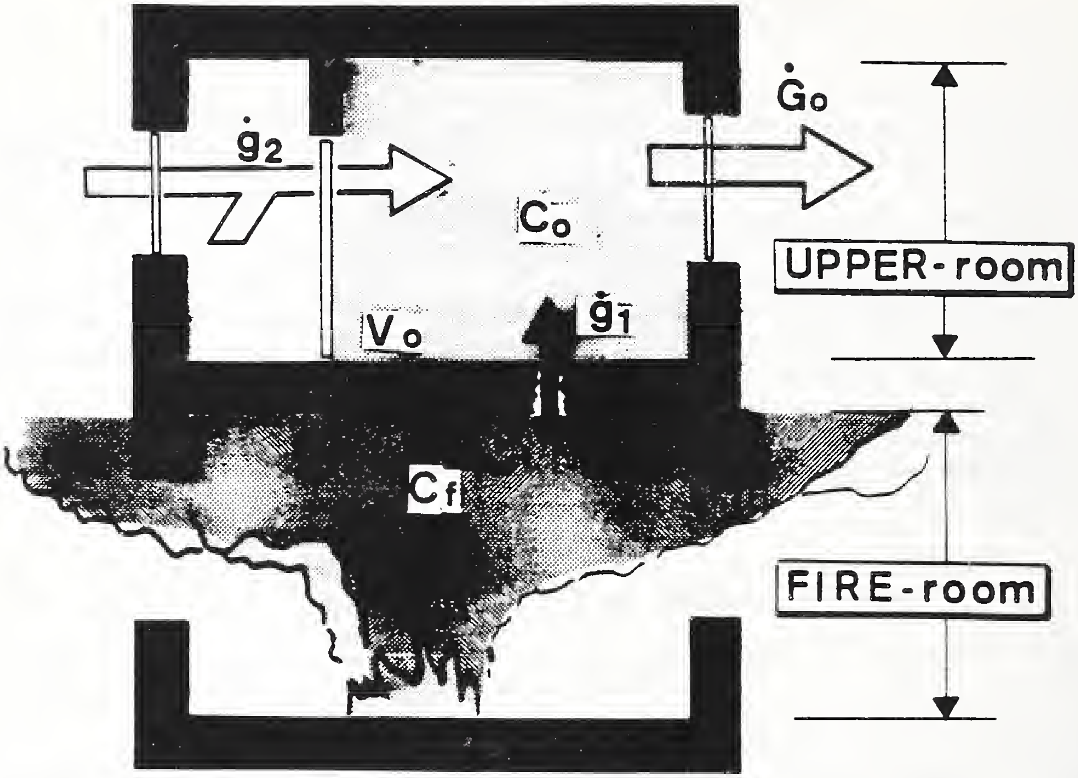
[3] Fung C.W. Zile R.H. :"San Antonio Veterans Administration Hospital Smoke Movement Study",CFR NBSIR 75-903,(1975).

[4] Kamata M.et al. :"Air Tightness and leakage of Dwelling", Bull. of Japan Architecture Assoc. Environment Eng. division, p.19,(1983)

[5] Yoshino H. et al.:"Measurement Methods for multiple room ventilation with tracer gas",Bull.of Japan Air conditioning and Sanitary facility Engineering Assoc.62-2,p.97,(1983)

[6] Sherman M.H., Grimsrud D.T. and Sondergger R.C. :"The Low Pressure Leakage Function of a Building", Lawrence Berkeley Laboratory, University of California, (1979)

LIST of FIGURE and TABLE



$$\overline{\dot{g}_1(t)} = \frac{\{C_o(t) - C_o(t_o)\}V_o + \int_{t_o}^{t} C_o(t)\,\dot{G}_o(t)\,dt}{\int_{t_o}^{t} C_f(t)\,dt}$$

NOMENCLATURE

- C ····· smoke concentration
- $\dot{G}_o$ ··· ventilation outflow
- $\dot{g}_1$ ··· smoke leakage
- $\dot{g}_2$ ··· fresh air inflow $(=G - g_1)$
- V_o ··· room volume

suffix

- o ···· UPPER room
- f ···· FIRE room
- — ··· $t - t_o$ time average

Fig.1. **Schema of smoke leakage model** ; Buoyant fire smoke leaks out from a FIRE room to an UPPER room through small openings, and air in the UPPER-room is contaminated by the smoke gradually with fresh air ventilation. Instant diffusion is assumed in this model.

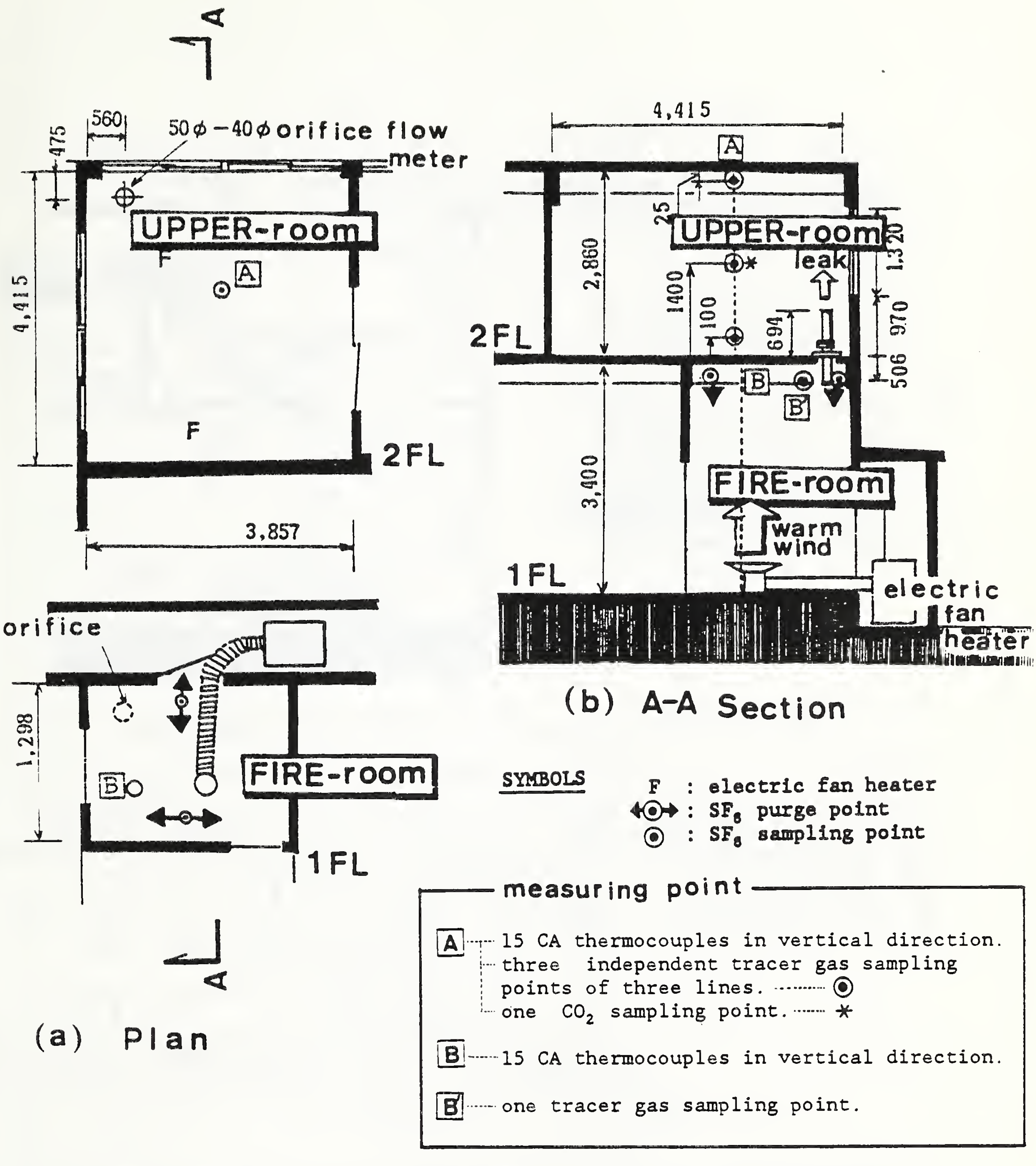
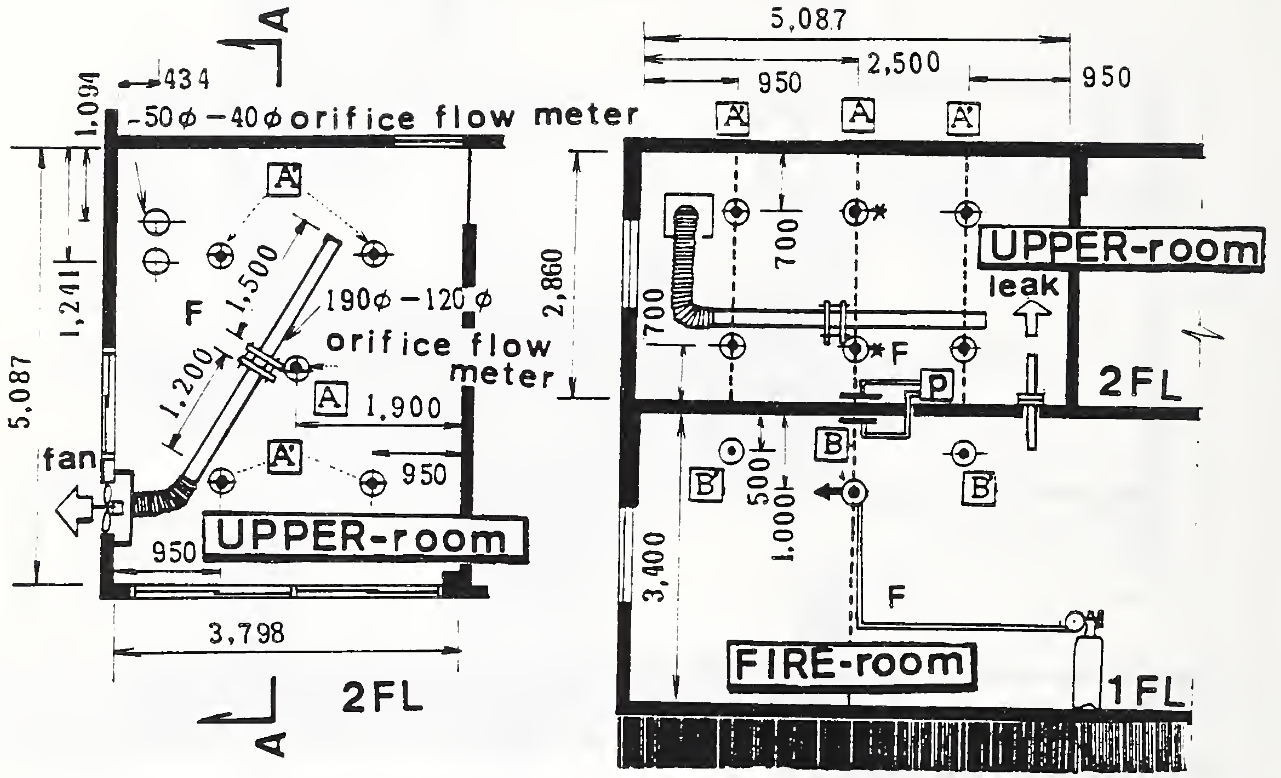


Fig.2. **Instalation of full scale test (series I)** ; A room on the 1st floor and another room directly above are supposed to be FIRE room and UPPER room respectively. Tracer gas is used instead of fire smoke to estimate leakage from FIRE-room to UPPER-room, while the leakage is measured by an orifice flow meter installed at a slab. pressure differnce is produced by natural ventilation due to buoyant effect.



(a) Plan (b) A-A Section

SYMBOLS

F : electric fan heater

P : pressure differnce measuring point

⊙→ : SF_6 purge point

⊙ : SF_6 sampling point

measuring point

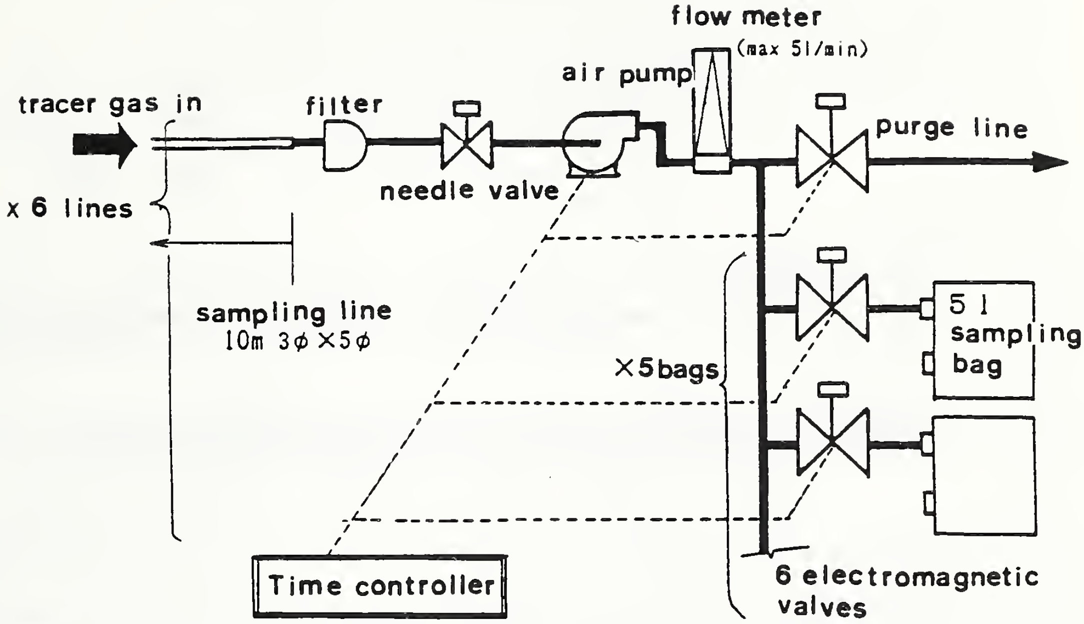
A — 15 CA thermocouples in vertical direction.
— two tracer gas sampling points of one line. ⊙
— two CO_2 sampling points of one line. *

A' — two sampling points of one line, which line has total eight sampling points. ⊙

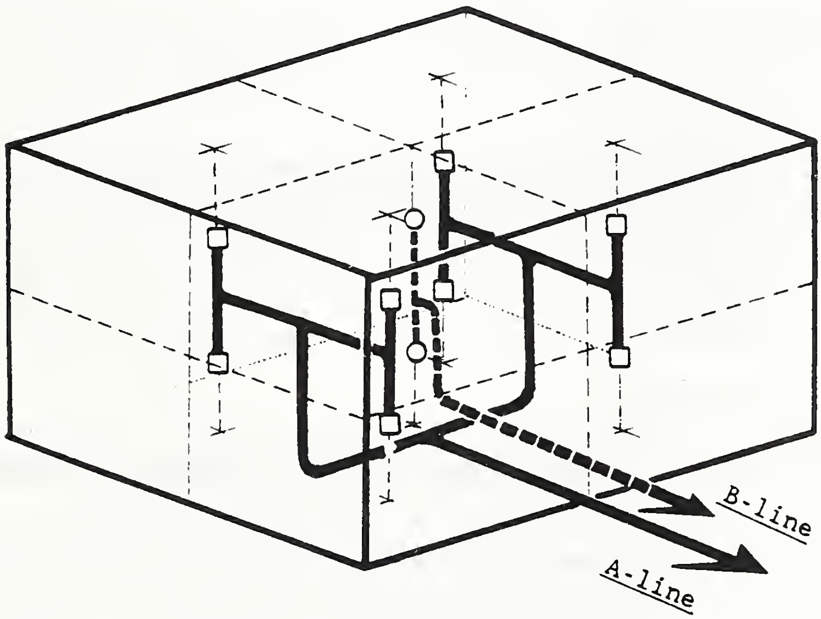
B — 15 CA thermocouples in vertical direction.

B' — one tracer gas sampling point of one line, which line has total four sampling points. ⊙

Fig.3. Instalation of full scale test (series II) ; Mechanical ventilation is used to produce pressure differnce between rooms. Ventilation rate is measured with orifice flow meter directly besides by CO2 decay method.



(a) Schema of auto gas sampling equipment.



A-line : Upper room is devevided into eight parts of same volume, and samplings are made at the center point of each parts.

B-line : UPPER room is devided into two upper and lower parts, then samplings are made at the center points of each parts. Two kinds of sampling are conducted under same time schedule.

(b) Schema of sampling points in UPPER room (series-II)

Fig.4. Schema of tracer gas sampling equipment

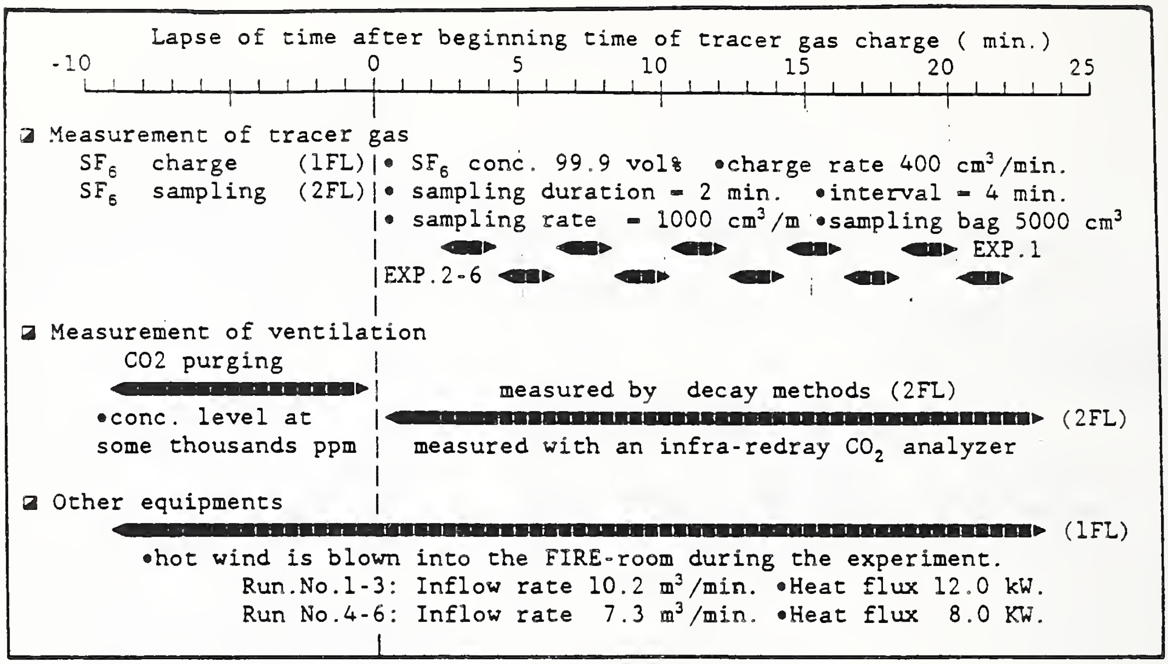


Fig.5 Time Schedule of Experiments (series I) ; A starting time of experiments is defined as the beginning time of point when tracer gas is charged in FIRE-room.

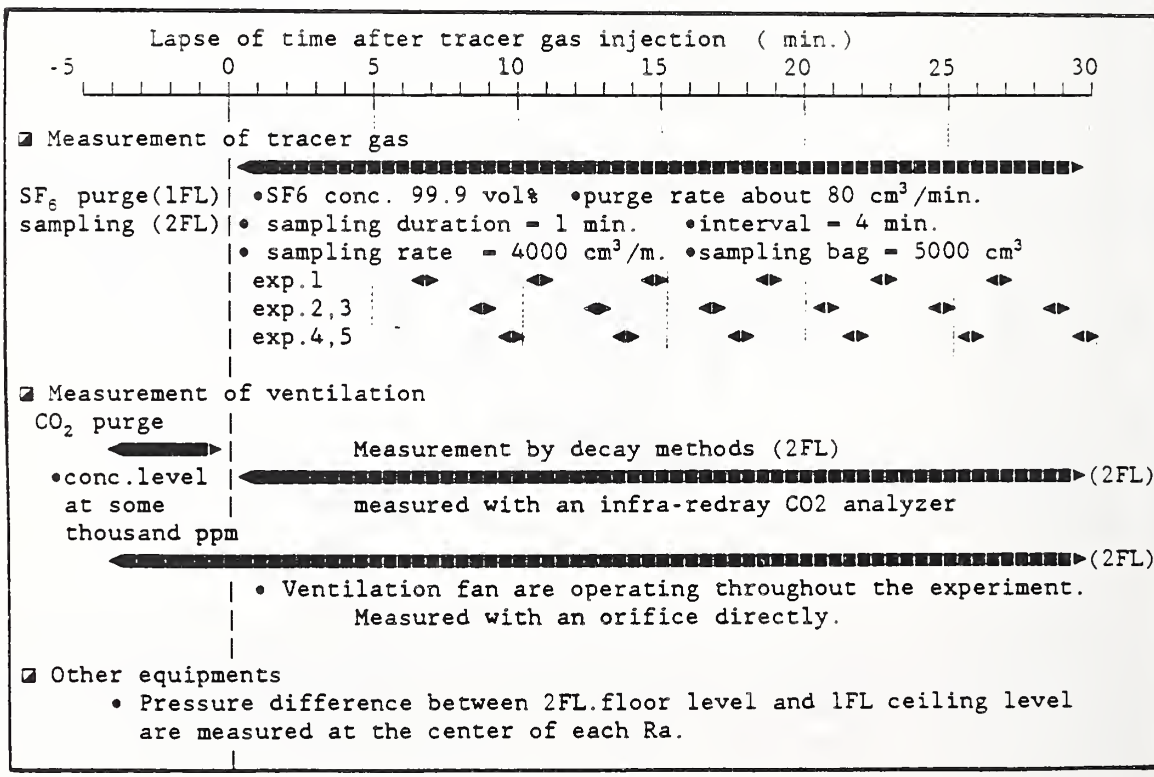


Fig.6 Time Schedule of Experiments (series II) ; A starting time of experiments is defined as the beginning time of point when tracer gas is charged in FIRE-room.

Full Scale Simulation of a Fatal Fire and Comparison of Results with Two Multiroom Models

ROBERT S. LEVINE AND HAROLD E. NELSON
Center for Fire Research
National Institute of Standards and Technology
Gaithersburg, MD 20899, USA

ABSTRACT

A fire in a kitchen in Sharon, Pennsylvania killed three persons in upstairs bedrooms, one with a blood carboxyhemoglobin content of 91%. Considerable physical evidence remained.

The fire was successfully simulated at full scale in a fully instrumented seven room test called Sharon 2. The data are used to evaluate the precision of two multiroom fire codes; FAST 18 and HARVARD 6.3.

During the simulation, a coherent ceiling layer flow was observed that quickly carried high CO concentrations to remote compartments. Such flow is not directly accounted for in either fire code. However, both codes well predict the CO buildup. Prediction of temperatures was less successful. Hypotheses are presented as to the reasons for the differences. At least some are believed due to phenomena not in the codes.

INTRODUCTION

About 2:00 a.m., on Saturday, September 26, 1987, a kitchen fire in a three-bedroom duplex house resulted in the deaths of three young women living in the house in Sharon, Pennsylvania. Figure 1 is a floor plan of the facility. For the most part, the fire itself was confined to the first floor kitchen. All three of the victims were on the second floor. All had apparently been awakened, presumably by one of the two smoke detectors in the house. Two died during the fire of carbon monoxide poisoning; one was rescued but badly burned. She died later that day. Since the kitchen had wood paneled walls and a combustible ceiling, the total burning surface in that room was very large and the fire generated much more fuel than that which could be burned by the air in the building plus that drawn in through the kitchen windows which broke during the fire.

Prior analysis by NIST (Nelson [1]), has indicated a potentially lethal condition when:

a. The fire has a large readily available fuel supply (in this case, the combustible walls and ceiling in the kitchen).

b. There is enough air to sustain a serious fire (in this case, the air drawn through the broken kitchen window is consumed by the fire).

c. The fuel source (burning walls and ceiling) continues to supply more fuel to the fire than can be burned by the available air within the building.

d. There is an opening from the burning room (kitchen in this case) to the rest of the building and the potential victims are in that portion of the structure.

When this combination of conditions occurs, it is believed that the fire abstracts the oxygen from the air in the building and replaces it with harmful products of combustion, the main lethal products being carbon monoxide and carbon dioxide. In addition, the amount of available oxygen can be reduced below that necessary to sustain life. As has been demonstrated by Zukowski [2], Beyler [3], and others, the CO/CO_2 ratio rises sharply as the fuel to oxygen ratio rises beyond the stoichiometric ratio for the particular fuel.

The fire site was investigated by the authors. The on-site evaluation indicated that the conditions described above may well have occurred in this fire. The damage to the building (confined mostly to the kitchen) as well as the apparent causes of death of the victims supported this thesis. To better investigate this potential, a fully instrumented, full-scale test, involving arrangements and conditions approximating those in the actual fire were conducted in the NIST test facilities at Gaithersburg on September 28, 1988. This test has been identified as Sharon 2.

The two-story "townhouse" test arrangement was used. The townhouse was configured as shown in Figure 2. Nine thermocouple trees, each with eleven or more thermocouples and five sets of gas composition ($CO/CO_2/O_2$) instruments were installed. Three additional oxygen meters were used. The fuel load consisted of wood cribs and sheets of plywood. This load was weighed continuously during the fire by a load cell arrangement.

The breaking of the kitchen window during the Sharon, Pennsylvania fire was simulated by an aperture with a value of $A\sqrt{H}$ related to the kitchen windows broken in the actual accidental fire. Calculations made to plan the test indicated that twelve wood cribs would be sufficient to drive the simulated kitchen to flashover. Eighteen were actually used, along with sheets of 0.014m (1/2 inch) thick plywood. The total weight of the fuel was in excess of 200 kg. The total surface area was enough to insure that the fire would maintain itself in a flashed-over condition through a significant portion of the test. Ignition was made using heptane in trays to assure rapid involvement. There was no attempt to simulate the ignition conditions that occurred in the actual Sharon fire.

Video records were taken. Both an internal view through a window and external views were recorded. The internal view provided data until such time as smoke conditions obscured any further information.

Results

Flashover conditions occurred about 125 seconds after ignition. The "window" aperture was opened at 134 seconds. The fuel weight loss curve is shown in Figure 3.

Figure 4 shows several oxygen concentration-time curves. It should be noted that the oxygen concentration of gas coming out of the burn room and that at the head of the stairs are nearly identical. This is interpreted as an indication that the ceiling layer jet from the burn room traversed two downstairs rooms, made a 180° turn, and flowed up the sloped ceiling of the stairs without gaining oxygen or hence, losing CO concentration. This may provide an explanation for the very high COHB concentration in one of the victims. It is possible that briefly after flashover, she was inundated with a ceiling wave with a sudden massive increase in carbon monoxide concentration. As shown in Figure 5, the CO/CO_2 ratio reached nearly 0.5 early in the fire and remained there for 25 seconds.

The video recordings through the kitchen aperture (window) commenced when the window was opened. Flashover was developed by that time. These videos show intense mixing in the burn room and intense smoke. This is interpreted to mean that wood not near the opening is burning in an extremely oxygen deficient gas while pyrolyzing rapidly due to the high radiant flux from the regions near the opening that were accessible to the fresh air. It is believed that the fire in the burn room was heterogeneous and not a simple well mixed reactor. This may well account for the high CO output early in the fire.

The measured ceiling layer temperature in the upstairs bedrooms reached 220°C. This value was in the range corresponding to the fire damage and harm that occurred on the second floor in the actual Sharon fire.

Comparison of Mathematical Models with Data

FAST 18 [4] and HARVARD 6 [5] are multiroom models. FAST 18 is the basis for the current version of the HAZARD I evaluation system [6]. The extensive data recorded in this test provided an opportunity to evaluate these models. In such multiroom models, any erroneous results in calculating parameters for intervening rooms will not be compensated for in subsequent rooms. This instrumented test of a seven room facility provided an excellent opportunity to severely test these two models.

Figure 6 shows the CO-time curve for the ceiling layer in the sixth bedroom and compares it with the calculation of both models. This parameter has the best correlation of data and calculation of any of the variables tracked by the test and calculated by the models. The calculations diverge from the data only after the CO concentration exceeds 4%. There would be no human survival at this concentration.

Figure 7 shows upper level temperatures versus time measured in the test. Figure 8 shows calculated values from FAST 18 and Figure 9 shows calculations with HARVARD 6. Both programs calculated lower temperatures in the second room than that which was achieved in the test. This under-prediction cascaded in subsequent rooms. Therefore, all of the rooms beyond the fire room were under-predicted in terms of temperature. It is hypothesized that the hot gases in the real fire were shielded by a dense layer of soot and did not lose as much heat as calculated by the radiation routines in both of the models. The HARVARD 6 calculation indicates that such a radiation shield could have reduced the radiant losses by a factor of 4 to 5.

Further test runs were made with FAST 18, varying the value of Limiting Oxygen Index. In FAST 18, this is the value, in percent, below which the model assumes no burning in the oxygen depleted layer. The initial run (the solid lines in Figure 8) used an index of 6% and the under-prediction described above occurred. Additional runs were made with indices of 2% and 0%. The 0% results are shown as dashed lines in Figure 8. As the index is lowered, the temperatures calculated by FAST 18 for the Sharon simulation increased. This impact is present after flashover. The actual fire at this time was highly turbulent. It is possible that the plume entrainment assumptions used in FAST 18 are not valid under this condition.

One of the upstairs bedrooms (as shown in Figure 2) was vented to the outside by a small window. The other bedroom was not. HARVARD 6 calculates large differences in the flow through the doorways but as shown in Figure 10 (CO vs time), substantially the same flow entered each room.

This would indicate that some phenomenon is augmenting the flow through the doorway of the dead-ended room. It is possible that the warm gases in the room lose heat the walls, and the cooled gases losing buoyancy, flow out through the lower portion of the doorway. This sets up a circulation that encourages the flow of hot gas into the top part of the room.

This particular calculation was conducted only on HARVARD 6 because the version of FAST 18 used has a maximum of six rooms.

Modelers frequently look at the changing height of the interface between the ceiling layer and the floor layer as an indication of satisfactory operation of the model. In this case, only the burn room data shows a sharp interface. In all the other rooms, the thermocouple trees show a continuous gradation of temperature from floor to ceiling. If it is assumed that the "layer height" is the level of which temperature increase is 15% of the final temperature increase (a frequently used criterion), FAST 18 best matches the results for the first 200 seconds. If we assume the "layer height" is where half the temperature increase occurs, approximating the enthalpy definition of layer height, HARVARD 6 does best.

Several of the following items raise research issues.

1. The CFR simulation test results agreed with the physical evidence and the field hypotheses made during the on-site investigation.

2. Ceiling jet flows can occur without dilution by other gases and can carry toxic gases quickly from the fire room to remote locations (in this case, on a different floor).

3. Gas concentrations in a flashed over room with distributed fuel packages can quickly reach CO/CO_2 ratios as high as 0.5.

4. Both FAST 18 and HARVARD 6 reasonably calculate the onset of toxic hazards in a multiroom flow. An exception to this conclusion is the additional ceiling jet flow observed in the CFR test and suspected in the Sharon fire.

5. Radiant heat losses from very hot gas appear to be over-predicted in both models. This may be due to shielding by soot surrounding the hot gas flow.

6. There may be a mechanism increasing the doorway flow and the transfer of hot gases into dead-ended rooms beyond that calculated by FAST 18 and HARVARD 6.

7. Combustion in the flashed over burn room may not properly be simulated by current plume entrainment assumptions.

8. The ceiling layer height is a questionable parameter on which to judge the success of a model, particularly in rooms remote from the fire.

9. The test data produced are available for comparing other model predictions.

REFERENCES

1. Nelson, H.E., An Engineering Analysis of Fire Development in the Hospice of Southern Michigan, December 15, 1985, Fire Safety Science - Proceedings of the Second International Symposium, International Association for Fire Safety Science, Hemisphere Publishing Corp., New York, NY, (1989).

2. Zukowski, E.E., Personal Communications.

3. Beyler, C.L., Major Species Production by Solid Fuels in a Two-Layer Compartment Fire Environment, Fire Safety Science - Proceedings of the First International Symposium, International Association for Fire Safety Science, Hemisphere Publishing Corp., New York, NY, (1986).

4. Jones, W.W. and Peacock, R.D., Technical Reference Guide for FAST Version 18, NIST Tech. Note 1262, National Institute of Standards and Technology, Gaithersburg, MD, (1989).

5. Rockett, J.A. and Morita, M., The NBS/Harvard VI Multi-Room Fire Simulation, Fire Science and Technology 5, no. 2, p.159, (1985).

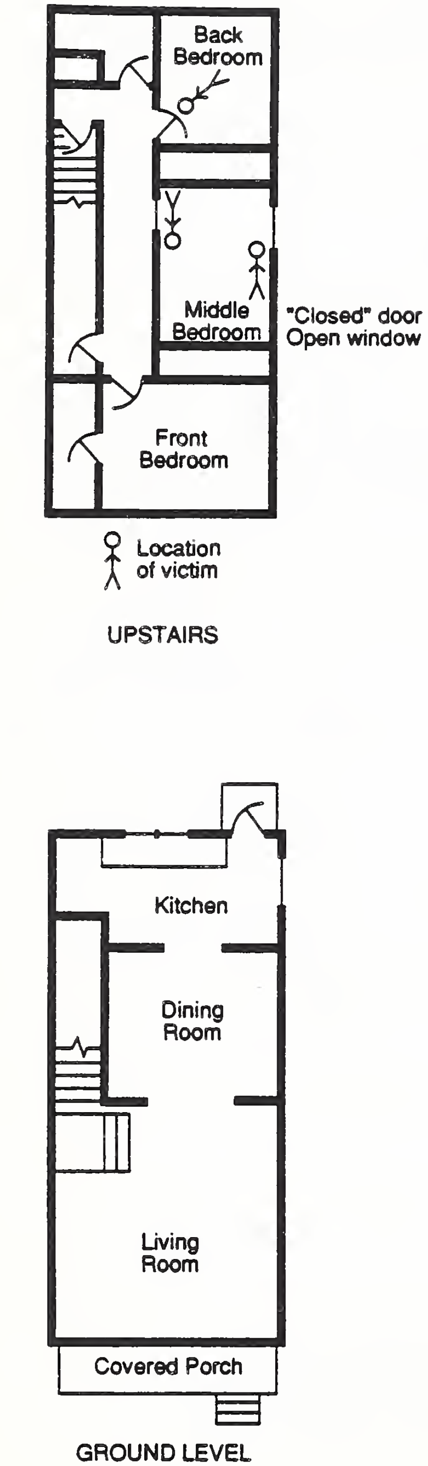


Figure 1. Floor plan of
Sharon, Pa. fire

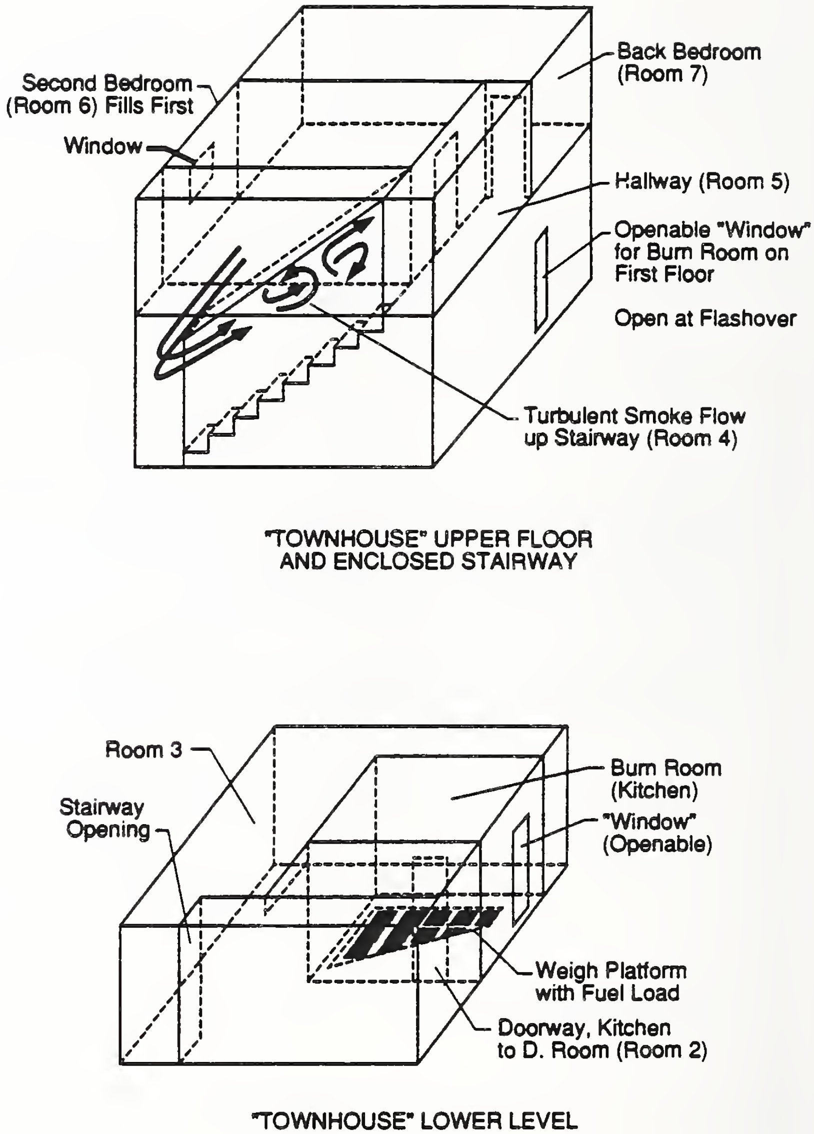


Figure 2. Floor plan of Sharon 2 test

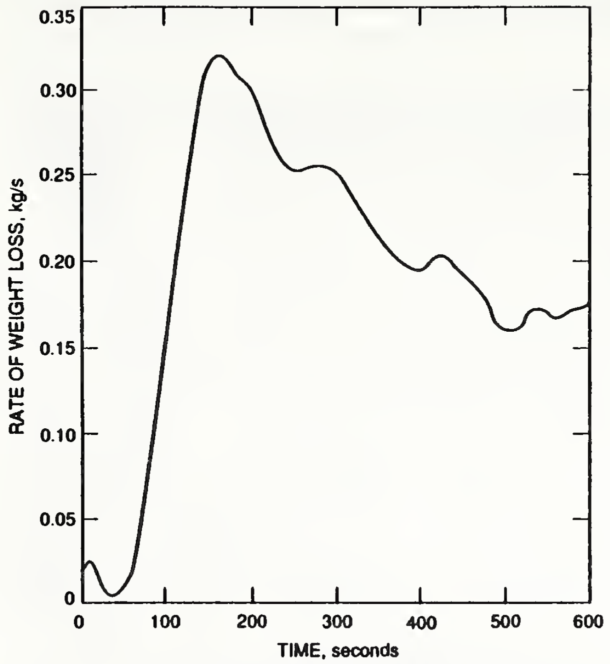


FIGURE 3. Rate of fuel weight loss
Sharon 2 Fire Simulation

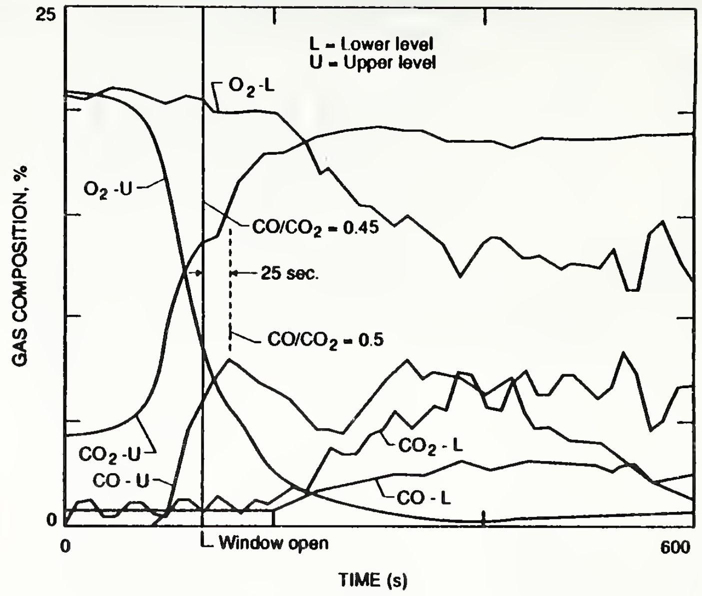


Figure 5. Gas composition of layer flows near burn room doorway
Sharon 2 fire simulation

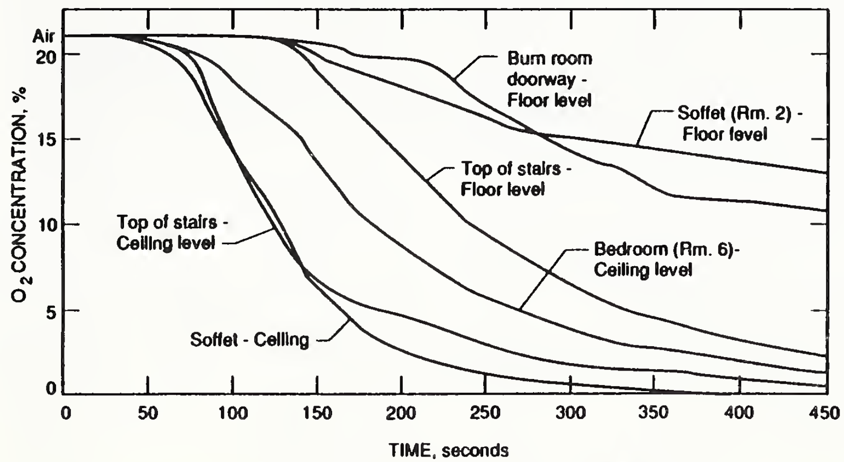


Figure 4. Sharon 2 data - O_2 content at various sampling sites

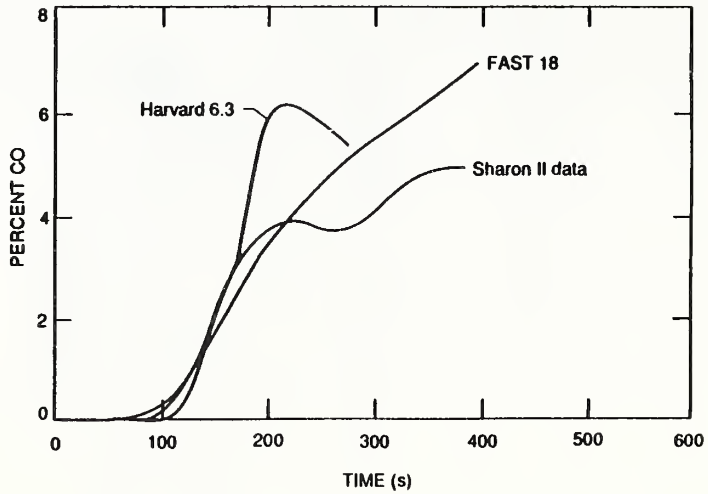


Figure 6. Comparison of Sharon II data and predictions of two multiroom models for the 6th room.

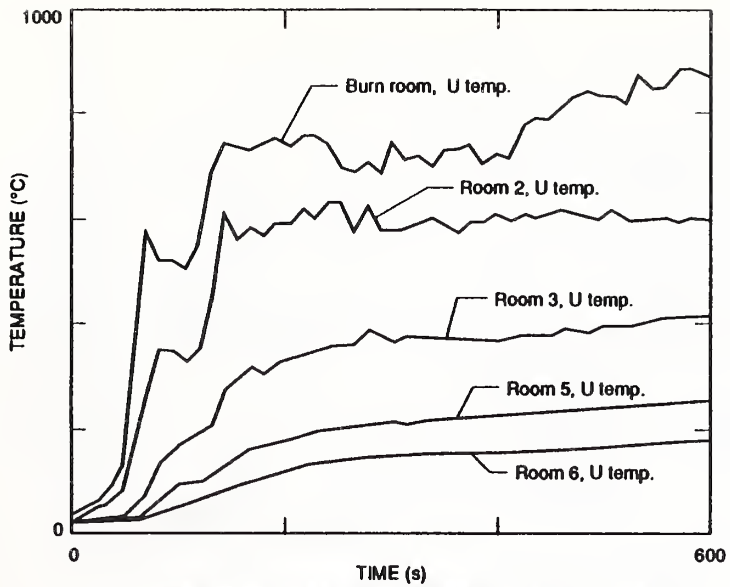


Figure 7. Average ceiling layer temperature for several rooms Sharon 2 Simulation data

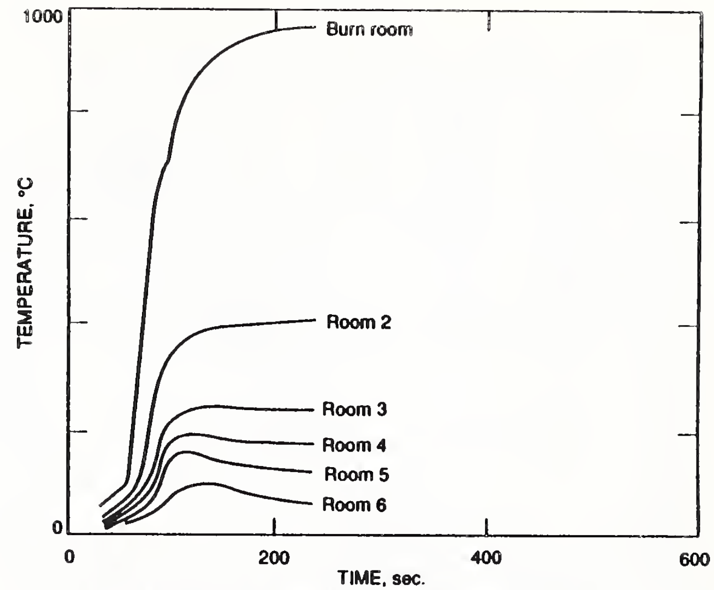


Figure 9. Average ceiling layer temperatures calculated using Harvard 6.3 model of Sharon 2 test

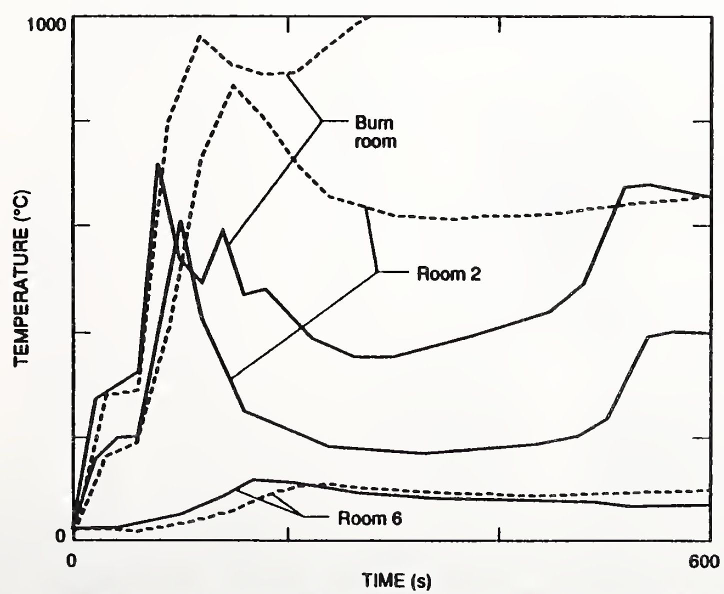


Figure 8. Average ceiling layer temperaures calculated using FAST 18 model of Sharon 2 test

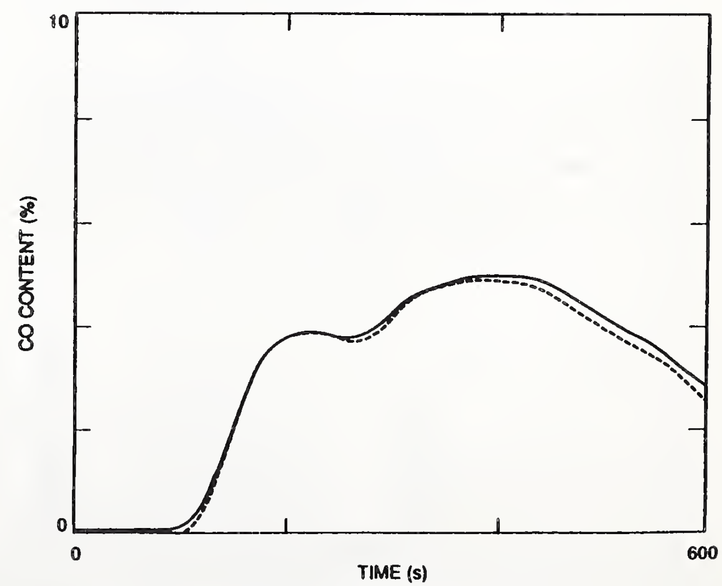


Figure 10. Comparison of CO concentration in ceiling layers of rooms 6 & 7. Measured data from Sharon 2 test

Burning of Oil Spills

David D. Evans
William D. Walton
Center for Fire Research
National Institute of Standards and Technology
Gaithersburg, MD 20899

ABSTRACT

This study is directed at understanding the oil spill combustion process and the smoke generated from the burning. Measurements of 1.2 m diameter Murban crude oil pool fires show an initial steady energy release rate of 840 kW/m^2 which increases to 1860 kW/m^2 during the vigorous burning associated with boiling of the water sublayer. During the burning of the crude oil pools approximately 10 percent of the crude oil was converted to smoke with a high elemental carbon content in excess of 90 percent. Measurements of polycyclic aromatic hydrocarbon (PAH) components found in the original oil, showed that soot produced in the burning process carried a different distribution of PAH compounds, but that the total concentration of these compounds was equal to that found in the original crude oil.

1. INTRODUCTION

In 1985, the Center for Fire Research (CFR) at the U.S. National Institute of Standards and Technology (NIST) began studies of oil spill combustion. The long range goal of the research program is to provide measurements and means to make quantitative predictions of the fraction of oil in a spill that can be consumed by an in-situ combustion process, the characteristics of the residual oil, and the characteristics of the combustion product flow from the burning oil. It is hoped that this information may be cast into a form that is usable by local officials and oil spill response professionals as part of the decision making process in the event of an oil spill.

Previous results from experiments in which crude oil was burned in a 0.6 m diameter oil pool fires included measurements of burning rate, thermal radiation emission, smoke production and the chemical composition of both the oil and the burn residue (Evans, et al., 1986).

This effort is the first in a two year program to quantify the thermal properties and burning characteristics of the crude oil, the physical and chemical properties of the smoke generated in the combustion process, and the expected dispersal of the soot through the atmosphere and deposition downwind of the oil fires. This report summarizes results from some of the main research thrusts all of which are incomplete at this time.

2. POOL BURNING CHARACTERISTICS

Crude oil burn tests were conducted in the CFR large-scale test building. Details of the experimental apparatus for 0.6 m diameter pool fires with gas analysis and soot sampling are recorded in a previous report (Evans, et al., 1986). Larger test burns were conducted in a new 1.2 m diameter pan installed under a calorimeter hood. Instrumentation for the larger burns provided for the measurement of flame temperature; oil and water temperature; energy release rate; radiation feedback from the flames to the liquid surface; and radiation from the flames to the surrounding. The energy release rate of the fires burned under this hood are determined using the oxygen consumption calorimeter technique.

The burning characteristics of three types of crude oil were investigated in the large calorimeter -- Alberta Sweet, La Rosa and Murban. These oils differ in composition, notably in the percent of the heavier wax plus asphaltene fractions, with Alberta Sweet crude being the lowest and La Rosa crude being the highest.

The burning characteristics of the three crude oils were measured in burns under the large calorimeter hood. The use of a 1.2 m diameter pan permitted controlled burning experiments to be conducted under conditions representative of the radiation-dominated, turbulent flow regime of larger pool fires. Each oil was studied at four initial layer thicknesses -- 2 mm, 5 mm, 10 mm, and 25 mm. The energy release rate for the Murban crude exhibited an approach to steady-state for the 10 mm and 25 mm layer thicknesses prior to reaching a peak value during the vigorous burning period. The quasi-steady-state energy release rate for the Murban crude was approximately 0.95 MW (840 kW/m^2), actually decreasing noticeably prior to the rapid increase in burning corresponding to a peak level of 2.1 MW (1860 kW/m^2) just before burnout. The decrease in energy release rate during the steady burning phase (100 to 500) seconds appears to be associated with the changing composition of the crude oil towards the heavier fractions. The corresponding values of steady-state and peak energy release rates for the Alberta Sweet crude were 1.15 MW (1000 kW/m^2) and 2.7 MW (2400 kW/m^2). These values are significantly greater than the area specific energy release rate for Alberta Sweet crude (720 kW/m^2) measured in the smaller 0.6 m diameter pan fire used for soot measurements. The peak energy release rate for the La Rosa crude was approximately 50% greater than for the Murban crude.

The oil residue remaining following burnout varied with the type of oil and the layer thickness. With one exception, more oil remained from the thickest (25 mm) layer of each oil and slightly more residue remained with the La Rosa crude than with the other oils. The measured residue for all tests ranged from 0.6 kg to 1.2 kg corresponding to a layer depth of approximately 0.6 mm to 1.2 mm.

3. SMOKE AND GAS EMISSIONS

The chemical characterization of the smoke produced by burning crude oil is important data for total evaluation of the effects of oil spill combustion. Measurements in this study included the organic versus elemental carbon in the smoke, the quantity of selected polynuclear aromatic (PAH) compounds in the smoke, and the amount of CO_2, CO, NO, and NO_x emitted. Much of the analysis effort was concentrated on the PAH analysis. These PAH compounds are of environmental concern, because some have been reported to be carcinogenic to animals (Boyland, 1981). The results of the PAH analysis are compared with the PAH content of the original crude oil.

In all tests in this series, Alberta Sweet crude oil was burned in a 0.6 m diameter pool. Approximately 9 liters of crude oil were burned in each test, which corresponded to a fuel depth of about 30 mm. The sample burning time was found to be about fifteen minutes. Smoke samples were collected on filters heated to match the stack temperature, about 100°C, using a heated transfer line ("H" series tests). The smoke sample was collected during the time of visually steady burning. Smoke samples were also collected and diluted before collection on filters with air cooled to about 10°C to simulate the cooling that would naturally occur in a rising smoke plume ("C" series tests). In all tests two samples (sample 1 before sample 2) were collected on the filters before the rapid burning period.

The results of the smoke emission measurements are contained in Table 1. The smoke yield, ϵ, which is defined as the mass of smoke aerosol generated per mass of fuel consumed, is found to have a value of about 0.10. This is similar to the value found in previous test with Prudhoe Bay crude oil (Evans, et al.,1986). The value of ϵ increases in going from sample 1 to sample 2 indicating that the smoke emission increases as the fuel presumably distills leaving the sootier component for the later stage of burning.

The smoke collected in tests C-5 and C-7 was first diluted and thus cooled by the stack sampling probe. The mass flow of ice cooled dilution air is approximately twice the mass flow of the air sampled from the stack. The manifold temperature just prior to the filter is observed to be within two °C of the ambient temperature. The value of ϵ obtained under these conditions is 15% to 20% less than the value obtained for the heated, undiluted sample. Normally, one would expect an increase in ϵ with dilution by cool air resulting from the condensation of organic vapors. The PAH analysis discussed below clearly shows that the higher vapor pressure PAH's are greatly enriched in the diluted sample compared to the high temperature sample. The observed decrease in these tests may be the result of smoke deposition by thermophoresis in the entrance portion of the diluter and by turbulent flow in the mixing region of the diluter.

The emission of CO, CO_2, NO, and NO_x was monitored during selected tests. The concentrations of CO and CO_2 were measured by standard gas analysis instrumentation based on nondispersive infrared spectroscopy. The CO_2 accounts for over 95% of the gaseous products measured as indicated in Table 2. The other principal product of combustion, H_2O, was not measured. The volume fraction of CO, NO, and NO_x relative to CO_2 were found to be about 0.038, 1.5×10^{-4}, and 4×10^{-4}, respectively. The concentrations of NO and NO_x were just above the detection threshold.

Smoke aerosol produced by flaming combustion is composed of a graphitic or so called elemental carbon fraction and an organic carbon fraction. Smoke samples were collected on quartz fiber filters and sent to a contract laboratory for thermal-optical analysis for organic/elemental carbon (Johnson, et al., 1981). The elemental carbon content of the smoke was found to be over 90%.

Eight smoke samples weighing 10 mg to 15 mg each were deposited on teflon filters and were analyzed for 15 polynuclear aromatic hydrocarbons (PAH's) using combined liquid and gas chromatographic techniques at both NIST and Environment Canada.

It is known that the crude oil fuels themselves have a PAH component. Overall, for the compounds measured, the total PAH fraction of the smoke and the original oil burned are nearly equal. It is also of interest to compare the amount of selected PAHs per gram of fuel versus the amounts of PAHs collected in the smoke per gram of fuel consumed. As seen in Table 3, the relative concentration of the individuals PAHs compounds is different in the fuel compared to the smoke. For example, the concentration of phenanthrene plus anthracene in the fuel (296 μg/g) is about 2 times greater than for the smoke (133 μg/g fuel burned), while the concentration of benzo[a]pyrene (BaP) is a factor of three lower for the fuel (5 μg/g) compared to the smoke (18 μg/g). This indicates that the combustion process itself is generating specific PAHs and that the PAH content of the fuel will not represent the distribution of PAHs emitted. There is about a four-fold enrichment of the four-six ring PAHs in the smoke compared to the crude oil.

BaP has been used as a surrogate for the overall carcinogenic effect of PAHs. The higher BaP concentration in the smoke relative to the fuel is of environmental concern; however, two key issues must be addressed before a full assessment of PAH emission can be made. The effect of burning rate on PAH emission should be analyzed. Smoke was not collected during the very rapid burning stage near the end of a test, but this burning phase may be dominant in a large fire with a thin oil layer. An analysis of the vapor phase PAHs should be made to complete the present analysis that has concentrated on condensed phase products.

4. SUMMARY

An experimental facility was completed to examine the burning conditions of crude oil in a 1.2 m diameter pool fire configuration. This facility permitted controlled burning experiments to be conducted under conditions representative of the radiation-dominated, turbulent flow regime of larger pool fires that might occur on the open ocean or in pools confined by broken ice. Tests with three different crude oils, Alberta Sweet, La Rosa, and Murban were conducted using initial oil depths of 2 mm, 4 mm, 10 mm and 25 mm floated on a deep water layer.

At oil depths of 10 mm and 25 mm each oil exhibited two distinct burning stages. The first was associated with a progressive vaporization of the burning oil layer and the other with more intense, short duration burning in which the oil surface was churned and splattered by boiling water under the thin oil layer. For Murban crude oil, the steady burning resulted in energy release rates of 840 kW/m^2 which increased to 1860 kW/m^2 during the vigorous burning before extinction. Residual oil left on the water surface at the end of natural burning corresponded to a uniform layer depth of 0.6 mm to 1.2 mm.

The burning of Alberta Sweet crude oil results in a high smoke emission with ϵ about 0.10 (10% conversion to smoke). The smoke has a high elemental carbon component in excess of 90% resulting in a highly light absorbing soot. The primary gaseous product of combustion is CO_2 with the CO concentration about a factor of 25 lower than CO_2. The emission of NO and NO_x are less than one thousandth the concentration of CO_2.

Independent analyses of the PAH content of the smoke by the National Institute of Standards and Technology and Environment Canada showed the same trends and had good overall agreement for 12 individual PAHs. The PAH content of the smoke was nearly equal to that in the original oil burned. The PAH content of the smoke was enriched in the larger species in comparison with the fuel. The concentration of benzo[a]pyrene, which is often used as a surrogate for the carcinogenic effect of PAH, was found to be three times greater in the crude oil smoke per gram of fuel consumed compared to the crude oil itself. The concentrations of the three ring PAHs were found to be very sensitive to the filter collection temperature. Thus, it is important to use a diluter when sampling the PAHs to simulate the conditions existing in a rising smoke plume.

5. ACKNOWLEDGEMENTS

This work was supported under the joint sponsorship of the Minerals Management Service, U.S. Department of the Interior, Environmental Protection Service, Environment Canada, and the Office of Research and Development, U.S. Coast Guard. This paper was the result of contributions made by Dr. G. Mulholland, Mr. D Gross, Dr. H. Baum, and Professor K. Saito.

Special thanks is extended to Mr. Edward Tennyson who was instrumental in organizing this program of research. Dr. M. F. Fingas was especially helpful in consultations about the chemistry and analysis of crude oils. The assistance of Mr. B. Benner and Dr. S. Wise was indispensible in the analysis for PAH compounds in the crude oil and soot.

The authors also wish to thank the many individuals on the CFR staff involved with the large scale testing effort among them were Dr. K. M. Tu, Mr. N. Bryner, Mr. J. S. Steel, and Mr. R. Zile.

5. REFERENCES

Evans, D., Baum, H., McCaffrey, B., Mulholland, G., Harkleroad, M., and Manders, W., Combustion of Oil on Water, NBSIR 86-3420, National Bureau of Standards, Center for Fire Research, Gaithersburg, MD 20899, (1986).

Boyland, E., The Toxicology of Soot, Soot in Combustion Systems and its Toxic Properties, ed. by J. Lahaye and G. Prado, Plenum Press, New York, 13, (1981).

Johnson, R. L., Shah, J. J., Cary, R. A., and Huntzicker, J. J., An Automated Thermal-Optical Method for the Analysis of Carbonaceous Aerosol, in ACS Symposium Series, No. 167, Atmospheric Aerosol: Source/Air Quality Relationships, ed. by E. S. Macias and P. K. Hopke, 1981.

TABLE 1. SUMMARY OF SMOKE EMISSION DATA FOR 60 CM DIAMETER ALBERTA SWEET CRUDE OIL POOL FIRES

Property	Test H-1 sample 1	Test H-1 sample 2	Test H-4 sample 1	Test H-4 sample 2	Test H average	Test C-5	Test C-7	Test C average
dQ/dt, kW	217	172	234	191	204	205	203	204
dm/dt, g/s	5.27	4.40	5.63	4.93	5.06	4.98	5.57	5.28
H, kJ/g	37.4	39.8	41.7	38.8	39.4	41.1	36.3	38.7
ϵ_1	0.076	0.119	0.100	0.110	0.101	0.087	0.079	0.083
ϵ_2	0.070	0.110	0.089	0.101	0.093	0.080	0.079	0.080

Legend:
H-1 and H-4 refer to identical crude oil burns in which the filter collection system was heated to about 100 °C. C-5 and C-7 refer to identical crude oil burns in which the smoke is cooled to ambient temperature in a sampling dilution system. dQ/dt - heat release rate of the fuel. dm/dt - burning rate of the fuel. H - heat of combustion. ϵ_1 and ϵ_2 refer to the smoke yield based on a flux method and a carbon balance method, respectively.

TABLE 2. GASEOUS EMISSION FROM ALBERTA SWEET CRUDE OIL

Species	C-6 ppm	C-7 ppm	C-6 fract.[a]	C-7 fract.[a]
CO_2	4600	4900		
CO	174	187	0.038	0.038
NO	0.7	0.7	1.6×10^{-4}	1.5×10^{-4}
NO_x	2.3	1.7	5.0×10^{-4}	4.0×10^{-4}

[a] Volume fraction of gas species relative to CO_2.

TABLE 3. COMPARISON OF PAH CONTENT OF ALBERTA SWEET CRUDE OIL AND SMOKE FROM BURNED OIL

PAH	Crude Oil µg/g[a]	Smoke µg/g[b]
Acenaphthylene	61	
Acenaphthene	N.D.	
Fluorene	188	
Phenanthrene	296[c]	104
Anthracene		29
Fluoranthene	22	73
Acephenanthrylene		40
Pyrene	21	84
Benzo[ghi]fluoranthene		22
Cyclopenta[cd]pyrene		54
Benz[a]anthracene	N.D.	22
Chrysene/Triphenylene	30	23
Benzo[b,j,k]fluoranthene	N.D.	39
Benzo[e]pyrene	21	12
Benzo[a]pyrene	5	18
Perylene	N.D.	4
Indeno[1,2,3-cd]pyrene	N.D.	19
Benzo[ghi]perylene	N.D.	21
Total Concentration of PAHs	395	448

a µg PAH/g crude oil. Analysis performed by Environment Canada.

b µg PAH/g of crude oil burned assuming smoke emission factor, ϵ, of 0.10 and PAH emission data from C-5, #2. Analysis performed by NIST.

c This number represents the sum of penanthrene and anthracene.

Experimental Study on Gasoline Pool Fire Using A Full Scale Service Station Model and 1/15 Reduced Scale Model

by

Osami SUGAWA, Kunio KAWAGOE, Yasushi Oka and Tomoyuki Mizuno*

Center for Fire Science and Technology
Science University of Tokyo
2641 Yamasaki, Noda-shi, Chiba 278 Japan

ABSTRACT

Fire tests were carried out using a full scale model of a semi-enclosed gasoline service station and a 1/15 reduced scale model. Two sizes of fire pool, 10 m^2 with 600 liters and 15 m^2 with 900 liters of gasoline, were used for the full scale tests and a gas diffusion burner was used for the reduced scale model. Fire source located at the end corner or at the opening. Thermal re-radiation contributed the burning rate enhancement of about 24% compared to free burning one, and both convection and wind effect gave about 78% enhanced burning rate at the maximum. Reduced scale model experiments were carried out to compare the flame lengthen from the opening. Good agreement was obtained between full scale and reduced model with regard to the similarity in the correlation on flame length versus dimension-less heat release rate (Q*).

key words : full scale model, reduced scale model, gasoline pool fire, fire whirl, flame length, Karman-vortex

1. INTRODUCTION

Japanese Fire Code for a design of gasoline station building was changed partly in March, 1989. Before the change of the code, a series of full scale fire test had been carried out [1] in order to assess the fire safety of a gasoline station building with one side opeing. Because, if a fire occurred in a service area in such designed station, extended flame may produce a serious fire damage to the upper stories.

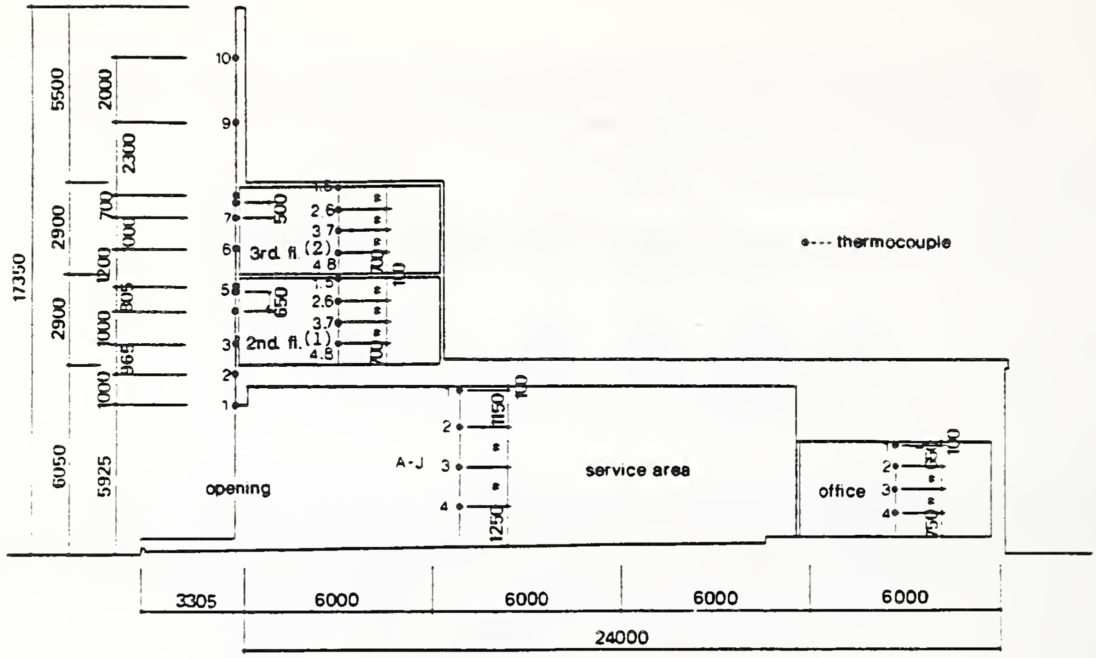
The one of the objectives of the experiments is to obtain the flame behavior extended from an opening of a one-side-opening gasoline service station with multi-story. In this paper, we will present extended flame length behavior with regard to the dimension less heat release rate Q*. Similarity on the flame length as a function of Q* between the full scale and reduced model was considered, but the other similarity were not dealt. Some experimental results are also presented which dealt with a test with a water drencher and tests with a pent roof of 1.0 m and 1.5 m [1].

2. EXPERIMENTAL PROCEDURE

To obtain the basic fire behavior which may occur in a semi-enclosed space for a gasoline service station, a full scale model was built in an open field of which opening faced to almost north. A 1/15 reduced scale model was also composed with a wind generator.

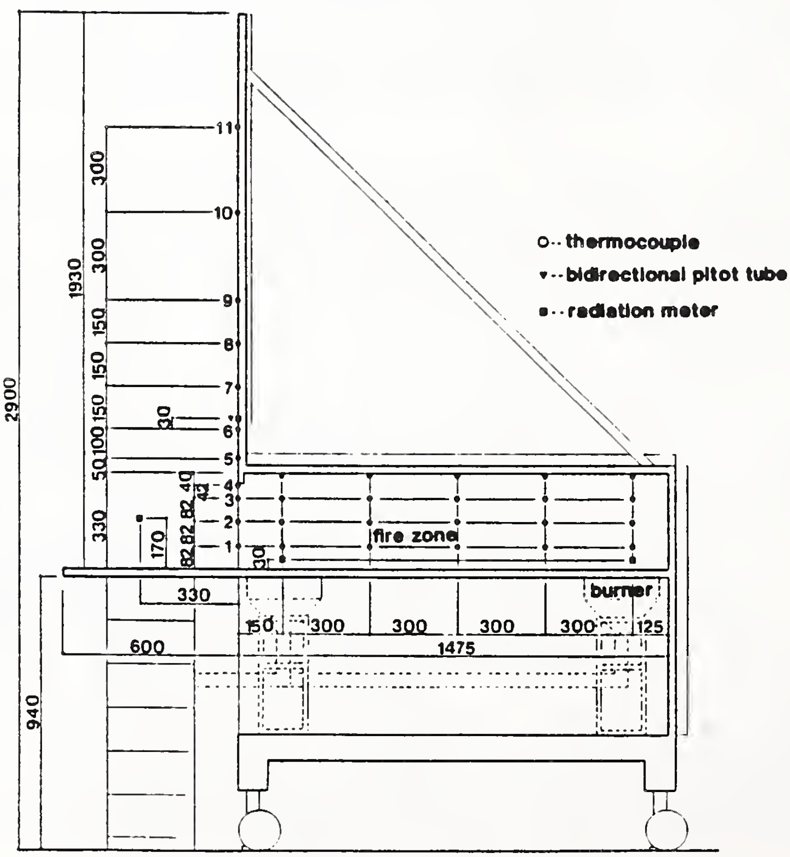
2-1. Full Scale Model

Figure 1 shows the plan and front elevation with the locations



Elevation (Cross Section) of Full Scale model

Figure 1 Full scale model of a gasoline station, side elevation.



1/15 Reduced Scale Model

Cross Section

Figure 2 1/15 reduced scale model of the side elevation, with measuring postions.

of instrumentation attached. The model had partly three story and extended wall which corresponds to another two higher story. Ceiling and wall in a service area were covered with ALC (Autoclaved Lightweight Concrete) panels of 50mm and 100 mm thickness panels. Window sashes of the second and third story were aluminum frame with plastic seal, and wired grass of 6.8mm thickness were set.

The temperatures were measured at 100 points by means of 0.3 mmø K-type thermocouples. Radiative heat fluxes were also measured at 7 points. Hot air velocities were measured at the wall of second floor and at the ceiling of the opening, respectively. The natural wind direction and velocity were measured at the top of the full scale model. Outputs from these sensors were recorded every 10 seconds. The locations of the measuring points are illustrated in Figure 1. Gasoline fuel was ignited electrically and ignition time was adopted as the start time.

For full scale experiments, three pool locations were selected; at the end corner, middle position and at the foot of opening. A pool area was reduced from 15 m^2 to 10 m^2 in the first three experiments. The pool depth was about 30 cm, and of which 23 - 24 cm depth was filled with fresh water prior to each experiment. The fuel depth was about 50 - 58 mm.

2-2. Reduced Scale Model

Figure 2 shows the 1/15 reduced model. The structure of the reduced scale had an iron frame and was covered with ceramic panels of 25mm thickness. A gas (propane) diffusion burner of 27cm x 27cm square was used. Almost the same measurement method employed as in the the full scale model was also employed, and the measuring positionsare also shown in Figure 2.

3. RESULTS AND DISCUSSION

3-1. Burning Behavior

It was obviously expected that enhanced burning rate (burning rate was defined as the decreasing rate of the fuel depth) of gasoline fuel must be given by re-radiation from the hot ceiling and walls. Radiative heat flux at the foot of the flame (at the pool periphery) was also measured. Table 1 shows fire locations, burning rates, and natural wind condition. Observation showed the flame behavior was different depending on the natural wind direction. As the opening faced to downwind of natural wind, a pair of Karman-vortex appeared at the both sides of the opening and which was clearly visualized by dense smoke and as a fire whirl. In this case, hot smoky layer in the service space was well disturbed and thus unclear boundary between hot layer and lower air layer was obtained. As the pool located at the foot of opening and almost south wind was given, turbulent flame plume appeared for first 30 sec and changed to fire whirl within 1 min after the ignition. Fire whirl extended as high as about 18 - 20m with roaring. The diameter of the fire whirl was as almost same size as the pool. The intensive circular wind generated by Karman-vortex sucked out the flame from the original pool surface, so that the flame slid out toward the downstream direction forming an apparent burning area on the floor. The fire whirl disappeared several times corresponding to the breath of natural wind.

In experiments #4, the natural wind was mild as 1 - 2 m/sec with direction of almost north. Two zones of smoke and lower air layer were clearly observed. Flame extended along the ceiling and facade as long as about 30 m from the pool, and extended flame reached frequently to the wired window glasses of the second floor. The glasses were heated by radiation of about 9 W/cm^2 instantaneously from a fire whirl, and some cracks were observed but they were neither broken down nor fallen down. These glasses performed resistance against the fire propagation into the room with and without the pent roof or water drencher system.

Table 1 Burning Rate and Wind Condition

Exp.	Location of Pool	Burning rate(mm/min)	Natural Wind Condition direction	vel.(m/sec)
1	E	5.27 (0- 9'29")	SSW	2.4
2	M	5.74 (0- 9'35")	NNW	2.5
3	F	7.05 (0- 7'58")	SSW	1.7
4	E	4.93 (0-11'34")	NNE - NE	1.8
5	M	5.18 (0-10'37")	SSE	4.3
6	F	6.5 (0- 8'55")	SSW	1.5
7	F	5.32 (0-10'20")	SE - SSE	2.9
8	F	6.35 (0- 8'40")	SSW	5.8
9	F	6.28 (0- 8'46")	SSW	6.3
10	F	5.24 (0-10'41")	ENE - NNE	4.1

E:end corner, M:middle location, F:foot of the opening

Table 2 Radiative Heat Flux at the foot of Flame

Exp. No.	ave.	max. (W/cm^2)	min.	period (min:sec)
1	5.5	11.79	2.38	0:20 - 6:10
2	11.10	16.26	4.79	0:20 - 9:40
3	7.27	15.06	1.64	0:20 - 8:00
4	11.26	16.79	3.32	0:30 - 12:00
5	9.09	16.53	3.51	0:40 - 10:00
6	8.98	14.78	2.33	0:20 - 8:10
7	10.70	16.80	1.98	0:30 - 10:30
8	5.45	12.21	1.93	0:20 - 8:40
9	3.51	12.32	1.43	0:20 - 8:50
10	9.97	13.17	5.39	0:20 - 3:00

3-2. Burning Rate Enhancement by Radiation and Flow

It have been expected that the heated walls and ceiling produce burning rate enhancement. However, observation indicated that another factor of wind (or convection flow) also gave burning rate enhancement. The highest average radiative heat flux was obtained in test #4, as shown in Table 2. Remembering the average wind velocity and direction as shown in Table 1, we can assume that radiation was the main effect in test #4 which accelerated the burning rate of the fuel. Burning rate of gasoline pool fire in an open field is about 4.0 mm/min [2] - 4.3 mm/min [3] for the turbulent flame. Therefore, it was estimated roughly that the radiation effect gave about 1.14 - 1.24 times greater burning rate in test #4. The outward hot air mass flux of about 52.6 kg/sec was estimated depending on temperature, velocity, and depth under the ceiling at the opening in the test #4. Inflow velocity of about 1 m/sec was estimated assuming the same amount of the inflow mass flux was given into the space. About 1 m/sec wind may give 4% burning rate enhancement according to the equation (1) which Blinov and Khudiakov had proposed [2,4]. Therefore, we could estimate that the re-radiation effect gave 10 - 20 % burning rate enhancement than the the burning rate in open field.

$$m_{wind} / m_{still} = 1 + 0.15 (u/D) \quad (1)$$

where, u is wind velocity (m/sec), D is pool diameter (m), and m is burning rate of the fuel.

The wind effect due to convective flow and/or Karman-vortex on a pool fire is quite complex and alternative. The flame temperature is raised due to improved mixing and combustion [2] and resulted in radiant heat fluxes enhancement and this gives greater burning rate. And at the same time, flame thickness above the original pool is reduced due to suction and/or sliding out induced by the vortex flow. This phenomena gave burning rate reduced. Lois and Swithenbank [5], and Yumoto [6] observed a doubling of the burning rate of a hexane pool in a 4 m/sec wind and no further increase for greater velocities. In the experiments of #3, #6, #8, and #9 [1], we observed a fire whirl. And about 20 m/sec circulating velocity was estimated roughly from the picture analysis. Applying the equation (1) with the circulating velocity of about 20m/sec, we can estimate 6.7 - 7.1 mm/min burning rate. The measured average burning rates in these experiments were 6.3 mm/min - 7 mm/min as shown in Table 1. It is not clear of the effects and mechanism of wind on the burning rate enhancement but the equation (1) appears to be well fitted to the results.

3-3. Water Drencher system

In test #9, the water drencher system was set at the soffit of the opening. The system has 6 heads at 2.5 m spacing and 792 l/min of water was sprinkled at the pressure of 3kgf/cm^2. The water pump was initiated 3 min after the ignition and, at 3min 30 sec water sprinkling was started. Figure 3 shows the wall temperatures before and after the water sprinkling. It is clearly observed that the temperatures on the facade dropped 400 - 450 to 70 - 100°C within a few minutes, and the average radiative heat flux on the wall at the second floor level changed drastically 1.8 W/cm^2 to 0.42 W/cm^2. Radiative heat flux to the external point, 5m from the opening and 3m from the ground, showed 1.16 W/cm^2 before the sprinkling and 0.13 W/cm^2 after it.

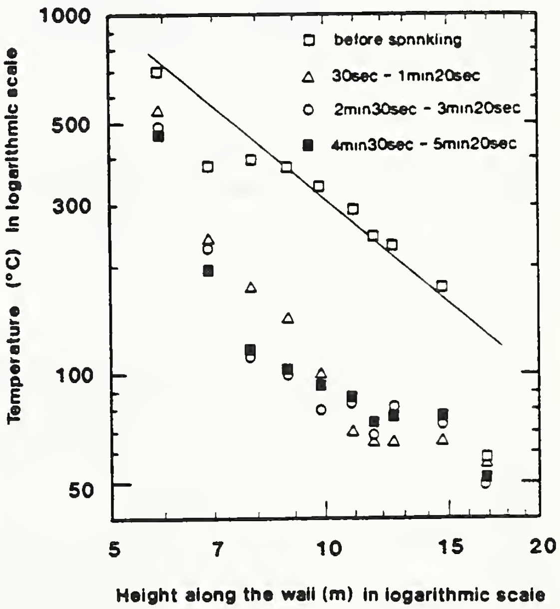


Figure 3 Temperatures along the front wall of the full scale model before and after the drenching.

4. Similarity of Flame Length with Heat Flux

Extened flame length which came out from the opening is an important factor for assessments on fire spread to the upstair. In order to evaluate the extened flame length with changing the heat flux rate, and with and without wind against the opening, we carried out the supplementary experiment using a 1/15 scale model.

4-1. Estimation of Heat Flux given to the Reduced Scale Model

Dimensional analysis on the relation between flame height and $Q/D^{5/2}$ [7], and its significance is represented often by non-dimensional heat release rate Q^* [8,9,10,11,12]. Where Q^* is defined as $Q^* = Q/\ Cp_{\cdot}T\ D^{5/2}\ g^{1/2}$, and Q is heat release rate given by stoichiometric combustion, is hot air density, Cp is specific heat, T is temperature, and g is acceleration constant. These correlations were established for an open fire, however, which implies that burning rate enhancement gives higher flame geometry (in our case longer flame). Dimensionless flame geometry L_f/D depends on the Q^* [12] as in the form of equation (2).

$$L_f = A\ (Q^*)^n/D \qquad (2)$$

where L_f is flame height (length), A is coefficient, D is representative pool length. For convenient sake, we adopt the enhanced burning rate of 5 mm/min as the temporary standard value for the gasoline pool fire. The pool area in the full scale model was 15 m^2 and assuming 100% combustion efficiency, the heat flux is expected about 41 MW. Burning rate increased due to both re-radiation enhancement and wind effects in the full scale tests, and the value of Q^* were estimated between 1 and 2. For these range of Q^*, $n = 2/5$ is given in equation (3). Employing "k" as a reduced factor of 1/15,

$$k = L_{model}/L_{full} = (Q^*_{model}/Q^*_{full})^{2/5}. \qquad (3)$$

Therefore, the heat release rate have to be given to the reduced model is estimated as

$$Q_{model} = k^{5/2}\ Q_{full}. \qquad (5)$$

We used a diffusion gas burner with propane as a fuel for a reduced model. For about 40 MW gasoline fire in the full scale, about 35 l/min of propane gas fuel must be charged. In order to cover the wide range of the burning rate enhancement, the gas supply rate to the reduced model was chosen from 30 - 50 l/min.

4-2. Comparison of Flame Geometry between Full and Reduced model

Estimation of the flame tip location was carried out on successive 300 frames from the video recordings. The flame tip location was adopted as the highest visible location in each frame. Figure 4 shows the accumulated percentage probability of the flame height measured in test #6. The same process was employed to the reduced scale tests.

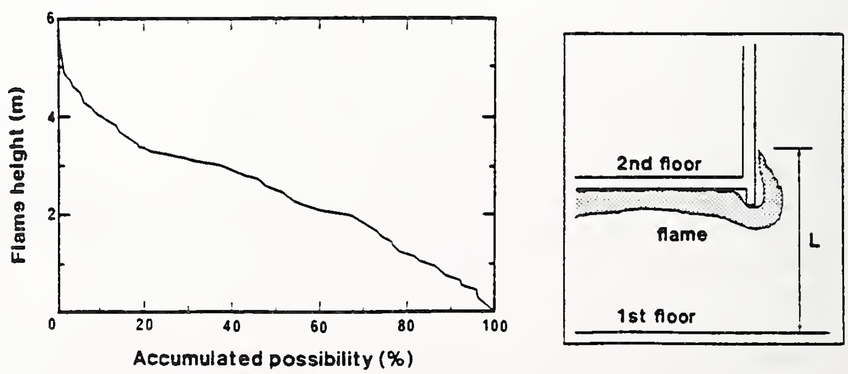


Figure 4 (a) Accumulated possibility of the flame height based on the flame tip location, and (b)flame height definition.

Average flame height was adopted at the 50 % possibility of existence of the flame tip. Flame geometry L/D was estimated depending on the average flame height (L) and characteristic pool/burner length (D), and are plotted as a function of non-dimensional heat release rate Q* as shown in Figure 5. The data of Q* in these figures have influence of 80 - 100 % combustion efficiency. These figures indicate close agreement on the correlation of flame geometry (L/D) and Q* between reduced model and full scale tests.

4-3. Estimation of the Effects of Downstand

When we adopt the similarity on flame length and Q* between full scale and reduced scale models based on the results described in Figure 5, we can discuss on effective length of a downstand which could interrupt of the flame lengthen. Two kinds of the fire source location, at the end corner and at the opening, were employed in a 1/15 reduced model. The flame length which spread out under the downstand was estimated from the successive video recorded frames as the same method as described in the previous section. Figure 6 shows the variation of the external flame length with length of the downstand. The external flame length was evaluated from the level of ceiling height and which was employed as standard height. As the fire source located in the end corner, the external flame length decreased with the increase of downstand length as shown in Figure 6-(a) and (b) with and without the external wind. It is very clear that the 10 mm downstand gave about 10 mm external flame length so that almost no interruption on the lengthen of the external flame was applied by the set of downstand. However, as shown in Figure 6-(c), when the fire source located at the foot of the opening without external wind, 10 mm downstand gave the external flame lengthen more than downstand length. In this case, the existence of downstand provided higher potential of the fire propagation to upstair than without downstand. The downstand interrupt the entrainment of fresh air into the flame zone so that the hot combustible gas spread out under the downstand and then mix and reacts with air (oxygen) outside of the opening. Then the lengthen of the external flame was formed along the wall by the secondary combustion which took place outside of the semi-enclosure.

5. CONCLUSION

It was estimated that re-radiation gave about 20 - 24% burning rate enhancement in a full scale semi-enclosed compartment of which ceiling and walls were covered with ALC panels. Wind/vortex effect gave burning rate enhancement of about 50 - 75 % and is much greater than re-radiation effect in our full scale tests.

When an opening faced to downwind, the flame was sucked out by Karman vortex and made a fire whirl of 18 - 20m high at the front of the opening. Fire whirl may have a propagation potential to upstair and to combustible advertising panels attached to the external wall. To reduce the possibility of fire propagation potential to upstair, the pool which is prepared for collection of leaked gasoline may be located at the end corner.

Reduced scale model provides a powerful tool for the estimation of the extened flame length which took place outside of the opening when a building has a downstand or a pentroof.

6. ACKNOWLEDGMENT

The authors wish to thank to the Petroleum Energy Center (PEC)

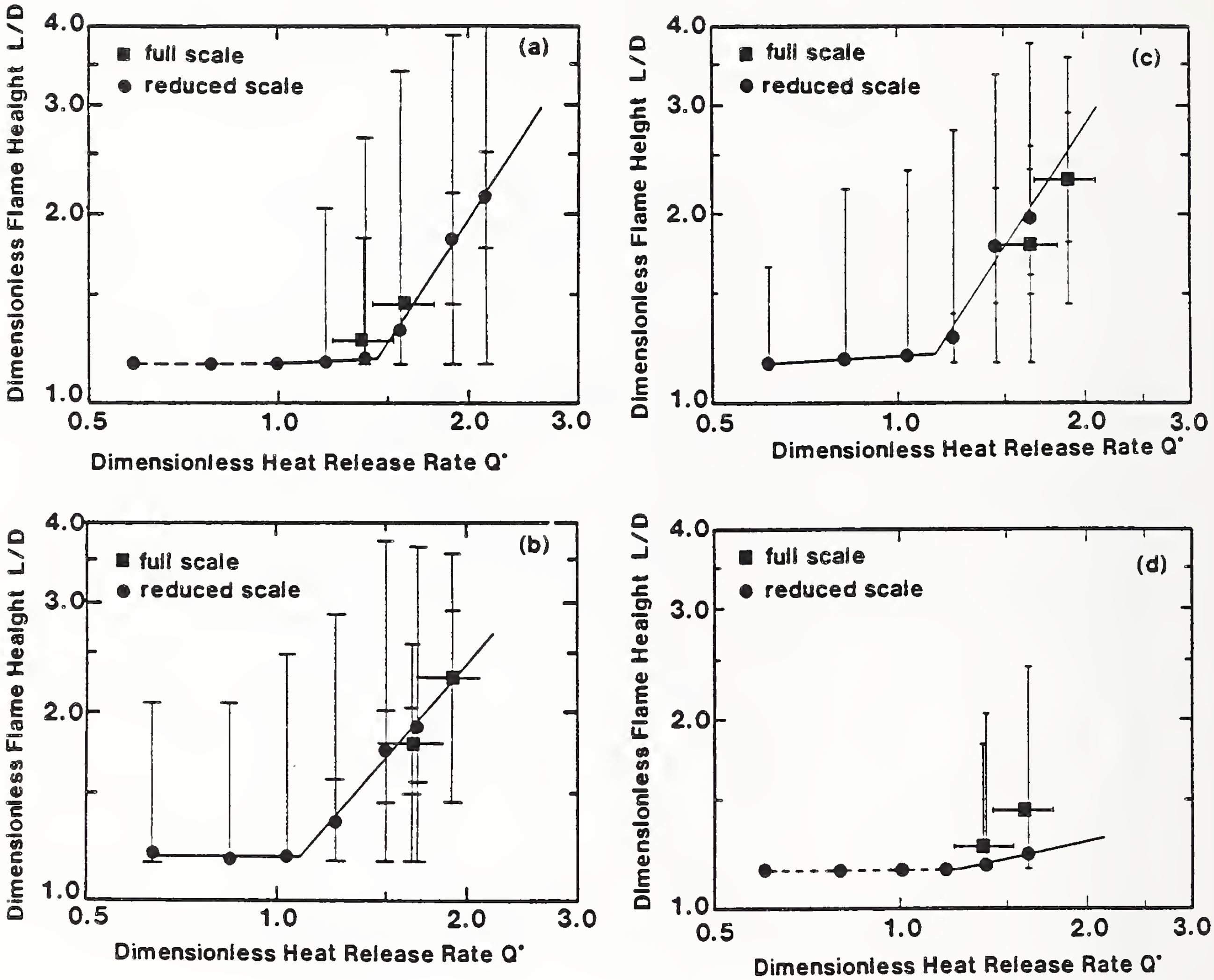


Figure 5 Correlation of the flame geometry (L/D) versus Q*, (a) no wind was given to the reduced model and fire source located at the end corner, (b) no wind was given to the reduced model and fire source located at the front of the opening, (c) wind was given and fire source located at the end corner, and (d) wind was given to the reduced model and fire source set at the front of the opening.

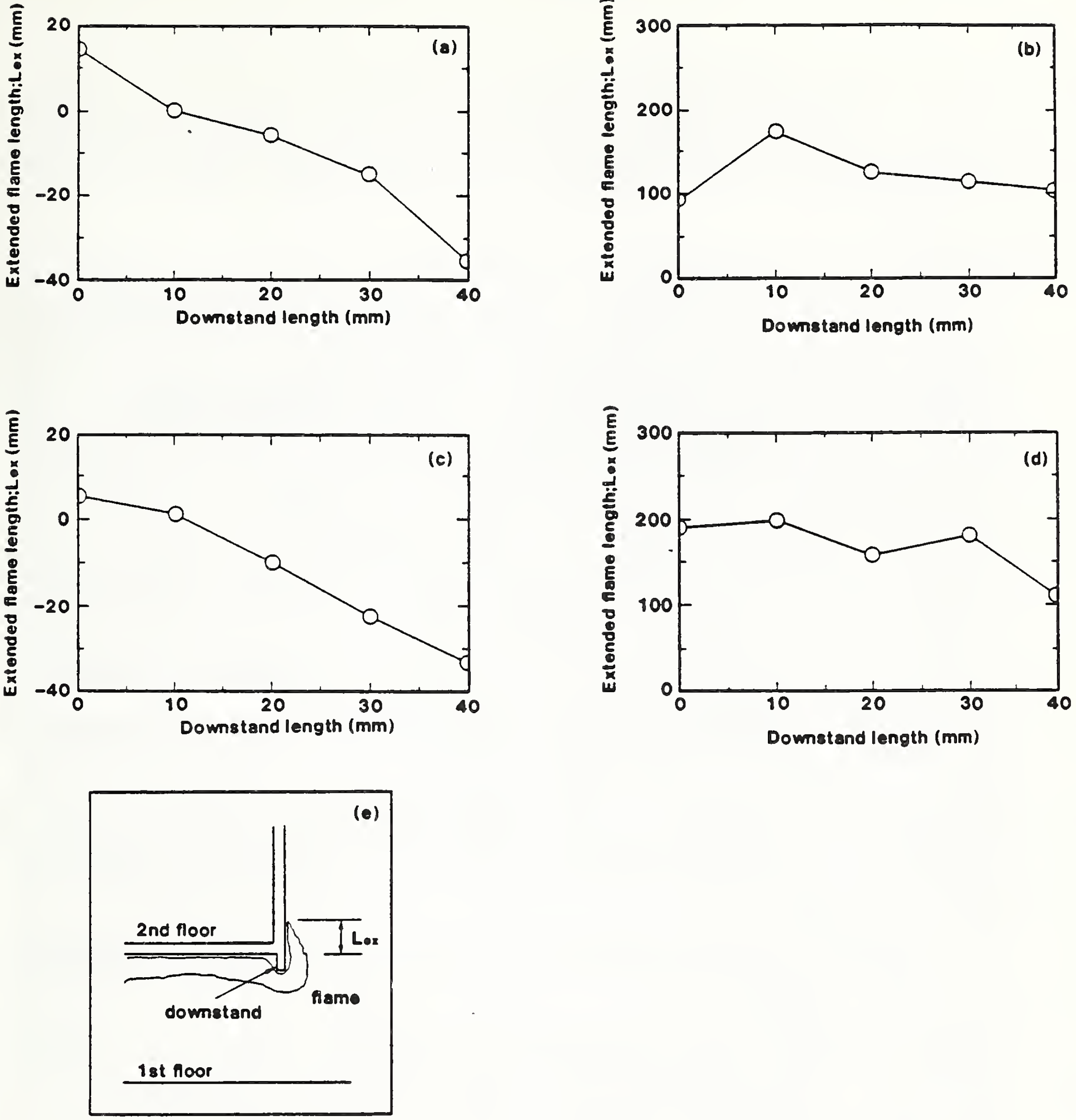


Figure 6 Correlation of the extended flame length from the ceiling versus length of the downstand. (a) no wind was given to the reduced model and fire source located at the end corner, (b) no wind was given to the reduced model and fire source located at the front of the opening, (c) wind was given and fire source located at the end corner, and (d) wind was given to the reduced model and fire source set at the front of the opening, and (e) extended flame length definition.

and Ministry of International Trade and Industry of Japan (MITI) for their financial support. This series of experiments were carried out as a part of PEC-86P06 Project of the PEC. The authors are grateful to Mr. Kazuo Takahashi, who made basic design of the full scale model.

7. REFERENCES

1) Mizuno, T., and Sugawa, O., "Experimental Study on Gasoline Station Fire -- Evaluation of Fire Safety --", Proceding of the 2nd Symposium of the International Association on Fire Safety Science, p751-760, July, Tokyo (1988)

2) Blinov, V.I., and Khudiakov,G,N., "Diffusion Burning of Liquid", U.S. Army translation, NTIS No. AD296762 (1961)

3) Blinov, V.I., and Khudiakov,G,N., "The Burning of the liquid pools" Doklady Akademi Nauk SSSR, 113, 1094 (1957)

4) Babrauskas,V., "Estimating Large Pool Fire Burning Rates", Fire Technology, vol.19, No.4, p251-261 (1983)

5) Lois, E., and Swithenbank, J.,"Fire Hazards in Oil Tank Arrays in a Wind", Seventeenth Symposium (international) on Combustion, The Combustion Institute, Pittsburgh, pp1087-1098 (1978)

6) Yumoto,T. Doctor Thesis,"Burning rate and Radiative Heat Flux of Pool Fire, Section 3.3.5",(written in Japanese), Science University of Tokyo, (1977)

7) Thomas,P.T., Webster,C.T., and Raftery,M.M.,"Some experiments on buoyant diffusion flames" Combustion and Flame, Vol.5, p359-367, (1961)

8) Zukoski,E.E., Kubota,T., and Cetegan,B. "Entrainment in Fire Plumes", Fire Safety Journal, vol.3, p107-121, (1980/81)

9) Steward,F.R. "Prediction of the Height of Turbulent Diffusion Buoyant Flames", Combustion Science and Technology, vol.2, p203-212,(1970)

10) Cox,G., and Chitty,R."A study of the Deterministic Properties of Unbounded Fire Plumes", Combustion and Flame, vol.39, p191-209, (1980)

11) Hasemi,Y., and Tokunaga,T.,"Flame Geometry Effects on the Buoyant Plumes from Turbulent Diffusion Flame", J. Fire Science and Technology, vol.4, No.1, p15-26, (1984)

and Hasemi,Y., and Nishihata,M.,"Deterministic Properties of Turbulent Diffusion Flames from Low Q* Fires", J. Fire Science and Tecnology, vol.7, No.2 p27-34, (1987)

12) Hasemi,Y., "Experimental Wall Flame Heat Transfer Correlations for the Analysis of Upward Wall Flame Spread", J. Fire Science and Technology, vol.4, No.2, p75-90, (1984)

Thermal Analysis of Effect of a Compartment Fire on Window Glass

A. Joshi† *and* *P. J. Pagni*‡

Department of Mechanical Engineering
University of California
Berkeley, CA 94720, USA

† Graduate Student
‡ Professor

ABSTRACT

Glass breaking in fires is an important practical problem since a window acts as a wall prior to breaking and as a vent after breaking. This geometric change can have a dramatic effect on the evolution of a compartment fire. As Emmons explained, windows break in fires due to thermal stress from the differential heating of the central portion and the shaded edge. If the depth of shading around the edge is much greater than the glass thickness, one can assume that the edge remains at its initial temperature T_i. This paper determines the surface temperature history, $T^*(0,t^*)$, of the glass. The temperature at breaking is when $(T^*(0,t^*) - T_i)\alpha = \sigma_b/E$, where $\alpha\Delta T$ and σ_b/E both give the strain at breaking in tension. The glass coefficient of linear thermal expansion is α, the glass modulus is E and σ_b is its tensile strength. Typical property values suggest the range $50°C-100°C$ for the breaking ΔT. Here the transient, one-dimensional (into the glass normal to the pane), in-homogeneous (in-depth radiation absorption) energy equation is solved using an innovative Laplace Transform technique suggested by Baum. Two coupled non-linear Volterra equations of the second kind are obtained for the temperatures of the two surfaces of the glass. Time varying incident radiative flux and the glass temperatures are included. These equations are solved numerically by using the trapezoidal rule for numerical integration and Newton-Raphson's method for determining the roots of the non-linear equations. Results are presented for typical values of the governing dimensionless parameters.

INTRODUCTION

Breaking of window glass due to heat from fires is a very commonly observed phenomenon. This phenomenon is of great importance as the glass breakage can be a cause of fire spread (if the window is between two adjoining rooms) or a broken window can act as a vent for the escape of toxic fire gases and an inlet for fresh air (if the window opens to the outside). Glass absorbs thermal radiation from the fire and also gets heated by convection from the hot air surrounding the fire leading to thermal stresses. The thermal stresses arise due to the temperature difference between the central portion of the window which is exposed to fire products and the insulated or protected edge of the window. These stresses lead to cracks and eventually to breakage. In this paper, a thermal analysis of the effect of radiation and convection on the glass is carried out by including the exponential decay of thermal radiation within the glass and heating and/or cooling of the surfaces due to convection and radiation heat transfer.

Emmons (1986) indicated that the process of the initiation and propagation of cracks in glass due to the heat is not very well understood. Finnie et al (1985) carried out an analysis which implied that the only factor governing the breakage is the net temperature difference between the central heated portion of the glass and the protected edge, which can be calculated from the glass properties. Since the protected edge temperature is not expected to rise much in a fire, the difference between the temperature of the central portion and the edge can be approximated by the net temperature rise of the heated portion. The side exposed to the fire is expected have the highest temperature and thus a knowledge of the temperature history of only this side is adequate in determining the time for breakage.

The problem governing this phenomenon is transient and non-linear due to the radiation boundary condition. Keski-Rahkonen (1988) linearized the boundary conditions and obtained an exact solution for the temperature field. Recently, Davies (1985) used an integral method for determining the temperature field in a plate losing heat by combined radiation and convection. In Davies' method, inaccuracies arise due the assumed nature of the temperature profile. For solving the complete non-linear problems the use of a numerical method is essential. Methods such as finite-difference, finite-element and boundary element have been used before. However the implementation of these methods leads to the inaccuracies arising from the discretization of both the time and space domain. Also the whole temperature field has to be evaluated. In the present case, the temperature of interest is only of the side exposed to the fire and hence the knowledge of the whole temperature field is irrelevant.

The thickness of the window is usually an order of magnitude smaller than the other dimensions and so in the case discussed, the window has been assumed to be an infinite slab. Thus the equation governing the system is a one dimensional inhomogeneous heat equation with non-linear boundary conditions. To solve this equation, the method of Laplace transform is utilized. After simplifications, only two equations for the temperature of each surface need to be solved. This method is similar to Chambres (1959) method which was used to determine the temperature distribution in a semi-infinite solid with radiation type boundary conditions. In Chambres methods one non-linear Volterra equation of the second kind for the surface temperature needs to be solved, whereas in the present case, a system of two coupled non-linear Volterra equations of the second kind for the temperatures of each side have to be solved. These equations are solved numerically by using the trapezoidal rule for numerical integration and Newton-Raphson's method for determining the roots of the non-linear equations. The equations are exact and inaccuracies arise only due to the discretization of the time domain. This method is applied to the general case of time varying radiative flux and surrounding temperatures.

THEORY AND FORMULATION

Consider an infinite slab of thickness L, initially at a temperature T_i. At time $t' = 0$ it starts getting heated on the side $x = 0$ due to radiative flux $I_0 j'(t)$ and loses or gains heat by combined convection and radiation on both sides. Suppose the heat transfer coefficients on the two sides are represented by h_1 and h_2, the ambient temperatures are represented by $T_{1\infty}(t')$ and $T_{2\infty}(t')$. Let β be the absorption length and k be the thermal concuctivity of glass. Also let ρ and C_p be the density and specific heat respectively of the glass. Also let ε and ε_∞ be the emissivities of the glass and the surroundings. σ is the Stefan-Boltzmann constant. Then the governing equation for this system will be

$$\rho C_p \frac{\partial T'}{\partial t'} = k \frac{\partial^2 T'}{\partial x'^2} + I_o j'(t') \frac{e^{-x'/\beta}}{\beta} \tag{1}$$

where $j'(t')$ is some specified function of time. The initial and boundary conditions for this problem are

$$at\ t' = 0,\ T' = T_i \tag{2}$$

$$at\ x' = 0,\ -k\frac{\partial T'}{\partial x'} = h_2(T_{2\infty}(t') - T'(0,t')) - \varepsilon\sigma T'^4(0,t') \tag{3}$$

$$at\ x' = L,\ -k\frac{\partial T'}{\partial x'} = h_1(T'(L,t') - T_{1\infty}(t)) + \varepsilon\sigma T'^4(L,t') - \varepsilon_\infty\sigma T^4_{1\infty}(t) \tag{4}$$

Nondimensionalization

This equation is nondimensionalized by using the following dimensionless variables

$$x = \frac{x'}{L};\ t = \frac{t'k}{\rho C_p L^2};\ T = \frac{T' - T_i}{T_c};\ \gamma = \frac{\beta}{L} \tag{5}$$

where T_c is the characteristic temperature defined by

$$T_c = \frac{I_o L}{k} \tag{6}$$

Hence, in the dimensionless form, the governing equation becomes

$$\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial x^2} + j(t)\frac{e^{-x/\gamma}}{\gamma} \tag{7}$$

with initial and boundary conditions

$$at\ t = 0,\ T = 0 \tag{8}$$

$$at\ x = 0,\ -\frac{\partial T}{\partial x} = q_2(t) \tag{9}$$

$$at\ x = 1, -\frac{\partial T}{\partial x} = q_1(t) \tag{10}$$

where

$$q_2(t) = A + BT(0,t) + CT^2(0,t) + DT^3(0,t) + ET^4(0,t) \tag{11}$$

and

$$q_1(t) = F + GT(1,t) - CT^2(1,t) - DT^3(1,t) - ET^4(1,t) \tag{12}$$

where

$$A = \frac{h_2 L(T_{2\infty}(t) - T_i)}{kT_c} - \frac{\varepsilon\sigma L T_i^4}{kT_c} \tag{13}$$

$$B = -\frac{h_2 L}{k} + \frac{4\varepsilon\sigma T_i^3 L}{k} \tag{14}$$

$$C = -\frac{6\varepsilon\sigma T_c T_i^2 L}{k} \tag{15}$$

$$D = -\frac{4\varepsilon\sigma T_c^2 T_i L}{k} \tag{16}$$

$$E = -\frac{\varepsilon\sigma T_c^3 L}{k} \tag{17}$$

$$F = \frac{h_1 L(T_i - T_{1\infty})}{kT_c} - \frac{\varepsilon_\infty \sigma T_{1\infty}^4 L}{kT_c} + \frac{\varepsilon\sigma L T_i^4}{kT_c} \tag{18}$$

$$G = \frac{h_1 L}{k} + \frac{4\varepsilon\sigma T_i^3 L}{k} \tag{19}$$

METHOD OF SOLUTION

We use the method of Laplace transforms to solve this equation. The Laplace transform is taken with respect to time and is defined as

$$T^* = \int_0^\infty T e^{-pt}\, dt \tag{20}$$

Substituting the transformed variable into the governing equation and applying the boundary conditions leads to the solution

$$T^* = A_1 j^* \frac{e^{-x\gamma}}{\gamma} + B_1 \cosh(\sqrt{p}\,x) + C_1 \cosh(\sqrt{p}\,(1-x)) \tag{21}$$

where

$$A_1 = \frac{1}{p - \frac{1}{\gamma^2}} \tag{22}$$

$$B_1 = \frac{A_1 j^* e^{-1/\gamma} - \gamma^2 q_1^*}{\gamma^2 \sqrt{p}\, \sinh\sqrt{p}} \tag{23}$$

$$C_1 = \frac{\gamma^2 q_2^* - A_1 j^*}{\gamma^2 \sqrt{p}\, \sinh\sqrt{p}} \tag{24}$$

We need to solve for both the surface temperatures as the temperature on the hotter surface depends on the temperature on the other surface and vice versa. Hence, the transformed form of the temperatures are

$$T^*(0) = \frac{A_1 j^*}{\gamma} + B_1 + C_1 \cosh\sqrt{p} = f_1^* q_1^* + f_2^* q_2^* + \frac{1}{\gamma} f_3^* j^* \tag{25}$$

$$T^*(1) = \frac{A_1 e^{-1/\gamma} j^*}{\gamma} + B_1 \cosh\sqrt{p} + C_1 = g_1^* q_1^* + g_2^* q_2^* + \frac{1}{\gamma} g_3^3 j^* \tag{26}$$

Using convolution theorem and after simplifications, the equations to be solved look like

$$T(0,t) = \int_0^t q_1(\tau) f_1(t-\tau) d\tau + \int_0^t q_2(\tau) f_2(t-\tau) d\tau + \frac{1}{\gamma}\int_0^t j(\tau) f_3(t-\tau) d\tau \tag{27}$$

and

$$T(1,t) = \int_0^t q_1(\tau) g_1(t-\tau) d\tau + \int_0^t q_2(\tau) g_2(t-\tau) d\tau + \frac{1}{\gamma}\int_0^t j(\tau) g_3(t-\tau) d\tau \tag{28}$$

where $f_1, f_2, f_3, g_1, g_2, g_3$ are the kernels which depend upon γ and are specified in Appendix I. The equations to be solved are coupled non-linear Volterra equations of the second kind. The equations are non-linear because both q_1 and q_2 are non-linear functions of T_1 and T_2 respectively.

Transformation of variable

We observe that the integrands are not bounded as $f_2(t)$ and $g_1(t)$ at $t = 0$ go to infinity as $t^{-1/2}$. So if we now transform the equations using the variable $u = \sqrt{t-\tau}$, the equations become

$$T(0,t) = 2\int_0^{\sqrt{t}} uF_1(u) q_1(t-u^2) du + 2\int_0^{\sqrt{t}} uF_2(u) q_2(t-u^2) du + \frac{2}{\gamma}\int_0^{\sqrt{t}} uF_3(u) j(t-u^2) du \tag{29}$$

and

$$T(1,t) = 2\int_0^{\sqrt{t}} uG_1(u)q_1(t-u^2)du + 2\int_0^{\sqrt{t}} uG_2(u)q_2(t-u^2)du + \frac{2}{\gamma}\int_0^{\sqrt{t}} uG_3(u)j(t-u^2)du \qquad (30)$$

where $F_1(u) = f_1(u^2)$ etc. and the integrands are bounded.

Numerical procedure

The numerical procedure chosen was trapezoidal rule with constant time steps (thus variable Δu) for numerical integration and Newton-Raphson's methods for finding roots of the non-linear equations. By looking at the equations, it appears that the equations are coupled. However, since $f_1(0)$ and $g_2(0)$ are equal to 0, at a particular time step the equations can be solved independently of one another.

RESULTS

Figure 1 shows the comparison with the exact solution of the linear problem (given in Appendix II) for the case of no heat loss due to thermal radiation. This figure shows the dimensionless temperature variation with respect to dimensionless time of the sides exposed and unexposed to incoming radiative flux. The agreement is within 0.5% for a dimensionless time step of 0.002 suggesting that the the time step was quite accurate.

Figures 2(a) and (b) show respectively the variation with respect to time of the dimensionless temperature of the side exposed to and the side unexposed to the incoming heat flux. Only the Biot numbers were changed. In this case the initial temperature of the material is set equal to the ambient temperatures on either sides. Also the incoming radiative flux is assumed to have a constant value. The ambient temperatures are assumed to be constant.

As expected, the temperature of the side exposed to the heat flux increases more rapidly compared to the temperature of the unexposed side. As Biot numbers increase, heat loss is greater and hence the rate of increase of temperature is lower.

Figure 3 shows the variation of the temperatures for varying dimensionless absorption length for constant value of Biot number. Here also, the input radiative flux function is assumed to be a constant. Here, as γ decreases, the temperature of the exposed side increases as small γ corresponds to small absorption length, implying that most of the radiation gets absorbed within a short distance. And for large values of γ, the material behaves more like a transparent medium. For large values of γ an artificial temperature drop is encountered as the approximation of surface emission but absorption within the body breaks down.

Figure 4 shows the variation of the temperatures of the sides corresponding to varying input radiation flux, holding the other parameters constant. It can be seen here that the rate of increase of the temperature of the exposed side varies roughly as the integral with respect to time of the incoming radiation function. This is because the rate of increase of temperature is dependent on the rate of incoming heat as can be seen in equation (29)for $T(0,t)$.

Table 1 shows the various values used for the calculations. These values represent the typical values which might be encountered in the situations of real fires. The time of glass breakage solely depends upon the net temperature rise of the glass, and it was found that for ordinary plate glass, the value was found to be about 60^o C. This value is obtained from Hooke's law and it was verified by Finnie et. al. that this value does not depend on the rate of temperature rise. This would imply that for a particular value of the radiative flux, a value of the dimensionless critical temperature can be obtained. Hence in the computer program, the computations are stopped as soon as the critical temperature is reached.

REFERENCES

Chambres, P. L. (1959) "Nonlinear Heat Transfer Problem", *Journal of Applied Physics*, vol.30, no.11, pp 1683-1688.

Davies, T. W. (1985) "The Cooling of a Plate by Combined Thermal Radiation and Convection", *International Communication in Heat and Mass Transfer*, vol.12, pp 405-415.

Emmons, H. W. (1986) "The Needed Fire Science", *First International Symposium on Fire Safety Science*, pp 33-53.

Finnie. I and Chang, Wei-Li (1985) *private communication.*

Keski-Rahkonen, Olavi (1988) "Breaking of Window Glass Close to Fire". *Fire and Materials*, vol.12, pp 61-69.

APPENDIX I

The Laplace transforms of the kernels in equations are

$$f_1^* = \frac{-1}{\sqrt{p}\sinh(\sqrt{p})} \quad (31)$$

$$f_2^* = \frac{\cosh(\sqrt{p})}{\sqrt{p}\sinh(\sqrt{p})} \quad (32)$$

$$g_1^* = -f_2^* \quad (33)$$

$$g_2^* = -f_1^* \quad (34)$$

$$f_3^* = \frac{\gamma\sqrt{p}\sinh(\sqrt{p}) + e^{-1/\gamma} - \cosh(\sqrt{p})}{(p - \frac{1}{\gamma^2})\gamma\sqrt{p}\sinh(\sqrt{p})} \quad (35)$$

$$g_3^* = \frac{\gamma\sqrt{p}\sinh(\sqrt{p})e^{-1/\gamma} + \cosh(\sqrt{p})e^{-1/\gamma} - 1}{(p - \frac{1}{\gamma^2})\gamma\sqrt{p}\sinh(\sqrt{p})} \quad (36)$$

And hence the kernels are

for short time

$$f_1(t) = -g_2(t) = -\frac{2}{\sqrt{\pi t}}\sum_{k=0}^{\infty}\exp\left[-\frac{(2k+1)^2}{4t}\right] \quad (37)$$

$$f_2(t) = -g_1(t) = \frac{1}{\sqrt{\pi t}} + \frac{2}{\sqrt{\pi t}}\sum_{k=1}^{\infty}\exp\left[-\frac{(2k)^2}{4t}\right] \quad (38)$$

$$f_3(t) = e^{\frac{t}{\gamma^2}}\left\{1 + \right.$$

$$e^{-1/\gamma}\sum_{k=0}^{\infty}\left[e^{-\frac{2k+1}{\gamma}} erfc\left[\frac{(2k+1)}{\sqrt{4t}} - \frac{\sqrt{t}}{\gamma}\right] - e^{\frac{2k+1}{\gamma}} erfc\left[\frac{(2k+1)}{\sqrt{4t}} + \frac{\sqrt{t}}{\gamma}\right]\right]$$

$$- \frac{1}{2}\left[erfc(-\frac{\sqrt{t}}{\gamma}) - erfc(\frac{\sqrt{t}}{\gamma})\right]$$

$$- \sum_{k=1}^{\infty}\left[e^{-\frac{2k}{\gamma}} erfc\left[\frac{2k}{\sqrt{4t}} - \frac{\sqrt{t}}{\gamma}\right] - e^{\frac{2k}{\gamma}} erfc\left[\frac{2k}{\sqrt{4t}} + \frac{\sqrt{t}}{\gamma}\right]\right]\Bigg\} \quad (39)$$

$$g_3(t) = e^{\frac{t}{\gamma^2}}\Bigg\{ e^{-1/\gamma} -$$

$$\sum_{k=0}^{\infty}\left[e^{-\frac{2k+1}{\gamma}} erfc\left[\frac{(2k+1)}{\sqrt{4t}} - \frac{\sqrt{t}}{\gamma}\right] - e^{\frac{2k+1}{\gamma}} erfc\left[\frac{(2k+1)}{\sqrt{4t}} + \frac{\sqrt{t}}{\gamma}\right]\right]$$

$$+ \frac{e^{-1/\gamma}}{2}\left[erfc(-\frac{\sqrt{t}}{\gamma}) - erfc(\frac{\sqrt{t}}{\gamma})\right]$$

$$+ e^{-1/\gamma}\sum_{k=1}^{\infty}\left[e^{-\frac{2k}{\gamma}} erfc\left[\frac{2k}{\sqrt{4t}} - \frac{\sqrt{t}}{\gamma}\right] - e^{\frac{2k}{\gamma}} erfc\left[\frac{2k}{\sqrt{4t}} + \frac{\sqrt{t}}{\gamma}\right]\right]\Bigg\} \quad (40)$$

and for long time are

$$f_1(t) = -g_2(t) = -\left[1 + 2\sum_{k=1}^{\infty} e^{-k^2\pi^2 t}(-1)^k\right] \quad (41)$$

$$f_2(t) = -g_1(t) = 1 + 2\sum_{k=1}^{\infty} e^{-k^2\pi^2 t} \quad (42)$$

$$f_3(t) = -\gamma(e^{-1/\gamma} - 1) + \frac{2}{\gamma}\sum_{k=1}^{\infty}\frac{(-1)^k e^{-1/\gamma} - 1}{-k^2\pi^2 - \frac{1}{\gamma^2}} e^{-k^2\pi^2 t} \quad (43)$$

$$g_3(t) = -\gamma(e^{-1/\gamma} - 1) + \frac{2}{\gamma}\sum_{k=1}^{\infty}\frac{e^{-1/\gamma} - (-1)^k}{-k^2\pi^2 - \frac{1}{\gamma^2}} e^{-k^2\pi^2 t} \quad (44)$$

APPENDIX II

The exact solution to the linear problem of negligible heat loss due to radiation is

$$T = u(x,t) + v(x) \tag{45}$$

where

$$v(x) = px + q \tag{46}$$

where

$$p = -\frac{ABi_1 + BBi_2}{Bi_1 + Bi_2 + Bi_1Bi_2} \text{ and } q = -\frac{B - A - ABi_1}{Bi_1 + Bi_2 + Bi_1Bi_2} \tag{47}$$

Here

$$A = \frac{T_{2\infty}-T_i}{T_c}Bi_2,\ B = \frac{T_i-T_{1\infty}}{T_c}Bi_1 \tag{48}$$

where

$$Bi_1 = \frac{h_1L}{k} \text{ and } Bi_2 = \frac{h_2L}{k} \tag{49}$$

where h_1 and h_2 are the heat transfer coefficients. The solution for $u(x,t)$ is given by

$$u = \sum_{n=0}^{\infty}\left[C_n e^{-\lambda_n^2 t} + \int_0^t e^{-\lambda_n^2(t-\tau)} w_n(\tau)d\tau\right]\phi_n(x) \tag{50}$$

where the characteristic functions are

$$\phi_n(x) = \lambda_n \cos(\lambda_n x) + Bi_2 \sin(\lambda_n x) \tag{51}$$

and the eigenvalues λ_n are obtained from the solutions to

$$\cot\lambda_n = \frac{\lambda_n^2 - Bi_1Bi_2}{\lambda_n(Bi_1+Bi_2)} \tag{52}$$

The constants C_n appearing in the equation for $u(x,t)$ are defined as

$$C_n = -\frac{1}{N(\lambda_n)}\int_0^1 v(x)\phi_n(x)dx \tag{53}$$

the weight functions w_n are defined as

$$w_n(t) = \frac{1}{\gamma N(\lambda_n)} \int_0^1 j(t) e^{-x/\gamma} \phi_n(x) dx \qquad (54)$$

and norms $N(\lambda_n)$ are defined as

$$N(\lambda_n) = \frac{1}{2}\left[(\lambda_n^2 + Bi_2^2)\left(1 + \frac{Bi_1}{\lambda_n^2 + Bi_1^2}\right) + Bi_2\right] \qquad (55)$$

Table 1. Glass and Fire Parameters

thermal conductivity,	$k = 0.76 W/mK$
thermal diffusivity,	$\alpha = 3.6 \; X \; 10^{-7} \; m^2/s$
thickness,	$L = 6.25 \; X \; 10^{-3} m$
penetration depth,	$\beta = 10^{-3} \; m, \; 3.13 \; X \; 10^{-3} \; m, \; 6.25 \; X \; 10^{-4} \; m$
temperatures,	$T_{1\infty} = T_{2\infty} = T_i = 293 \; K$
emissivities,	$\varepsilon = 1.0, \; \varepsilon_{\infty} = 1.0$
incident flux,	$I_0 = 1000 \; W/m^2K$

FIGURE CAPTIONS

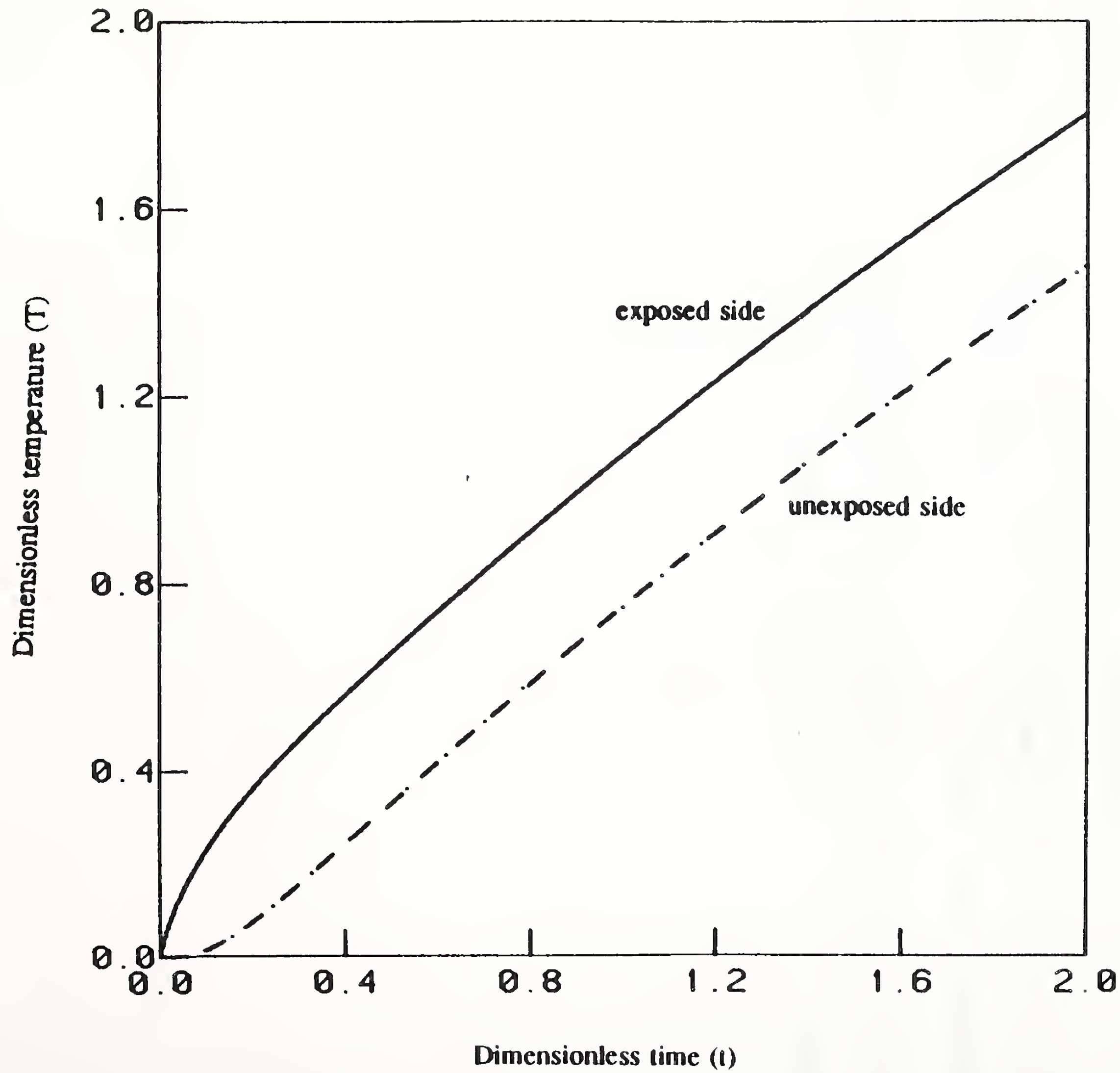
Figure 1. The surface temperatures, $T(0,t)$ and $T(1,t)$ are shown where $T = (T' - T_i)k/I_0 L$ and $t = t' \alpha / L^2$ for $\gamma = 0.16$ and $Bi_1 = Bi_2 = 0.1$. The exact linearized results and numerical results are indistinguishable.

Figure 2. The variation of the exposed surface temperature with Biot number for $Bi = Bi_1 = Bi_2$ is shown for $\gamma = 0.16$ and the other parameters as listed in Table 1.

Figure 2. The variation of the unexposed surface temperature with Biot number for $Bi = Bi_1 = Bi_2$ is shown for $\gamma = 0.16$ and the other parameters as listed in Table 1.

Figure 3. The variation of the exposed surface temperature with depth parameter, γ, for $Bi_1 = Bi_2 = 0.1$ and other parameters listed in Table 1.

Figure 4. The effect of different time dependencies of the incident radiative flux on the exposed surface temperature for $\gamma = 0.16$, $Bi_1 = Bi_2 = 0.1$ and the other parameters as listed in Table 1.



Dimensionless temperature (T)
2.0
1.6
1.2
0.8
0.4
0.0
exposed side
unexposed side
0.0
0.4
0.8
1.2
1.6
2.0
Dimensionless time (t)

Figure 1.

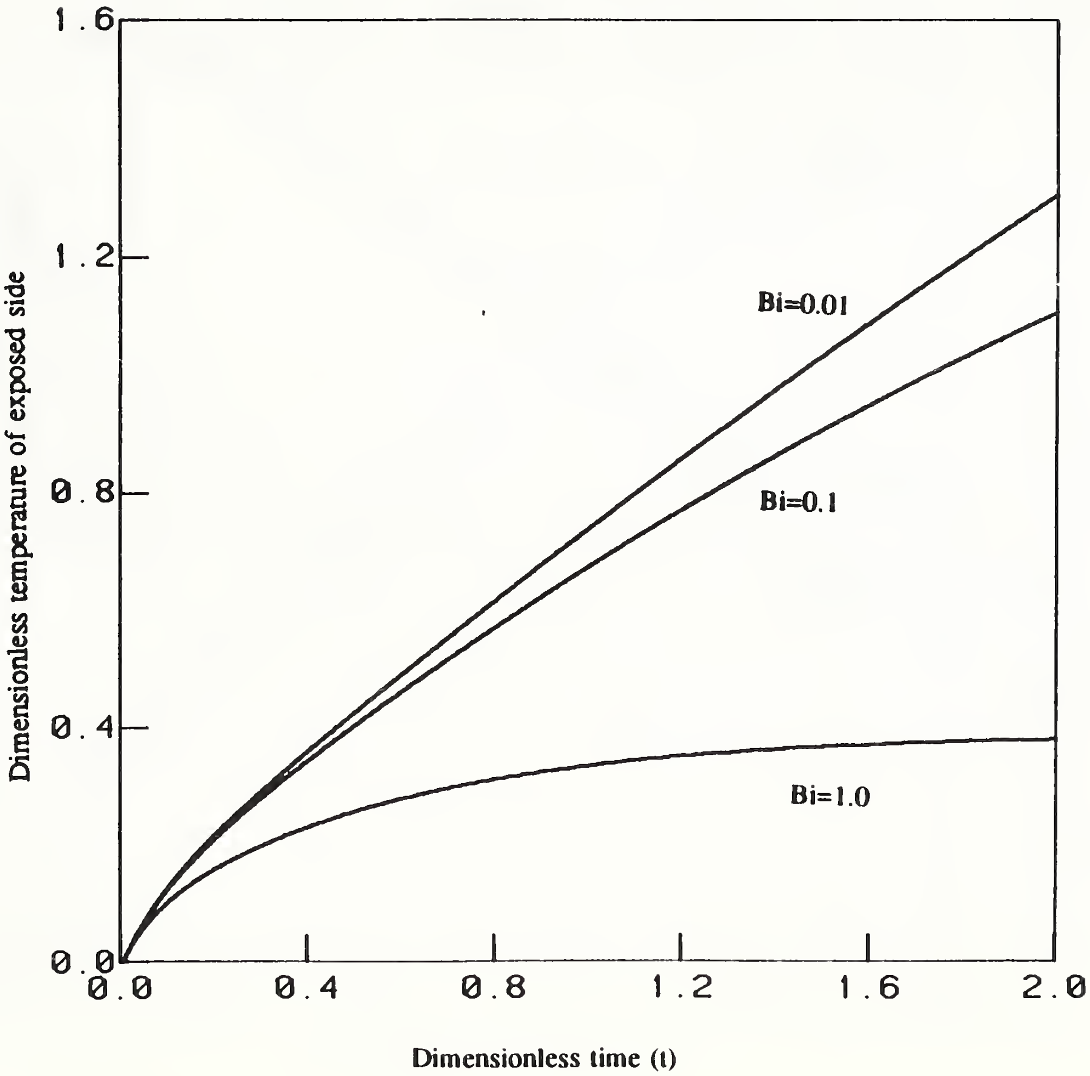

1.6
1.2
0.8
0.4
0.0
0.0
0.4
0.8
1.2
1.6
2.0
Dimensionless temperature of exposed side
Dimensionless time (t)
Bi=0.01
Bi=0.1
Bi=1.0

Figure 2a.

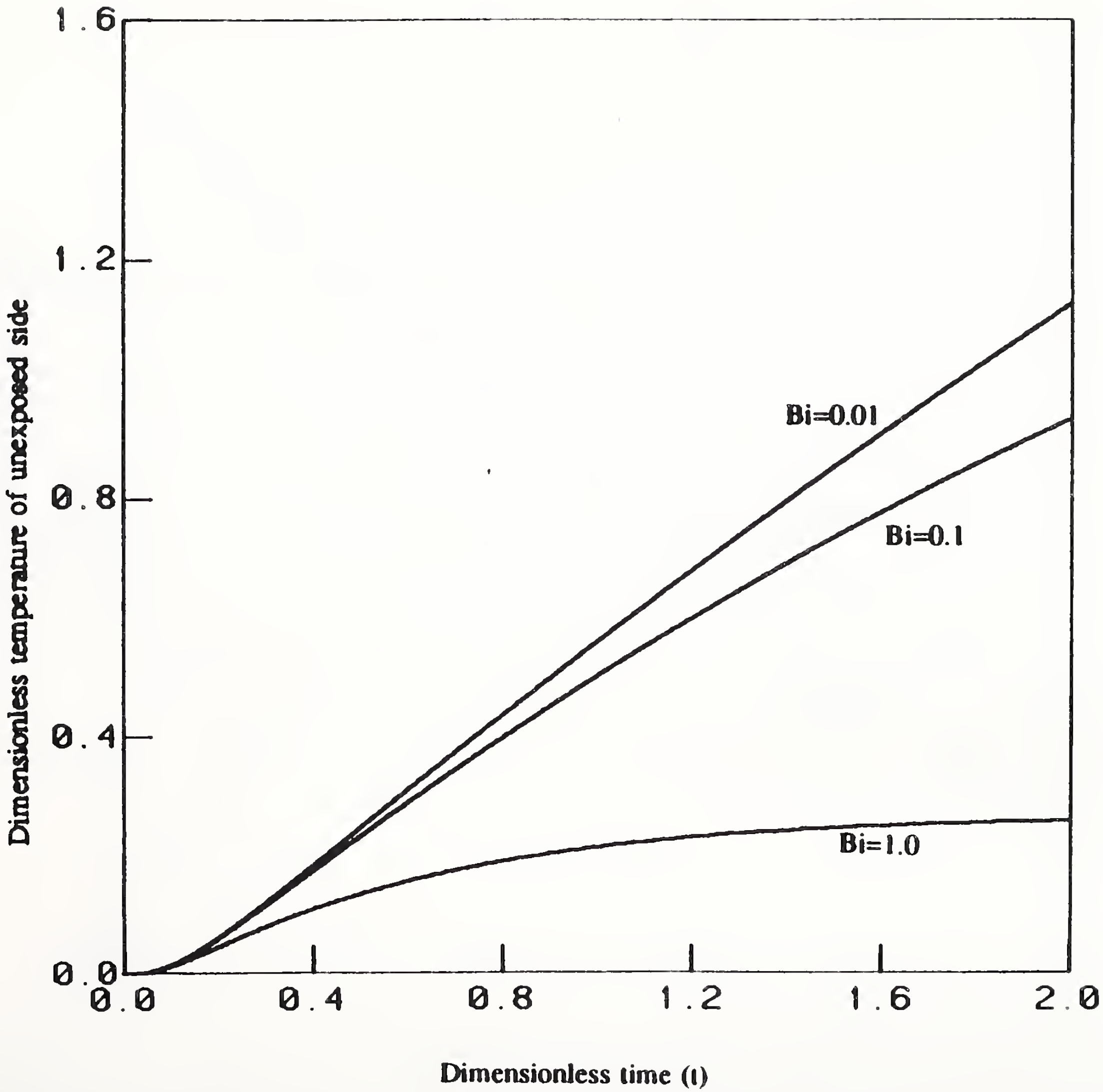

1.6
1.2
0.8
0.4
0.0
0.0
0.4
0.8
1.2
1.6
2.0
Bi=0.01
Bi=0.1
Bi=1.0
Dimensionless temperature of unexposed side
Dimensionless time (t)

Figure 2b.

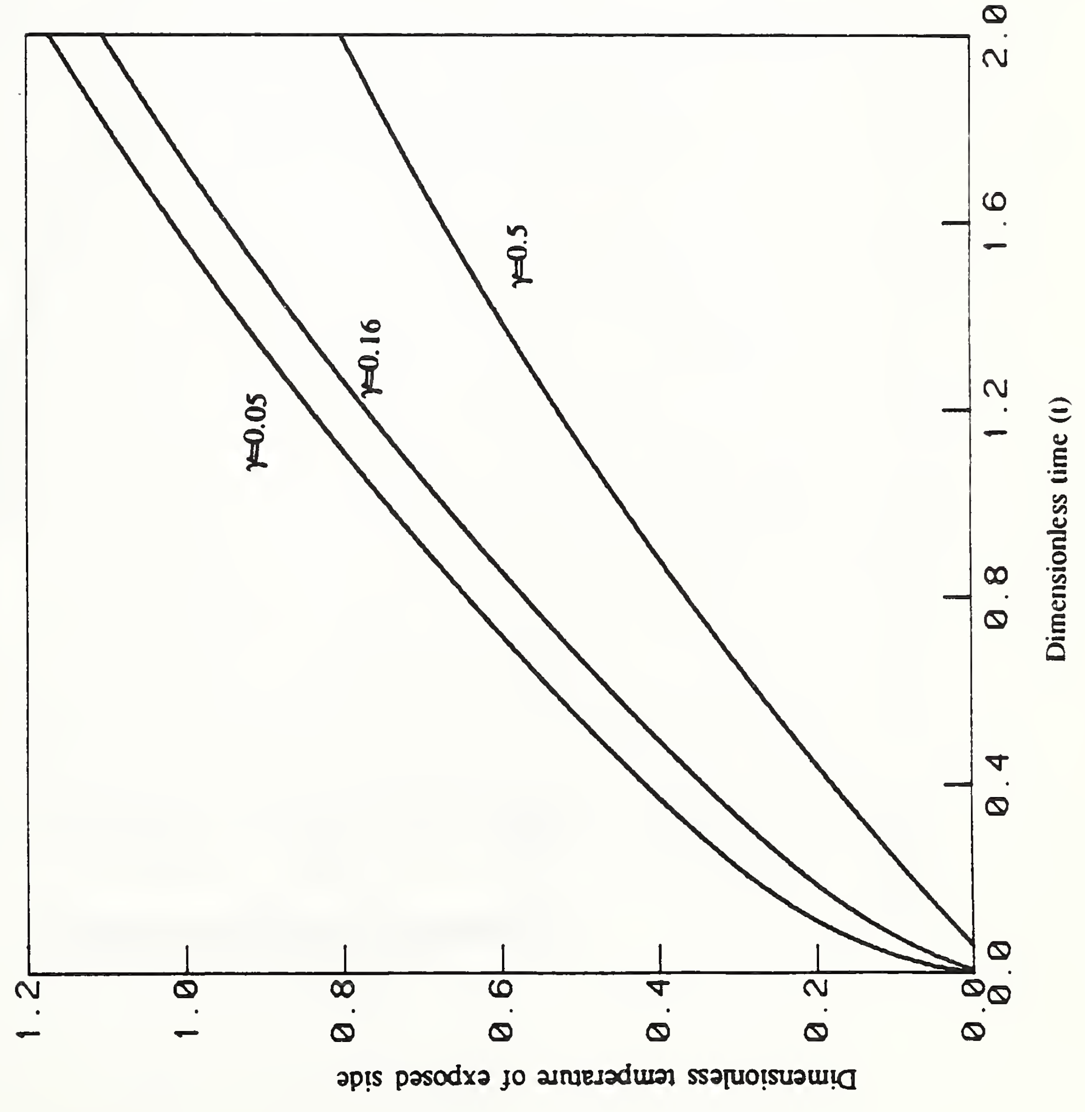
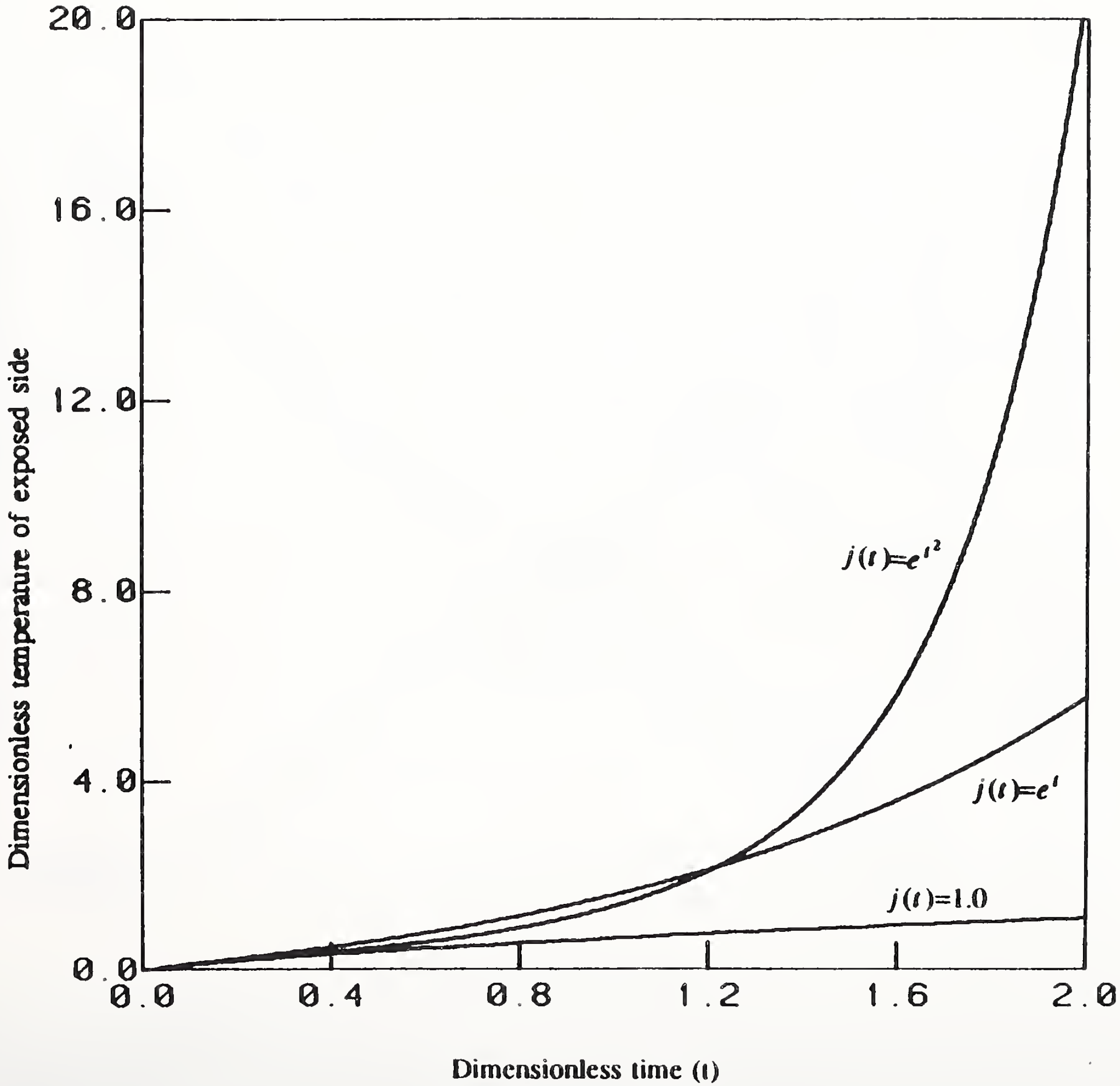

Dimensionless temperature of exposed side
Dimensionless time (t)
γ=0.05
γ=0.16
γ=0.5
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0.0
0.4
0.8
1.2
1.6
2.0

Figure 3.



20.0
16.0
12.0
8.0
4.0
0.0
0.0
0.4
0.8
1.2
1.6
2.0
Dimensionless temperature of exposed side
Dimensionless time (t)
$j(t)=e^{t^2}$
$j(t)=e^{t}$
$j(t)=1.0$

Figure 4.

SUPPORT PAPERS

HEAT TRANSFER MECHANISMS IN MATERIALS ON FIRE RETARDATION

Hideo Ohtani
Yokohama National University, Japan
156 Tokiwadai, Hodogaya-Ku, Yokohama 240
Hiroshi Koseki
Fire Research Institute, Japan
3-14-1 Nakahara, Mitaka-Shi, Tokyo 181
Toshisuke Hirano
University of Tokyo, Japan
7-3-1 Hongo, Bunkyo-Ku, Tokyo 113

ABSTRACT

A concept for the flame retardation was discussed from the viewpoint of heat transfer in a material. Recent experiences on the burning properties of wood in China and Japan[1,2] revealed that a composite material of two or more different elements shows the different characteristics compared with a homogeneous one. The differences were considered to be caused by differences in the physical properties of the elements rather than the chemical properties. Especially, thermal properties of the material were inferred to play an important role on the burning characteristics of the material. This suggests that appropriate selection and combination of the thermal properties contribute largely on fire retardation. Based on a simple analysis of heat transfer in composite materials, possible use of the composite materials was discussed.

1. INTRODUCTION

The growth ring is made of spring woods and summer woods. Therefore, a 'wood' is considered to be a type of composite material. A large difference in cell sizes of a spring wood and a summer wood suggests that thermal properties of a spring wood and a summer wood must be different. Such differences between a spring wood and a summer wood should cause differences in thermal properties with the heat flux direction against the growth ring direction, even if there was no directional difference in a spring wood or a summer wood. In this study, a 'wood' was considered as a composite material composed of two elements having different thermal properties. Numerical analyses were done on the temperature profiles in several types of composite materials exposed to external radiation.

2. ANALYTICAL MODEL OF 'WOOD'

As previously mentioned, a 'wood' was modeled as a composite material composed of two thermally different elements, namely a 'spring wood' and a 'summer wood'(Fig. 1). These 'summer wood' and 'spring wood' are rigid materials unlike a real wood. Therefore, heat transfer in the composite was considered to occur only through conduction. Convective heat transfer by transport of vapor, which plays an important role in heat transfer in the case of a real wood, was ignored. Four types of composite materials were considered as listed in Table 1.

Properties of the 'spring wood' and the 'summer wood' were determined from

Table 1 Structural types of composite materials

Types	Structure	Direction of layers to the surface	Material of surface layer
A	Layered	Parallel	Spring wood
B	Layered	Parallel	Summer wood
C	Layered	Normal	-
D	Overlay[a)]	Parallel	Summer wood

a) Overlay means the material has only one layer overlaid on the other element.

those of an actual wood(fir)[3]. In the literature, properties of fir are as follows; density ρ is $0.54 g/cm^3$, thermal conductivity transverse to the grain λ_t is $1.38\times10^{-3} J/cm/s/K$, longitudinal to the grain λ_l is $3.39\times10^{-3} J/cm/s/K$, thermal diffusivity transverse to the grain α_t is $1.869\times10^{-3} cm^2/s$, longitudinal to the grain α_l is $4.587\times10^{-3} cm^2/s$.

In this model, the 'spring wood' was assumed to be 0.3 cm wide and the 'summer wood' was 0.1 cm wide, though propriety of these widths remains uncertain. Concerning density and heat capacity, any information on directional differences is not available. In this calculation, therefore, the 'spring wood' and the 'summer wood' were assumed to have identical density and heat capacity. They were assumed to have difference only in thermal conductivity. Values used in this study were as follows; density and heat capacity c_p of both elements were $0.54 g/cm^3$ and $1.37 J/g/K$, respectively. Thermal conductivities of the 'spring wood' and the 'summer wood' were 1.07×10^{-3} J/cm/s/K and $1.04\times10^{-2} J/cm/s/K$, respectively.

Temperature profile in a composite material was calculated from the following equation.

$$\rho c_p(\partial T/\partial t) = \lambda(\partial^2T/\partial x^2+\partial^2T/\partial y^2).$$

where T, t, x, and y are the temperature, time, distances from the origin normal and parallel to the surface, respectively. The origin of coordinates was located at the center of the 'summer wood' surface. Thermal conductivity varies according to the material at the location. For composite A, B and D, there was no difference along layers, so calculation was reduced to one-dimensional one. For composite C, two-dimensional calculation was done for one set of a half of a 'summer wood' layer and a neighboring half of a 'spring wood' layer. This set was considered to represent the whole body.

A composite material was assumed to be semi-infinitely thick, and initially there were no temperature difference in the material, i.e. $T=T_0$ at $t=0$, where T_0 is room temperature. The boundary condition after exposure to the thermal radiation($t>0$) is given as

$$\lambda(dT/dt)_s + \rho c_p(\Delta T/\Delta t)(\Delta x/2) = \varepsilon\sigma(T_f^4-T_s^4)$$

at the surface. The first and the second terms of the left hand side are the heat conducted into the material and heat consumed at the surface. The right hand side represents the net heat flux from the external heat source. Temperature of the external heat source T_f was assumed to be constant while the material was exposed to radiation.

3. RESULTS AND DISCUSSIONS

3.1 Effects of Layered Structure

Typical surface temperature histories of composite A and B and fir, of which the surface is along the layer, are shown in Fig. 2. In this case, the initial external heat flux and the surface emissivity were assumed to be $0.5W/cm^2$ and 0.8, respectively. Surface temperature of all materials approached gradually to a certain value. This phenomenon was attributed to development of thermal boundary layers in the materials. Thermal boundary layers extended to more than four layers until t = 1 min for composite A and B, so the effective thermal diffusivities in the boundary layers approached to the same value, i.e., the thermal diffusivity of fir. Therefore, effective thermal properties of them became closer as time passed. However, there is a significant difference between composite A and B in required time to reach at a certain temperature, e.g. 400 K. This difference in transient phenomena may play an important role in flame retardation.

3.2 Effects of Heat Flux Direction on Thermal Behavior of Layered Materials

Surface temperature histories of composites B and C and fir, of which the surface is across the layers, are compared in Fig. 3. In the case of the composite C, there was temperature variation along the surface as shown in Figs. 4a and 4b. The highest and the lowest temperatures are shown in Fig. 3. The temperature difference between the highest and the lowest temperatures was about 35 K throughout the time period shown in this figure. For t<50sec(1st period), the highest temperature was larger than the surface temperature of composite B, and became lower for t>50sec. If the highest temperature of composite C in the first period was larger than the ignition point, ignitability of composite C is larger than composite B, and vice versa. Thus result shown in Fig. 4 should be important to evaluate ignitability of a material. Also, it should be noted that the highest temperature for composite C is always higher than the surface temperature of fir.

3.3 Effects of Overlay Thickness

Surface temperature histories of composite D with various overlay thickness are shown in Fig. 5. It is seen that the use of an overlay having larger thermal conductivity than the main body would decrease the surface temperature drastically. Thickness of the overlay need not to be large for reducing the surface temperature, 1 cm is thick enough in the case shown in this figure. Usage of a material with larger thermal conductivity as an overlay would be more effective in flame retardation.

4. CONCLUSIONS

An effective use of composite materials were investigated by using analytical models. Comparison of surface temperature histories for composite A, B and C showed that the composite B was most effective in the early period(t<50sec), and the composite C was most effective in the rest period for reducing the surface temperature. In the case of composite C, however, there should be a mechanical weakness in practice. In this study, the surface temperature for the composite D was the lowest. If the proper material was used as an overlay, surface temperature could be reduced much more. The results obtained throughout this study suggests that there is a possibility to accomplish flame retardation without chemical treatment.

REFERENCES

1. Wang, Q.A., Shen, H., Xu, X.D., and Wang, H.H., "Characteristic fire damage of trees in a forest fire", University of Science and Technology of China, 1989(to be published).
2. Ishihara, S., "Researches on retardation mechanisms of wood", Oral presentation at the 10th meeting of the groupe on fire control mechanisms(September, 1988).
3. Kanury, A.M. and Blackshear, P.L., Jr., Combustion Science and Technology, 1, 339-355(1970).

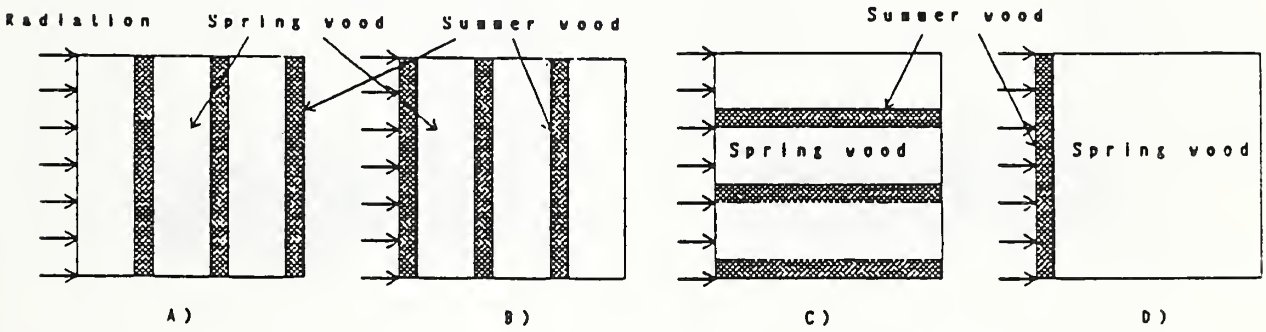


Fig. 1 Schematic illustration of model composites.

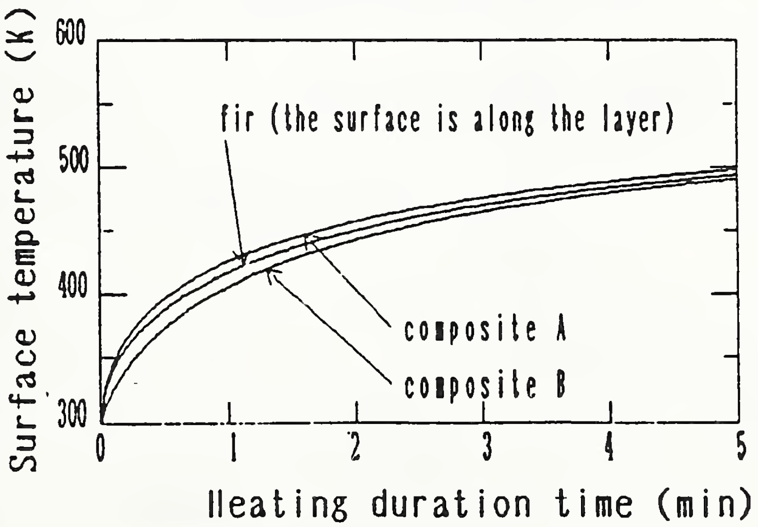


Fig. 2 Surface temperature histories of composites A and B, and fir.

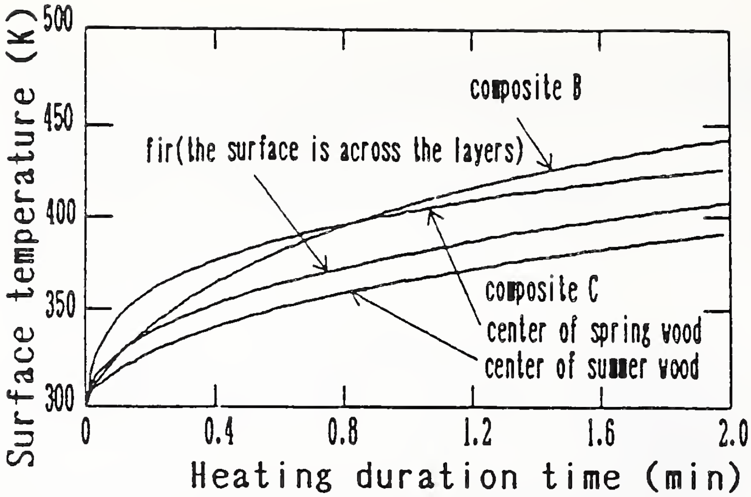


Fig. 3 Surface temperature histories of composites B and C, and fir.

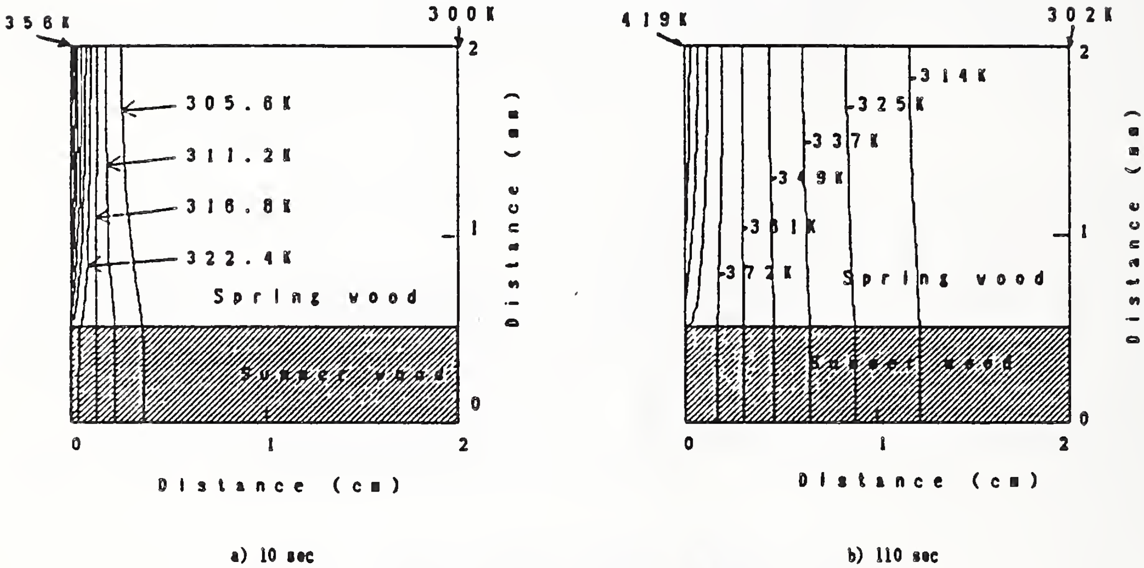


Fig. 4 Temperature contours in composite C.

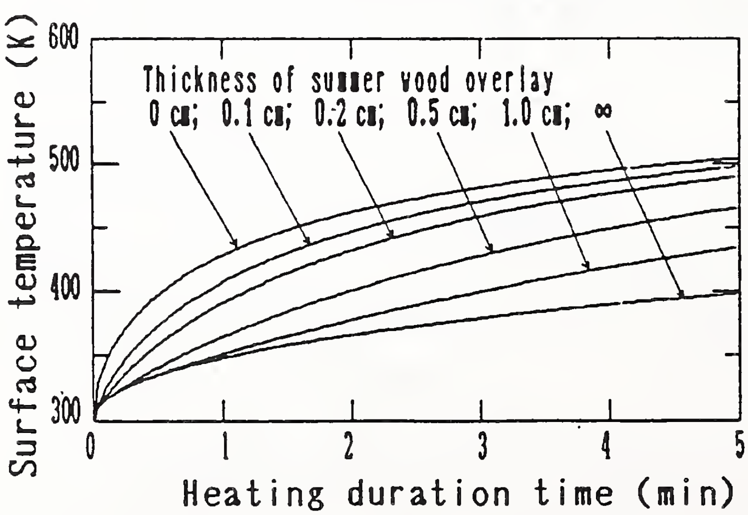


Fig. 5 Surface temperature histories of composite D.

EFFECTIVENESS EVALUATION OF EXPENSE FOR LOSS PREVENTION*

TOSHISUKE HIRANO
Professor
The University of Tokyo
Bunkyo-ku, Tokyo 113, Japan

SUMMARY

A study has been performed to establish a desirable procedure to evaluate effectiveness of the expense for loss prevention. The losses are divided into two categories, direct and indirect losses, and the sum of the indirect losses, each of which is scarcely predictable, is assumed to be inferable based on that of direct losses. The region to be under the influence of a disaster is divided into sub-regions, and an expected value of each direct loss is considered to be given by a product of the probability of disaster occurrence, the function relating a hazard degree to damage, and the cost of an object in the sub-region. The proposed procedure is attempted to apply for effectiveness evaluation of the expense for loss prevention against fires of large scale oil storage tanks, and the problems to be solved are pointed out.

INTRODUCTION

When a possibility to occur a disaster has been predicted, enormous efforts would be made to prevent the disaster or to reduce the loss to be caused. To make such efforts successful, various types of methods have been applied. However, there are few attempts to evaluate effectiveness of the method that they adopted or to examine the inter-relation of different types of methods for reducing losses to be caused by the same disaster. Thus, in the present situation, it seems not easy for engineers in process industries to evaluate effectiveness of a newly developed or improved method for loss prevention or to recommend a best combination of the methods.

In spite of the difficulty, a general and objective procedure to evaluate effectiveness of the expense for loss prevention is necessary because the expense should be supported by a logic similar to that for other economical activities[1-3]. We have to make efforts to establish such a procedure, although a long time will be necessary and an established one will not be realized in near future. The present study is of a preliminary stage of the efforts, but the results will be meaningful to establish an appropriate procedure for the effectiveness evaluation of the expense for loss prevention.

---

* To be presented at the International Conference on Safety and Loss Prevention in the Chemical and Oil Processing Industries; 23rd to 27th October 1989; Singapore

POSSIBILITY OF EFFECTIVENESS EVALUATION BASED ON PROCEDURES CURRENTLY USED FOR HAZARD ASSESSMENTS

For the adoption of a particular method for loss prevention, a comprehensive reason to support the method seems to be needed, and a hazard assessment would have been carried out instead of an effectiveness evaluation. Indeed, if it is possible to quantitatively evaluate hazards of every matters, the difference of hazards for the cases with and without application of the method for loss prevention can be elucidated, and effectiveness evaluation of the expense for loss prevention seems possible in principle. Thus, in the following part of this section, discussion will be presented on the possibility and limit of application of several currently used procedures for hazard assessments to effectiveness evaluation of the expense for loss prevention.

There are a few types of experimental methods for hazard assessments, such as property measurements, tests for examining characteristics, model experiments of accidents[1,4]. Each of the material properties such as flash temperature, ignition temperature, and minimum ignition energy can give a measure for hazard classification. The values of these properties are useful to compare the effectiveness of a method with that of a similar one. It may be easy to understand that keeping the material temperature below - 20 C is more effective for preventing fires than keeping it below - 10 C. However, the values are useless for the comparison with a method of a different type. On the basis of only the material properties, it is impossible to compare the effectiveness of the action to keep the material temperature below - 10 C with that to wear electrification free clothes in the room. For effectiveness evaluation of the method for loss prevention, the reduction of the expected loss attributable to adoption of the method should be evaluated. Only the material properties cannot give any conclusion on effectiveness of the expense for loss prevention.

The hazard assessment of an equipment, apparatus, or system has been performed on the basis of the results of tests for examining its characteristics. In a case when a part of the equipment, apparatus, or system is improved for loss prevention, the reduction of hazard degree may be predictable somewhat qualitatively by elucidating the resulting change of characteristics. However, in the case when an equipment is replaced by other one, the variation of effectiveness would not be predictable unless a unified procedure for hazard assessments is established. Several steps seem necessary between the tests for examining the characteristics and prediction of the expected value of loss, but so far discussion on these steps has never been heard.

Model experiments of accidents can be performed when an approximate process of the accident is known. This procedure for hazard assessments would relate to the effectiveness evaluation by exploring the difference of occurrence probabilities of or damages caused by accidents at the cases with and without application of a method for loss prevention. For applying this procedure, even if the result is a relative one, a number of elaborate experiments are needed. The purpose of the model experiments is not to evaluate the effectiveness of the method for loss prevention but to ascertain the cause or process of a particular accident.

Phenomenological analyses such as simulations and analyses of accidents and safety analyses such as FMEA, MORT, and FTA are theoretical procedures currently used for hazard assessments.

In the phenomenological analyses, the process of disaster occurrence should be assumed[4]. In order to relate each of these procedures to the effectiveness evaluation, the effect of the adopted plan for loss prevention on various phenomena during the process should be predicted. The prediction of the changes of various phenomena, as will be discussed in the later sections, is indispensable to evaluate the effectiveness and the most important process for it. The phenomenological analyses currently used for hazard assessments have been scarcely applied for the prediction of the changes of phenomena because of their purpose to elucidate the process of disaster occurrence. However, with each procedure of this type, comparison of hazards at various conditions can be easily carried out, i.e., the effectiveness evaluation is possible.

The safety analyses have been mainly performed for prevention of accident occurrence[5,6]. A procedure of this type would be convenient to the evaluation of the probability of accident occurrence and applicable to the effectiveness.evaluation. However, there have been few examples of suitable applications of a procedure of this type.

As mentioned above, currently used procedures for hazard assessments are for detecting hazards so that there have been few attempts to apply a procedure for hazard assessments to the effectiveness evaluation. Probably, perceiving that the hazard assessments are still needed much improvement prevents the procedures for the effectiveness evaluation from developing. However, the hazard assessments and effectiveness evaluation are different in the purpose and should be developed at the same time.

THEORY FOR EFFECTIVENESS EVALUATION

For effectiveness evaluation of the expense for loss prevention, it is necessary to estimate the expected value representing the reduction of loss attributable to the adopted method(s)(or plan). The evaluation will be effective for the following processes:

i) To select an optimum method among candidates for reduction of loss.
ii) To compare the expected reduction of loss attributable to a method to be adopted with the expense for the method.
iii) To decide the method to be adopted and timing to apply it for reduction of loss caused by a particular equipment, apparatus, or system.

Therefore, the effectiveness evaluation should keep the following characteristics:

a) To quantitatively infer the effects of the method for reduction of loss.
b) To compare the effects of the method for reduction of loss with the expense to adopt it(minus the reduction of expense if any).
c) To evaluate the change of hazard with time and/or circumstances.

These characteristics imply that by applying the effectiveness evaluation one can relatively and, if possible, absolutely evaluate the effectiveness of every type of methods for loss prevention in an amount of money. The evaluation should be general and quantitative.

It can be assumed that effectiveness of the expense for loss prevention can be expressed by the extent(practically an expected value) of loss reduction attributable to the expense. Thus, the effectiveness cannot be evaluated unless the expected loss to be caused by the disaster is accurately estimated.

Assuming that L is the sum of losses expected to be caused by a certain disaster, L can be given by the sum of the expected values l_1, l_2, $l_3 \cdots\cdots\cdots l_n$ of various types of direct and indirect losses, i.e.,

$$L=\sum_{k=1}^{n} l_k \tag{1}$$

The losses are not only those caused by fracture of equipments, apparatus, systems, and buildings, damages on raw materials and products, injuries, and fatalities but also those caused by wide range of effects such as the stop of operation of the plant broken at the disaster, reduction of products, control or stop of operation of the plants in own and relating companies, control or stop of traffic near the site of the disaster, increase of the insurance rate, and reduction of social confidence.

For an accurate evaluation of L, it is necessary to evaluate all conceivable losses. Since the indirect losses will be estimated on the basis of the direct losses, the latter ones should be estimated first. Thus, in the following, the direct losses will be attempted to estimate, and then based on the results, the effectiveness evaluation will be attempted to perform.

It seems not easy to classify the losses into direct and indirect ones. In the present study, the direct losses are defined as the losses caused by fracture of equipment, apparatus, systems, and buildings, damages on raw materials and products, injuries, and fatalities. Although the indirect losses are known to depend on the actions after the accident, they can be given as a function of the direct losses assuming appropriate actions.

An expected value of a loss l_k of a certain type can be assumed to depend on the value v_k of the object at a sub-region under the influence of the disaster(or accident), hazard degree h_k at the sub-region, and probability p of the disaster occurrence, i.e.,

$$l_k=p\cdot\alpha_k(h_k)\cdot v_k \tag{2}$$

where, $\alpha_k(h_k)$ represents the ratio of the lost value to original one.

The meaning of ak would be seen by supposing the situation that only one object is valuable in a sub-region. Assuming that the object completely loses its value at h_k above h_c and it keep its whole value at h_k below h_c, α_k is given as

$$\left.\begin{aligned}\alpha_k(h_k)&=1 && h_k>h_c\\ &=0 && h_k\leqq h_c\end{aligned}\right\} \tag{3}$$

Assuming that $l_1, l_2, \cdots\cdots\cdots l_l$ are direct losses and $l_m, \cdots\cdots\cdots l_n$ are indirect losses, then

$$L=p\cdot\sum_{k=1}^{n}\alpha_k(h_k)\cdot v_k=p\cdot\sum_{k=1}^{l}\alpha_k(h_k)\cdot v_k+p\cdot\sum_{k=m}^{n}\alpha_k(h_k)\cdot v_k=L_d+L_i \tag{4}$$

where, L_d and L_i are respectively, the sums of direct and indirect losses, i.e.,

$$L_d = p \cdot \sum_{k=1}^{l} a_k(h_k) \cdot v_k \tag{5}$$

$$L_i = p \cdot \sum_{k=m}^{n} a_k(h_k)\, v_k \tag{6}$$

The probability p of disaster occurrence should be predicted by a system safety analysis or disaster stochastics, and the values of the objects and persons can be predicted on the basis of daily operation and living. Also,

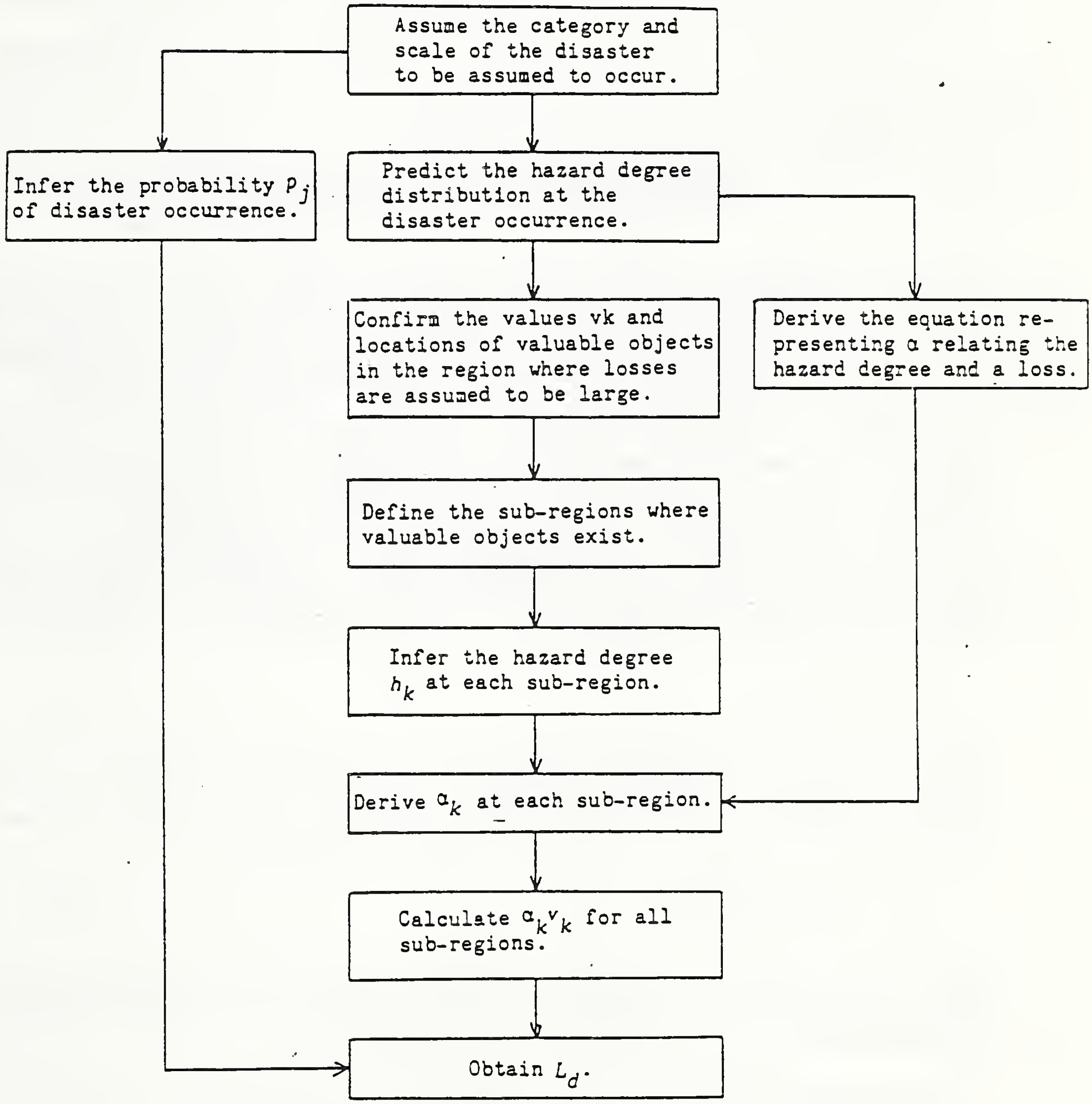


Figure 1. Procedure to evaluate an expected value of the sum L_d of direct losses.

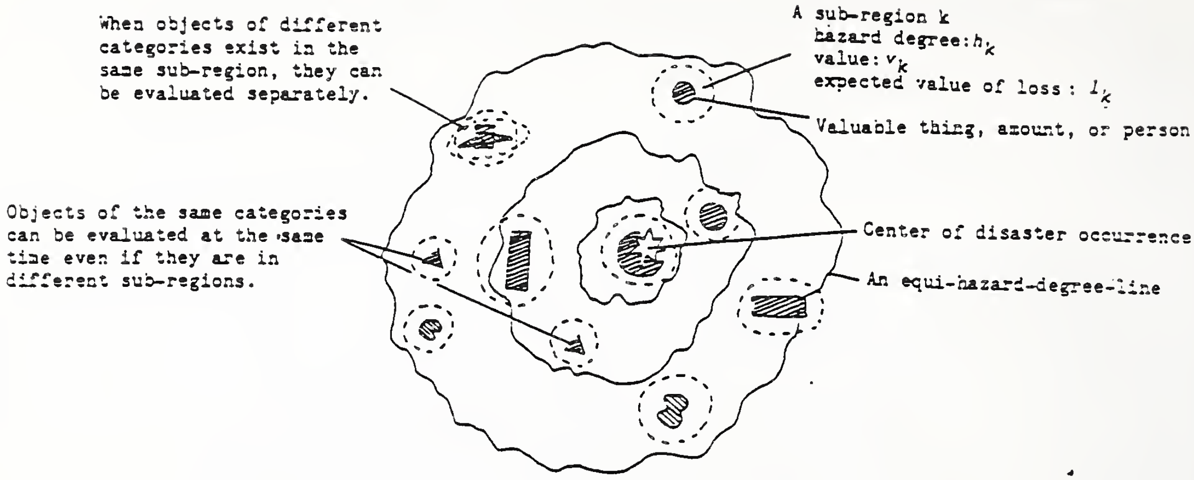


Figure 2. Distributions of hazard degree, valuable thing, amount and person, and determination of the sub-regions for effectiveness evaluation.

$\alpha_k(h_k)$ can be easily predicted from the predicted value of h_k if the endurance of the object(person, thing, or amount) to be discussed against hazard is known. Based on these facts, the procedure to predict L_d is presented in Figure 1, when a disaster occurs at the situation shown in Figure 2.

As shown in Figure 1 or Eq. 5, the values of p, $\alpha_k(h_k)$, h_k, and v_k or equations to predict these values are necessary to evaluate the sum of direct losses. If any one of them can not be obtained, the evaluation is impossible. The method effective for loss prevention means to be effective for reduction of one of these losses. A meaningful method for loss prevention is of benefit to the organization to adopt it[2,3]. Thus, the method, by adoption of which the benefit cannot be expected or is too small, will be ignored. If the method action does not satisfy the following equation,

$$\Delta C < \Delta L \tag{7}$$

where ΔC and ΔL represent the increase of expense and reduction of expected loss by adopting the method, respectively, the action does not make sense[1]. Further, when the ratio of the total reduction ΔL_d of direct losses to that ΔL_i of indirect losses is R, Eq. 7 can be rewritten as

$$\Delta C < \left(\frac{1+R}{R}\right)\Delta L_d \tag{8}$$

This indicates the limit to adopt the method for loss prevention. The following discussion is performed assuming that the relation expressed by Eq. 8 is satisfied.

The methods to reduce the probability p of accident occurrence can be easily pointed out by safety analyses. The discussion to reduce p has been presented in a number of previous reports[1-4]. In the present study, the emphasis is on the fact that the reduction of L_d is proportional to the reduction of p.

There are two different kinds of methods for reducing the hazard degree h_k, i.e., the methods for reducing the hazard degree of a whole region where damage will be suffered at the occurrence of a disaster and those of a limited region. It is easily seen that the former methods are effective to reduce L_d. The latter methods are sometimes more elaborate than the former ones, but by adopting them mainly for regions where expensive objects exist, a large reduction of L_d must be expected at the same amount of expense.

$\alpha_k(h_k)$ is a function of h_k. The function is not necessarily in the form as represented by Eq. 3, but in most cases, ak(hk) rapidly changes as h_k approaches a certain value (h_c in the case represented by Eq. 3). This fact implies that an method for reduction of h_k is not effective in a certain range but very effective in another range even if the reduction is slight.

The method to reduce v_k in the vicinity of the site of disaster occurrence is effective like that to reduce p. When a disaster is predicted to occur, the method for making v_k at that site zero, if it is possible, is perfect for loss prevention. Practically, the prediction of disaster occurrence is not easy, and in most cases, vk becomes a fairly large to keep daily operation and living even if the disaster is predicted likely to occur.

In the above discussion, a disaster to occur is assumed a specified one. However, the scale of the accident cannot be predicted in most cases, and in most cases, the method to be performed is effective for a particular type of disasters. Assuming that a certain type of disasters are predicted to occur but their scales are ambiguous, there remain ambiguities on the hazard degree at disaster occurrence. When the ambiguities can be represented by a probability distribution $p_j(h_{kj})$(p in Eq. (2) is equal to $\int p_j dh_{kj}$), Eq. 5 is replaced by the following equation.

$$L_d = \sum_{k=1}^{l} v_k \int_{h_{kj}} p_j \alpha_k \, dh_{kj} \tag{9}$$

For different types of disasters, the expressions of h_{kj} and equations representing the dependence of α_k on h_{kj} would be different. However, for

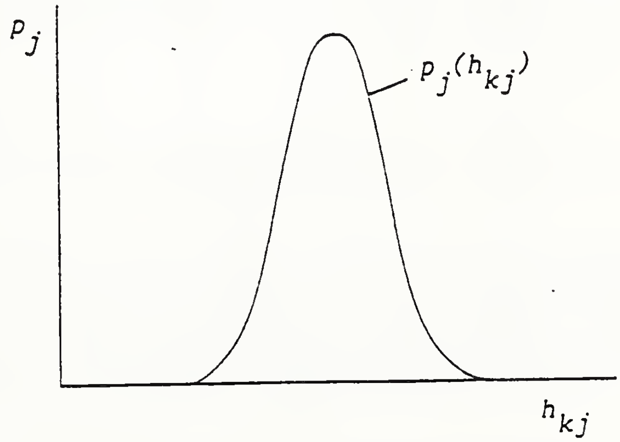


Figure 3. An example of the variation of probability p_j with hazard degree h_{kj}.

each type of disasters, the direct losses should be inferred in similar procedures. The expected value of the sum of losses caused by a disaster is the sum of all expected values of losses and can be evaluated by estimating individual expected values of losses caused by different types of accidents and adding them.

Assuming that the valuables, instead of discretely located objects, are distributed in a domain S, Eq. 9 is replaced by

$$L_d = \int_s v'_k dS \int_{h_{kj}} p_j \alpha_k \, dh_{kj} \qquad (9)'$$

where v'_k is a function representing the value distributed in S.

The effectiveness evaluation of the expense for loss prevention can be performed by predicting the difference ΔL_d of L_d with and without the proposed method.

For the prediction of the dependence of p_j on h_{kj}, a stochastic safety analysis, phenomenological analysis, or disaster statistics is needed. Available data are few at present but expected to be accumulated in near future because of their importance.

If the phenomena concerning disasters to occur are assumed, h_{kj} can be predicted, and the method for numerical expression of hazards will be used[2,3]. The hazard degree H in previous studies can be expressed by p_j and h_{kj} as follows:

$$H = \int_{h_{kj}} p_j h_{kj} dh_{kj} \qquad (10)$$

α (h_k) depends on the characteristics of objects under evaluation of their losses caused by disasters, and the loss evaluation is possible if the dependence of each loss on causative phenomena (fire radiation, blast wave pressure, vessel pressure, smoke toxicity, projectile behavior and so on) is

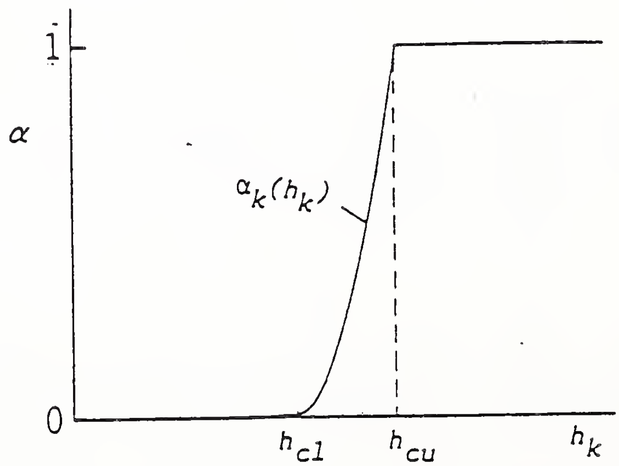


Figure 4. A typical variation of α with h_k.
h_{cl} : the lowest value of hk in the range where a changes.
h_{cu} : the highest value of hk in the range where a changes.

known. The dependence is generally expressed as shown in Figure 4(The most simple example of it was shown in Eq. 3). Such a dependence can be easily inferred on the basis of a number of presently available data.

Since v_k is the value of each object, it can be easily evaluated. Importance is to re-evaluate whenever any one of equipments, apparatus, and operators is changed.

APPLICATION OF THE PROCEDURE TO THE EFFECTIVENESS EVALUATION OF THE EXPENSE FOR LOSS PREVENTION AGAINST OIL RESERVOIR TANK FIRES

In order to apply the procedure proposed in the previous section to effectiveness evaluation of the expense for loss prevention in a practical case, one should overcome a number of difficulties and would need a plenty of time and elaborate efforts. Probably such a situation is a reason why there are so few examples of the effectiveness evaluation. This section presents the results of the attempt to apply the proposed procedure to a few examples concerning loss prevention methods against oil reservoir tank fires.

The distance between oil reservoir tanks has been frequently discussed in the process for evaluating or confirming the safety of the dangerous goods reservation. The increase of the distance has been considered to be effective to prevent the neighboring tanks from ignition. In this case, the imagined disaster is a tank fire, and the losses to be evaluated can be assumed to be the loss l_1 due to the burning or contamination of oil in the tank at fire occurrence, that l_2, due to the destruction of the tank, that l_3 due to the burning and contamination of oil in neighboring tank(s), and that l_4 due to the destruction of neighboring tank(s).

l_1 and l_2 cannot be reduced by increasing the distance, so that the losses to be estimated for evaluating effectiveness of the expense to increase the distance are l_3 and l_4. For the evaluation of 13 and 14 needed are the probability p_j of occurrence of an oil tank fire, hazard degree(s) h_{kj} $(k=3,4)$ at the location(s) of neighboring tank(s), the value v_3 of oil in neighboring tank(s), and that v_4 of the neighboring tank(s), when the fire intensity, tank scale, and oil properties are fixed. α_k needed for the evaluation is inferred on the basis of h_{kj}. In this case, h_{kj} can be assumed to correspond to the accumulation of the intensity $\dot{q}_k''$ of radiation at the location(s) of the neighboring tank(s), i.e.,

$$h_{kj} \doteq \int \dot{q}_k'' dt \qquad (11)$$

If the value of hkj is above that sufficient to ignite oil in the neighboring tank being evaluated, $\alpha_k = 1$, and otherwise, $\alpha_k = 0$.

The frequency of tank fires of a certain scale and specified kind of oil is very small. Consequently, available data are too few to infer reliable values of p_j. Therefore, I would recommend to use the values of pj inferred on the basis of the whole tank fires. Thus, although there are problems on the inference of p_j and efforts must be needed to infer α_k, the effectiveness evaluation will be possible.

A system for extinguishing fixed at a tank has been adopted to reduce the losses to be caused by a tank fire. Its purpose is the same as that of the tank distance discussed above, but the functions of these two are quite different. This system is considered to be effective for suppression of a tank fire growth, especially at its initial stage. On the similar discussion as the tank distance, the losses to be estimated are not l_3 and l_4, but l_1 and $l_{2,}$.

Since the system is effective for suppression of fire growth, the distribution of p_j on Figure 3 should shift to smaller values of h_{kj} (k=1,2). In this case, α_1 must be given as an equation representing the damage due to contamination of oil as well as that due to burning. Both p_j and α_1 are not easy to estimate, so that an appropriate evaluation of effectiveness of the system for loss prevention seems extremely difficult. However, it can be pointed out that adoption of the system shifts the distribution of p_j and reduces largely the damage.

When a system for extinguishing is not fixed, it is effective to suppress both fire growth at a tank and fire transfer to neighboring tanks. For effectiveness evaluation of this system, l_1, $l_{2\cdot}$, $l_{3\cdot}$, and l_4 should be predicted. α_k (k=1,2,3,4) and p_j, which depend on the ability and characteristics of the system, are also not easy to estimate.

The number and abilities of firemen are known very important for loss prevention against oil reservoir tank fires, but so far very few attempts has been done to find optimum number of firemen and/or optimum level of their education. For such an attempt, which will give us the most effective expense for loss prevention, effectiveness evaluation must be needed.

To find out an appropriate combination of the methods for reducing the losses caused by oil reservoir tank fires, effectiveness evaluation for all the candidates as discussed above. Since v_k, h_{kj}, p_j, and α_k depend on the situation of the objects at a disaster under consideration, the combination should depend on the factors to influence the situation, i.e., not unique. Some factory is at a site very close to a city. For effectiveness evaluation of the expense for loss prevention at such a factory, the distribution of a large values of v_k should be assumed in the region outside of the factory. This situation is quite different from that of a factory in countryside. Similar discussion can be done on maintenance, economic policy, and so on.

I believe the importance of effectiveness evaluation of the expense for loss prevention and recommend to attempt the procedure discussed throughout the present study. Also, I encourage to develop a novel concept for the effectiveness evaluation and to accumulate available data.

REFERENCES

1. Hirano, T.,"On Hazard Assessments Concerning Oil Reservoir Tank Fires," Saigai-no-Kenkyu, 19, 269(1988).
2. Hirano, T.,"Basic Concept of Safety," J. Japan Security System Association, 11, 9(1988).
3. Hirano, T.,"A Theoretical Approach to Hazard Assessments," on preparation for submission.
4. Hirano, T.,"Technology for Prevention of Gas Explosions," Kaibun-do, Tokyo (1983).
5. Hammer, W.,"Occupational Safety Management and Engineering," 2nd Ed., Prentice-Hall, London(1981).
6. Inoue, T., ed.,"FTA Safety Engineering," Nikkan-Kougyou, Tokyo(1979).

A PERFORMANCE BASED DESIGN METHOD FOR FIRE SAFETY OF BUILDINGS

Takeyoshi TANAKA
Building Research Institute, Ministry of Construction
1 Tatehara, Tsukuba-shi, Ibaraki-ken 305, JAPAN

1. INTRODUCTION

Traditionally, fire safety measures of buildings have been determined based on the prescriptive specifications in building and fire codes. One of the most important reasons of this may be that the progress in fire research has been too slow to keep abreast with the rapid evolution of building technologies, which have continued to produce unconventional buildings and new type of dangers due to fire as a by-product. Every time a serious fire disaster occurred, new provisions were added in these codes mostly based on the empirical judgments of "so-called experts", but old provisions were rarely eliminated even after they have already become out-of-dated. The results were the multiplication and the illegibility of the rules, the increase in the cost for fire protection, the inflexibility in designing of building etc. It has long been noticed by many fire interests that it will be much more difficult than ever to cope with the increase of scale, complexity and diversification of modern buildings by the conventional method, that is, the addition of prescriptive specifications.

Considering such circumstances and the considerable progress achieved recently in the area of fire science and engineering, the research project called "Development of Fire Safety Design Method of Buildings" was launched in Fy 1982 and carried out through Fy 1986 by Building Research Institute (BRI), Ministry of Construction (MOC) of Japan in an attempt to establish a performance based fire safety design method of buildings. The final report of this study has recently been published and the way to use this method in the design practice is now being explored among BRI staff and MOC administration. In this text, this design method is briefly outlined.

2. STRUCTURE OF THE FIRE SAFETY DESIGN METHOD

It is said that the present Building Standard Law of Japan has the following characteristics:
- it has nature of a public law, in other words, it control buildings with compulsory power,
- it provides technical standards,
- it prescribes minimum requirements,
- it operates through a system of certification for legal conformity by building authorities.

The "Fire Safety Design Method" is designed to provide minimum technical standards in the form of performance standards on the assumption that it operates in the same administration system as that of the Building Standard Law. The structure of "Fire Safety Design Method" is illustrated in Figure 1, making comparison with that of fire safety provisions in Building Standard Law.

(i) The ultimate objective

The first article of the Building Standard Law states that its ultimate goals are life safety, property protection and public welfare. Since the Fire Safety Design Method is intended to give an alternative to the fire safety provisions of the present Building Standard Law, the both of the two must share the same ultimate goals.

(ii) The safety level of technical standards

From the nature of the Fire Safety Design Method as an alternative to the Building Standard Law, which is compulsory, the level of fire safety achieved through its technical standards must be minimum.

(iii) Fundamental Requirements for Fire Safety

As for the fundamental requirements for fire safety measures of buildings, Article 35 of the Building Standard Law states that buildings must be so constructed and maintained that any hindrance is avoided with respect to evacuation safety, fire prevention and fire fighting. Since this statement is too inclusive and abstract to derive directly technical standards from it, the fundamental requirements of the Fire Safety Design Method are redefined more explicitly as follows:

(1) Requirements for Fire Safety as an Individual Building
(1.1) Precaution against outbreak and rapid spread of fire
(1.2) Assurance of life safety
  (a) Control of building materials which may cause serious hindrance to evacuation in the event of fire
  (b) Proper evacuation plan
  (c) Assurance of safe refuge
  (d) Assurance of safe egress routes
(1.3) Prevention of serious nuisance to the third parties
  (a) Prevention of fire spread to buildings or a part of buildings owned by third parties
  (b) Prevention of collapse of buildings
  (c) Assurance of reusability of buildings of multi-ownership
(1.4) Assurance of activities of fire brigades
  (a) Assurance of activities for search and rescue of occupants
  (b) Assurance of fire fighting activities

(2) Requirements for Prevention of Urban Fire

The requirements for fire safety as an individual building apply for any building which is elected on the territory of Japan, while those for prevention of urban fire apply only for buildings in fire prevention districts, which are designated in the context of each city planning.

(iv) Technical standards

Most of the technical standards for fire safety in the Building Standard Law, its enforcement orders and the related Ministry of Construction orders are given in the form of prescriptive specifications, in other words, they directly specify materials, dimensions, construction methods, equipments etc. of various elements of buildings. On the other hand, in Fire Safety Design Method, attempts were made to establish the technical standards in terms of performance standard as long as possible and beneficial. It should be kept in mind, however, that any technical standard has more or less temporary nature. Unavoidably, they have to reflect the current conditions about building construction and currently available technologies and knowledges for fire safety. So, there is a possibility that effective fire safety measures which cannot be dealt with well by the technical standards in the Fire Safety Design Method are proposed by designers etc. Such measures can be accepted as well in Fire Safety Design Method as long as they are considered to satisfy the basic requirements.

(v) Support technologies

Several fire tests are almost the only technical sources integrated into the traditional system of building control for fire safety. In order to run a performance based system, however, it is indispensable that the system is equipped with some means to predict various aspects of fire behavior so that the compliance to the technical standards can be assessed as early as at the stage of planning. So, the Fire Safety Design Method is provided with relevant calculation methods and computer codes for this purpose.

3. FUNCTIONAL DESCRIPTIONS OF THE REQUIREMENTS

The fundamental requirements of which the items are mentioned in 2. (iii) are described as follows:

(1) Requirements for Fire Safety as an Individual Building
(1.1) Precaution against outbreak and rapid spread of fire

- Proper precautions against outbreak of fire must be paid in conformity with the prescriptions of the Fire Service Law and other relevant regulations.
- The use of such materials or products that may be easily ignited or that may cause extremely rapid fire spread by a trivial misdealing of ordinary heat source is prohibited as building elements.

(1.2) Assurance of life safety

(a) Control of materials or products that may cause serious hindrance to evacuation in the event of fire

- The materials which may cause extremely rapid fire spread or which may produce extremely toxic combustion products cannot be used as building elements at the parts of buildings important for occupants' evacuation in the event of fire.

(b) Proper evacuation plan

- The evacuation plan of a building must be such that the safety of all the occupants normally expected in the building can be assured.
- The evacuation plan must be realistic as one in real fire when considering the characteristics of the occupants, use, management, operation, geometry, system of fire detection and alarm etc.
- The evacuation plan must be effective no matter when a fire may break out while the existence of occupants is normally expected.

(c) Assurance of safe refuge

A building must secure for the occupants a refuge which is free from smoke, fire, collapse, breakage or any other danger due to fire.

- A refuge must be planned in a free space, such as public way, except when it is difficult to complete the evacuation to outside of the building within a reasonable time.
- More than one refuges can be planned so that the most proper one can be chosen depending on the location of the room of origin, provided that it

does not complicate the evacuation plan.

(d) Assurance of safe evacuation routes

- For any part of building which is frequented by the occupants in normal use, a continuous evacuation route to the refuge with proper capacity, geometry, materials and equipments must be provided for the evacuation of the occupants.

- Evacuation routes of a building must be so planned that no matter where the room of origin may be, as long as the possibility of fire occurrence in the space is not negligibly small, at least one safe evacuation route can be secured for any potential occupant normally expected in the building.

- Proper measures must be taken so that, in the part of building of which the loss due to fire may totally jeopardize the safe evacuation routes for the occupants, the possibility of outbreak of fire or the effect of fire to the occupants is made negligible.

- Any part of an evacuation route must be designed so that the occupants are kept free from smoke, heat, collapse, breakage and any other danger due to fire during the time of their evacuation.

(1.3) Prevention of serious nuisance to the third parties

(a) Prevention of fire spread to buildings or parts of a building owned by the third parties

- Proper measures must be taken so that a fire occurred in a part of a building does not spread to the buildings or the parts of a building which are owned by the third parties or of similar character.

(b) Prevention of collapse of a building

- A building must not collapse due to fire when this may cause serious nuisance to the third parties.

(c) Assurance of reusability of a building of multi-ownership

- A building of multi-ownership or of similar character must be reusable after fire.

(1.4) Assurance of activities of fire brigades

(a) Assurance of activities for search and rescue of occupants

- A building must provide proper means for safe and prompt search and rescue by fire brigades of occupants who might have failed to escape at early stage.

(b) Assurance of fire fighting activities

- A building must provide proper means for safe and effective fire fighting activities by fire brigades.

(2) Requirements for Prevention of Urban Fire

- The buildings elected in the zone designated in view of prevention of urban fire must have a performance to prevent fire spread to and from neighbor buildings to the extent that the purpose of the zone is satisfied.

4. TECHNICAL STANDARDS FOR THE CONFORMITY TO THE FUNDAMENTAL REQUIREMENT

Since the descriptions of the fundamental requirements given in the above are only qualitative, it is indispensable to provide to each of them the technical standards in order to make it possible to examine if a concrete design of a building satisfy the requirements. These standards must be established at a level acceptable to the interested society because the level of safety depends on how much cost the society is prepared to pay and also it is impossible to attain perfect safety. On this regard, the standards in a performance based design method should be so determined that the level of safety realized by the existing fire safety regulations can be reproduced, at least for the first time, because it is considered that this level is the easiest to be accepted by the society concerned.

The technical standards in the Fire Safety Design Method consist of specification standards and performance standards. The former type of standards still remain, to less extent than in the existing building codes, because there are some standards of which the conversion to performance is premature or not necessarily beneficial.

4.1 The performance standards

The performance based technical standards mentioned in the above are classified into the two types as follows:

(a) Standard fire conditions
(b) Standard safety criteria

In concept, these respectively correspond to design loads and allowable stress in structural design, which is already being carried out in performance based method. With these standards, a proposed fire safety design method is examined for the conformity to the basic requirements through the procedure illustrated in Figure 2 for the case of the design of evacuation routes.

To operate a performance based design method, the relevant means to predict the various aspects of fire are indispensable in order to evaluate the proposed fire safety measures at the stage of designing. The standard fire conditions are given as input data to such prediction methods and the results are compared with the standard safety criteria to judge if the proposed fire safety design is acceptable.

4.2 Character of the prediction methods

In general, it is very difficult to develop the prediction methods for complex objects as a building, whether the method may be for structural behavior or for fire behavior. Accordingly, it is inevitable that such prediction methods are considerably simplified in the course of modeling. In addition to this, fire scenarios considered in the assessment will have to be significantly simplified. And these simplifications make it difficult to evaluate the discrepancy between what is predicted to be necessary and what is actually needed. Fortunately, however, constructing buildings has long been almost an everyday practice of men, so, for ordinary buildings, we have considerable knowledge on what are needed for fire safety by experience. This saying may sound that theories are useless but does not mean it. Empirical knowledges work well only where the experiences exist. They are powerless when we try to adopt unconventional way of building. It can be said that theories are the pilot when we tread in an inexperienced field, such as when we try new designs or unconventional fire protection means.

In many engineering designs, since the theories and the conditions considered are considerably simplified, some adjustments are usually needed to compensate the discrepancy between theories and empirical knowledges. The safety factors in structural design(as large as 3 for buildings and sometimes 8 for civil engineering structure in Japan) may be a good example of this. This concept of the harmonization of theories and experiences is illustrated in Figure 3. Once we have managed to find how to adjust theories and experience for where our experience exist, we will be able to extend this to inexperienced region. In a strict sense, it is not validated that the same technique for the adjustment in the experienced region is still valid for an inexperienced region, but this will be the risk we have to accept in conjunction with the benefit we can enjoy by introducing unconventional designs or methods.

4.3 Meaning of technical standards

As mentioned in the above, the technical standards of performance based design method consist of (a) standard fire conditions and (b) standard safety criteria. It is possible to harmonize theories and experiences by adjusting the values of the former and/or the latter of them so that a necessary level of safety can be attained.

In this particular case of the Fire Safety Design Method, however, since the safety criteria for men or building elements, such as human endurance against heat, ignition temperature of materials can be better defined than the design fire condition, it will be a good idea to let the standard fire conditions bear the principal role of the harmonization.

The standard fire conditions consist of scenarios of fire as well as the size of fire and their meanings are illustrated in Figure 4, in which a fire condition is simplified as the size of fire. The solid curve stands for the conceptual relationship of the size of fire and the frequency(or probability) of the appearance of fire. According to the general characteristic of accidents, the frequency of the appearance of fire is high when the size is small, but decreases dramatically as the size increases. Needless to say, the larger the size of fire, potentially the more dangerous, but the level of danger depends also on the fire safety measures provided. Generally speaking, a space having better safety measures can cope with severer fire conditions. The essential significance of the standard fire condition is to keep the probability of the appearance of fire of the size which may cause serious danger to occupants or other objects below an acceptable level by means of demanding to provide fire safety measures needed in order to clear the danger represented by the standard fire condition. In other words, when the condition of the fire occurred happens to be severer than that of the standards, the safety is not guaranteed. If we want to increase the level of safety, we can do it by raising the standards, but often this is accompanied by the increase of fire cost. Therefore, the standard fire conditions must be so determined that the fire safety measures can be provided for an acceptable cost for the society and yet the society is not disturbed by the remaining risk.

5. THE TECHNICAL STANDARDS FOR EVACUATION SAFETY

The technical standards for a performance based design method need to be given by calculable or measurable values so that the conformity to the standards can be examined without ambiguity. Here, the technical standards for assurance of safe refuges and evacuation routes are outlined as an example of those of the Fire Safety Design Method.

5.1 Assurance of safe refuges

Traditionally, final refuges of occupants of buildings in the event of fire have been taken on public ways or some sites of equivalent character. In such places as public ways, people can escape freely whenever dangers due to fire become imminent, so virtually no check is necessary for the safety. Public ways and such will continue to remain as the most important refuges in future as well for most of the buildings.

Although considered to be rare, refuges may have to be planned on a building site having no outlet to public ways in conjunction with the plan of the evacuation routes within the building. This type of refuges need check for safety against certain potential dangers from the buildings under fire.

As for refuges within buildings, we have not ample experience, yet in case of buildings which cannot be evacuated in reasonable time for some reasons, for example, high-rise buildings and hospitals, there may be cases where securing refuges within the buildings or protecting some parts of a building so as to be practically used as refuges are a better solution. In such a case, however, a sufficient level of safety must be assured against any conceivable hazard due to fire, which may attack the refuge through open air as well as through indoor spaces. The potential causes of danger for evacuees staying in a refuge consist of smoke, heat, air contamination, structural collapse etc. as shown in Figure 5.

The standard fire conditions for safe refuges are summarized in Table 1. In principle, any space of a building must be considered as a potential room of origin. However, in order to save work in design practice, the spaces which meet the conditions given in Table 1 are exempted. In particular, if the designer of a building can find the space which gives the severest case, it follows that it is the only space that must be considered as the room of origin in the process of designing the refuge. In the room of origin, a fully developed fire is assumed and the existence of sprinkler is ignored. The area of fire is limited within a compartment adequately enclosed by fire resistant walls. This implies that compartmentation of buildings becomes to be one of the safety measures for refuges because this reduce the impact of fire on refuges.

The standard safety criteria for refuges are determined to assure safety against each of the potential dangers to the evacuees in refuges as shown in Table 2. A couple of criteria were given for certain items so that designers can choose any of them according to their convenience.

5.2 Assurance of safe evacuation routes

Obviously, it is the evacuation routes that plays the most important role for the safety of occupants of the building in the event of fire. Naturally, in the existing building codes as well, stresses are given to the provisions on dimensions, materials, fire resistant ratings, exit signs, smoke control systems of the parts of buildings expected to function as evacuation routes. While the existing regulations directly give prescriptive solutions for evacuation safety, it is necessary for the establishment of performance standards to analyze the potential causes and mechanism of dangers due to fire on the occupants in the course of evacuation. As are shown in Figure 6, while the direct hazards for the evacuees are smoke, heat, collapse and breakage, it can be seen that the factors causing hindrance on the egress routes play an important role to induce or accelerate the direct dangers.
The standard fire conditions for the assurance of safe evacuation routes are

summarized in Table 3. The standards are given to evacuation routes in the room of origin, on the floor of origin and on the floor of non-origin for the clarity of designing. Any space must be considered as a potential room of origin unless exempted by the conditions shown in the table, but it is possible to reduce the number of spaces to be examined as in the case of refuges. The standard fires for evacuation in the room of origin and on the floor of origin are defined as illustrated in Figure 6. In sprinklered rooms, their maximum heat release rate is limited to the maximum rate which does not actuate the sprinkler heads, which is determined as a function of ceiling height, spacing and actuation temperature in case of ceiling mounted sprinklers. The standard fire for evacuation on the floors of non-origin is a post flashover fire of which the behavior is determined considering the ventilation condition of the room of origin.

As for the occupants conditions, the number of occupants in each space are calculated from the density of occupants specified according to the use of the space. The evacuation start time is taken as the shortest of the times at which occupants recognize the danger of fire by means of cues by smoke, other occupants and the detection and alarm system of the building.

The standard safety criteria concern with the allowable condition of the spaces which have to be protected against the potential dangers due to fire during the time of evacuation. In some cases, more than one solutions are given so that designers can choose the most convenient one.

6. AVAILABLE PREDICTION MODELS

A performance based evacuation safety design method of building is possible only when relevant prediction means for occupants' evacuation and smoke behavior are available. The followings are the computer models developed in our research project:

(a) Evacuation Model
This model predicts the numbers of occupants in each space and of crowdings at each opening on the designed evacuation routes at arbitrary time after the start of evacuation, assuming that occupants in each space start orderly movement of egress with uniform walk speed in the direction predetermined by the designer. The evacuation start time is given as input data for each of the spaces. This model agrees with the results of the field measurements of the evacuation times of an evacuation drill and the egress from several theaters in non-emergent condition within 10% of error(10).

(b) Smoke Propagation Models
Two computer models are currently available, that is:
- One layer zone smoke propagation model
- Two layer zone smoke propagation model

One layer zone model predicts the smoke propagation throughout a building assuming that smoke and air are uniformly mixed in each of the indoor spaces of the building. This model still remains as the most appropriate model when the behavior of smoke throughout a high-rise building or a large scale building need to be dealt with, although inadequate when we have to consider such a scenario as that occupants evacuate from a space involved in fire before the smoke layer descend to a hazardous level. The model can deal with transient as well as steady state flow of smoke(2).

Two layer zone model assumes an upper layer and a cold layer in each of the indoor spaces of a building. Theoretically, this model can deal with buildings with arbitrary number of floors, but considering the general behavior of smoke in tall buildings and the calculation time needed smoke filling in the room of origin, on the floor of origin, buildings with atriums etc. may be the most appropriate objects of the application of this model. At least for some simple geometries, the predictions by this model agree reasonably well with the full scale test results(3),(4).

In addition to these models, several simpler models, which are more or less limited in application but are thought to be still useful in design practices are also available(5),(6).

7. CONCLUDING REMARKS

For the establishment of a performance based design method for evacuation safety of buildings, the followings are considered to be of central importance:
- Availability of models for the prediction of occupants' evacuation and smoke behavior in building spaces. These do not have to be perfect. We should develop the design method taking into account their limitations.
- The objectives of fire safety measures of buildings must be clearly defined. Life safety is the objective common for all the societies, but property protection and prevention of urban fire depend.
- The requirements to the fire safety measures of buildings for achieving the objectives must be defined.
- The technical standards must be given in calculable or measurable forms so that wether or not the requirements are satisfied can be examined by designers, building official etc without ambiguity.
- The technical standards should be so determined that the level of safety attained through the standards becomes equivalent with that realized by the standards prescribed in the existing codes, at least for the first step. In future, the level of safety might be more rationalized taking into account the probabilistic aspects of fire.
- The design method must be sufficiently logical and simple so that it can be dealt with by designers, building officials etc. without causing excessive work load.

REFERENCES

(1) Takahashi,K. and Tanaka,T.:"An Evacuation Model for The Use in Fire Safety Designing of Buildings", NBSIR 88-3753, NBS, April 1988.
(2) Matsushita,T.and Terai,T:"Calculation of Smoke Movement in Case of Fire", Proc. of the first int'l symp., Fire Safety Science, 1985.
(3) Tanaka,T. and Nakamura,K.:"Refinement of A Multiroom Fire Spread Model", Proc. of the 1987 ASME/JSME Thermal Eng. Joint Conf.-Vol.1, Hawaii, 1987.
(4) Nakamura,K.:"Predicting Capability of A Multiroom Fire Model", NBSIR 88-3753, NBS, April 1988.
(5) Tanaka,T. and Yamana,T.:"Smoke Control in Large Scale Spaces-Part 1: Analytic Theories for Simple Smoke Control Problems", Fire Science and Technology, Vol.5, No.1, 1985.
(6) Yamana,T. and Tanaka,T.:"Smoke Control in Large Scale Spaces-Part 2: Smoke Control Experiments in A Large Scale Space", ditto.

	BLDG. STANDS. LAW	FIRE SAFETY DESIGN METHOD
Ultimate Goals	a) Life Safety b) Property Protection c) Public Welfare	a) Life Safety b) Property Protection c) Public Welfare
Level of Requirements	Minimum	Minimum
Principle for Fire Safety	Article 35 etc.	Fundamental Requirements for Fire Safety
Technical Standards	- Bldg. Stands. Law - Enforcement Orders - Minist. of Const. Orders (Specification Stands.)	(Performance Stands.) - Stand. Fire Condition - Stand. Safety Criteria (Specification Stands.)
Support Technologies	Fire Tests	- Fire Tests - Means of Fire Prediction - Computer Codes

Figure 1. The Structure of The Fire Safety Design Method in Comparison with the Building Standard Law of Japan

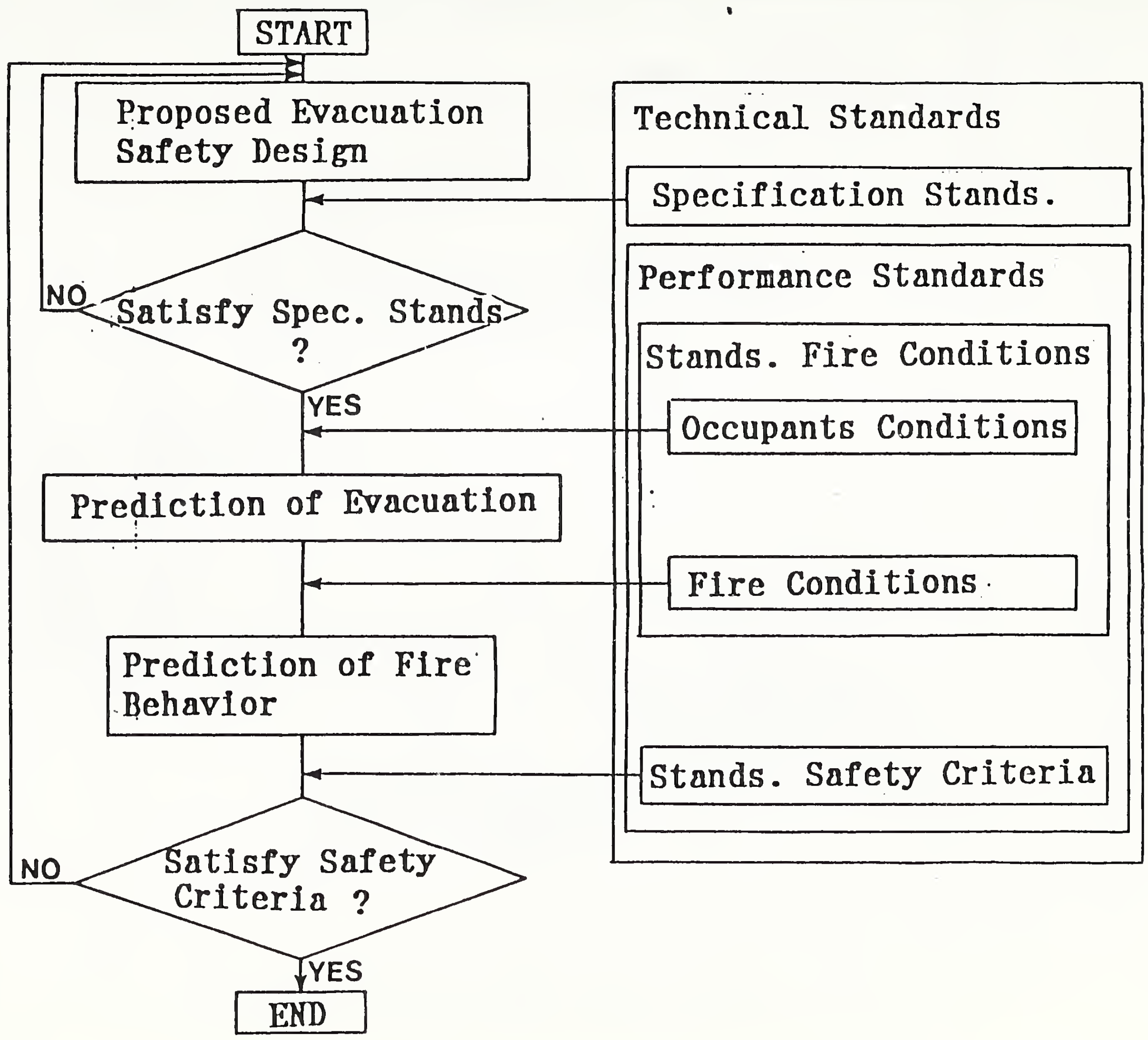


Figure 2. The Procedure of The Evacuation Safety Design

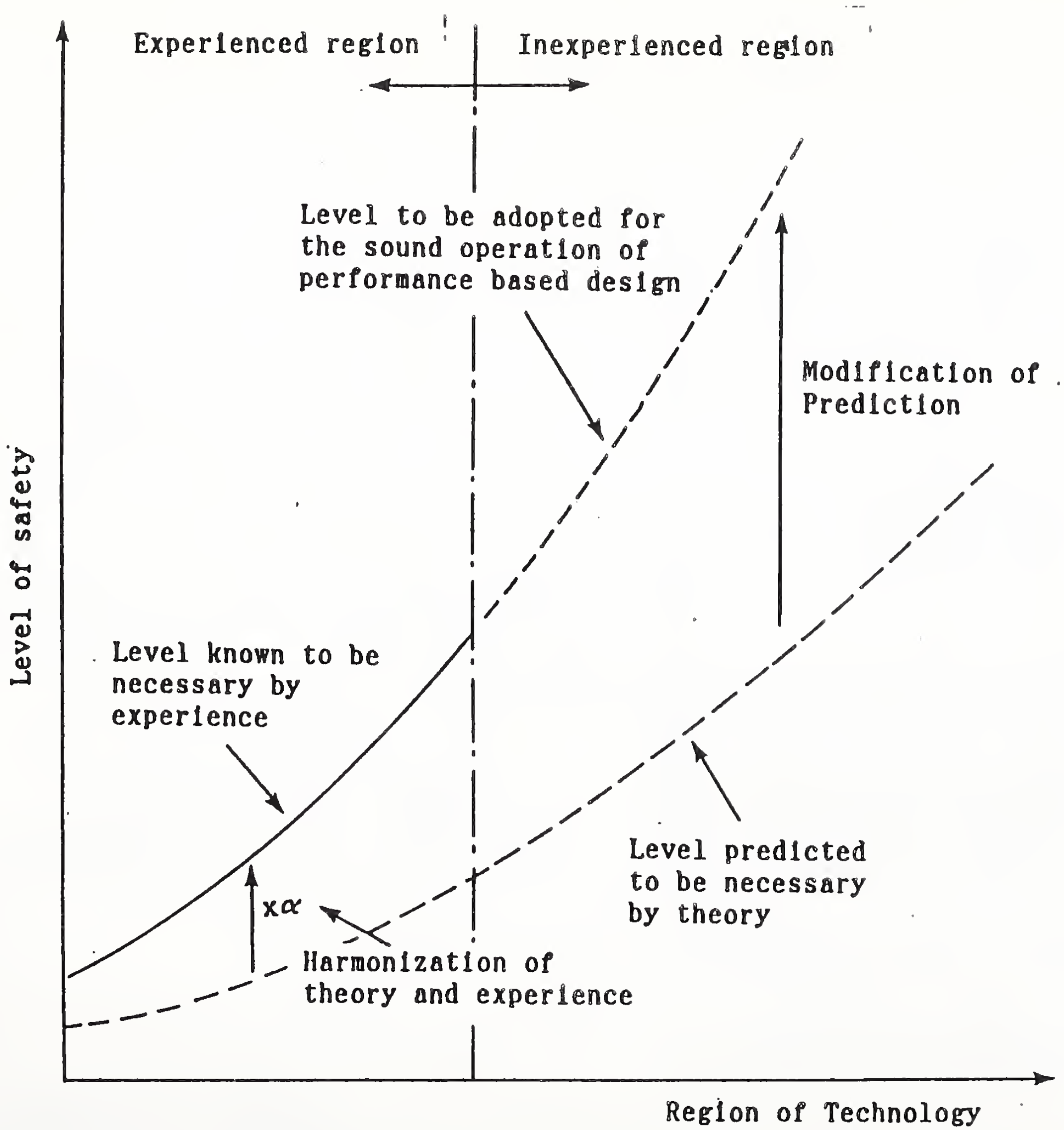


Figure 3. Concept of harmonization of theories and experiences

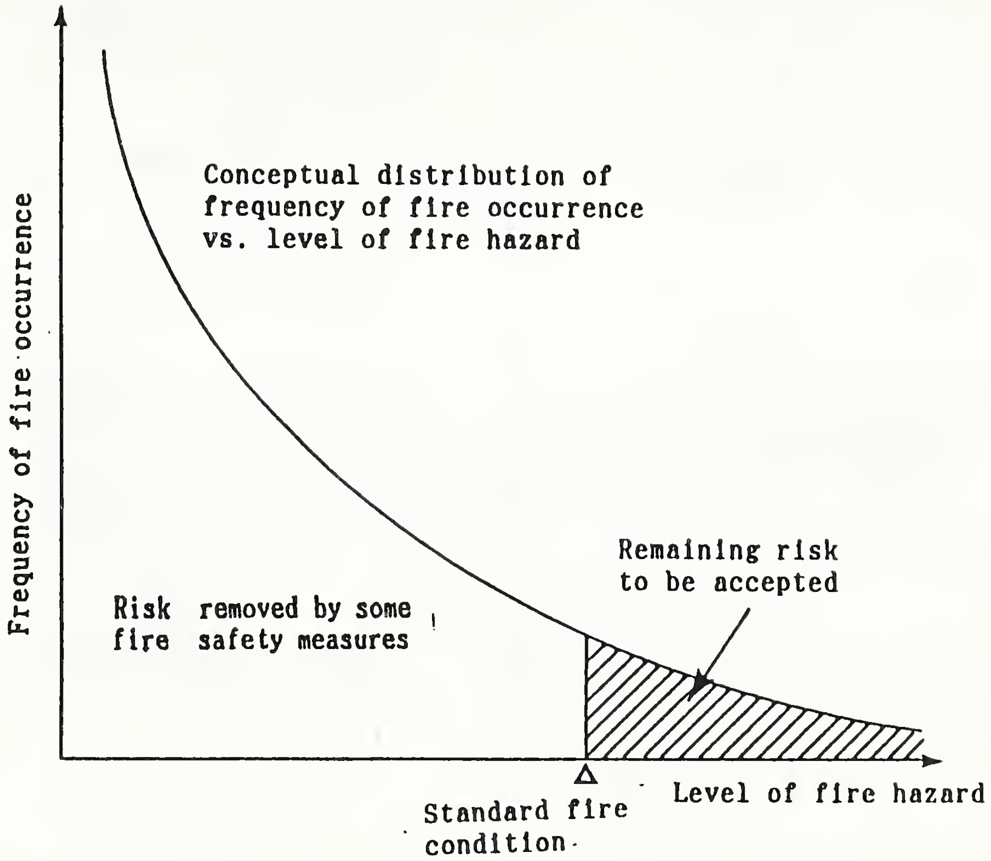


Figure 4. Meaning of standard fire condition

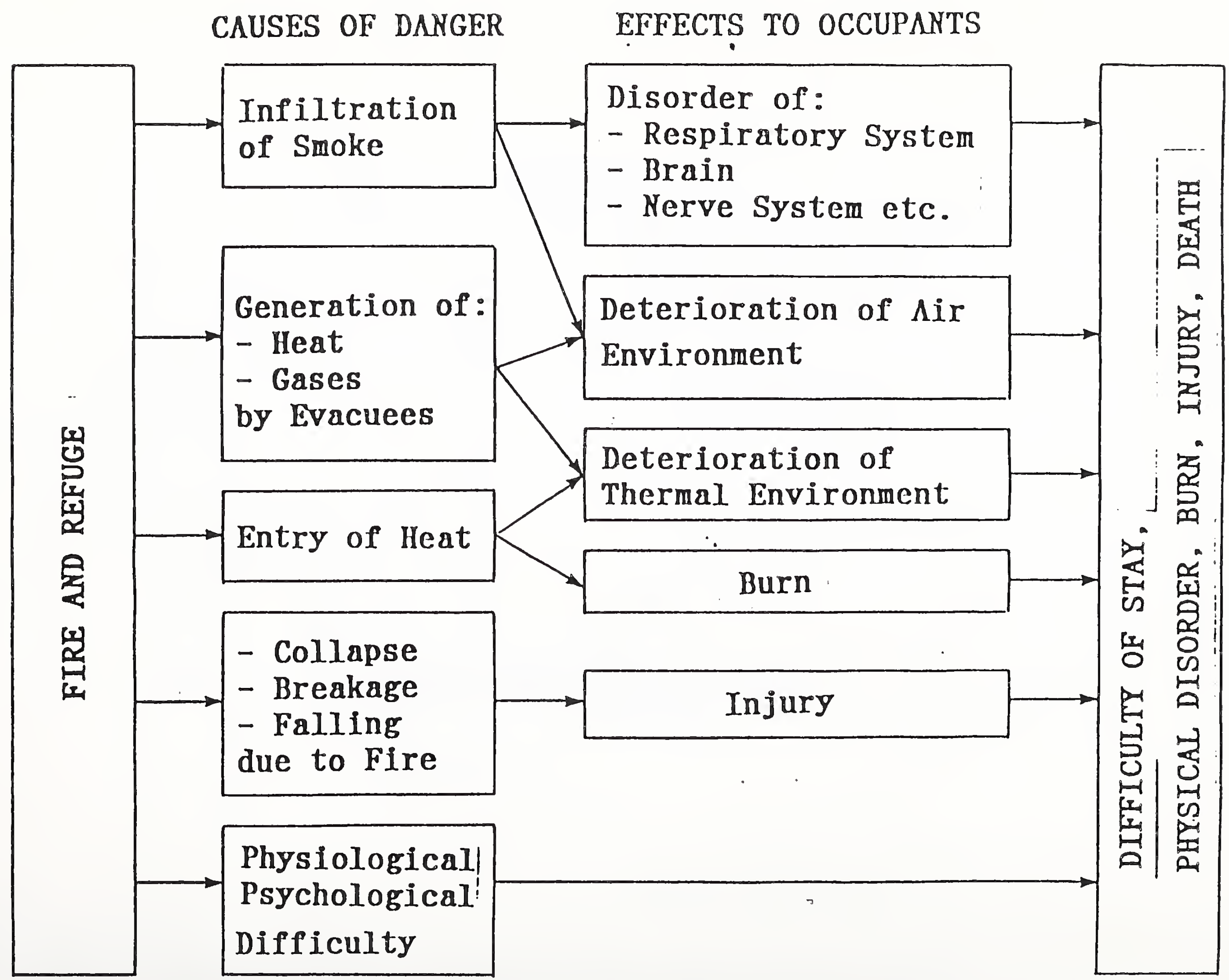


Figure 5 FIRE HAZARDS IN REFUGES

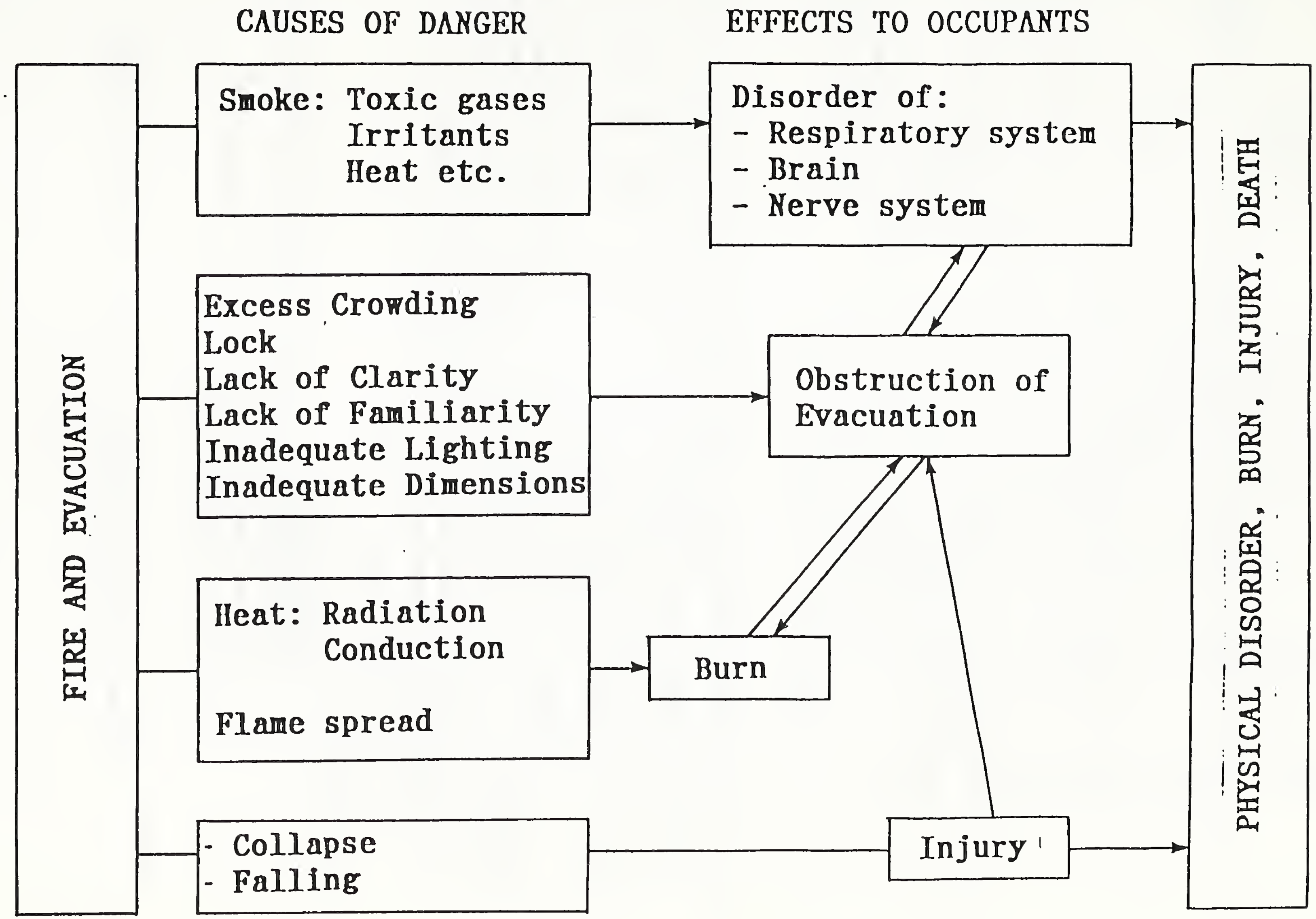
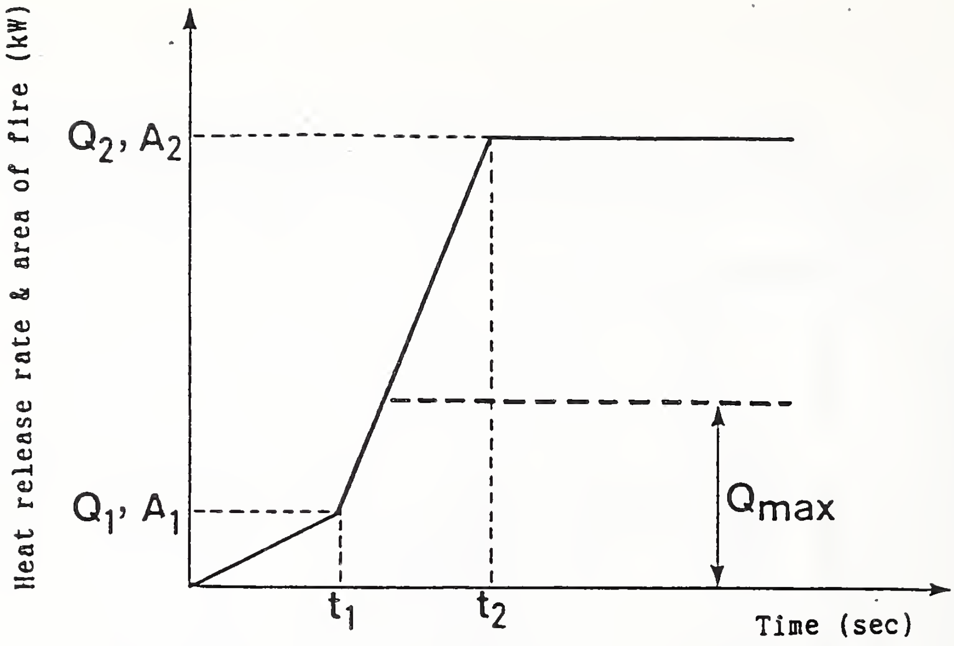


Figure 6 FIRE HAZARDS IN EVACUATION ROUTES



Occupants' condition	Quantity of Contents	Time (sec)		Heat release (kW)		Area (m^2)	
		t_1	t_2	Q_1	Q_2	A_1	A_2
Wake	Large	120	240	300	3,000	1.7	1.7
	Small	120	320	750	25,000	0.5	17.0
Sleeping		480	720	200	1,000	2.5	2.5

note: For spaces in which ceiling mounted sprinklers are installed, the maximum heat release rate Q_{max} is given by

$$Q_{max} = 0.08\ r\ \{(T_c - T_o)H\}^{3/2}$$

where H : ceiling height (m)
r : maximum horizontal distance between a sprinkler and the axis of fire plume (m)
T_c : critical temperature of sprinkler actuation (K)
T_o : ambient temperature (K)

Figure 7. Standard fire for evacuation routes in the room of origin and on the floor of origin

Table 1. Standard fire conditions for safe refuges

<table>
<tr><th></th><th>Public ways</th><th>Refuge isolated from public ways</th><th>Refuge within buildings</th></tr>
<tr><td>Space of origin</td><td>N/A</td><td colspan="2">All spaces which do not fall in any of the followings:
a) The refuge is not needed in case a fire occurs in the space
b) Possibility of the occurrence of fire in the space is negligible
c) Safer than the case when a fire occurred for which the safety standards are satisfied</td></tr>
<tr><td>Scale of Fire</td><td>N/A</td><td colspan="2">i) Area of fire:
The area within a fire can be limited by effective fire walls or confined by fire resistant compartment.
ii) Condition of fire:
Post flashover fire regardless of sprinkler systems</td></tr>
<tr><td>Radiation Source</td><td>N/A</td><td colspan="2">i) Fire resistant buildings
a) width: width of opening (m)
b) height: height of opening x2 (m)
c) radiation intensity: 100 (kW/m^2)

ii) Wooden houses
a) width: width of the house viewed from the point of refuge (m)
b) height: h (m) given by
$h = -A^{1/2} + 4.5A^{2/5}$
where A is the horizontally projected area of the house</td></tr>
<tr><td rowspan="2">Evacuees' Condition</td><td rowspan="2">N/A</td><td colspan="2">i) Number of Evacuees:
The number of evacuees determined by the specific evacuation plan</td></tr>
<tr><td></td><td>ii) Generation of heat:
400 (kW/person)
iii) Generation of CO_2:
0.02 (m^3/h/person)</td></tr>
</table>

Table 2. Standard safety criteria for refuges

The items to be checked		Public ways	Refuge isolated from public ways	Refuge within buildings
1. Smoke	thru outdoor	N/A	$D_1 > 12A^{2/3}$	any of (1),(2),(3)
	thru indoor		N/A	any of (3),(4),(5)
2. Heat			$q_{max} < 1$ (kW/m^2)	$q_{max} < 1$ (kW/m^2) and $T_i < 10$ (K)
3. Air quality			N/A	$C_2 < 0.02$ (%) and (6)
4. Collapse of building			$D_2 > 2H_2$ (m)	any of (7),(8)
5. Falling objects			$D_3 > 4.5H_3$ (m)	N/A
6. Area of refuge			$a > 2$ (m^2/person)	$a > 1$ (m^2/person)

A : horizontal projected area of the building (m^2)
D_1 : horizontal distance of the refuge from the building (m)
D_2 : horizontal distance of the refuge from the top of the building (m)
D_3 : horizontal distance of the refuge from potential falling part (m)
H_2 : vertical distance of the refuge from the top of the building (m)
H_3 : vertical distance of the refuge from potential falling part (m)
a : effective area of refuge per person (m^2/person)
q_{max} : maximum incident radiation flux to evacuees (kW/m^2)
T_i : temperature rise of interior surface of the refuge (K)
C_2 : concentration of CO_2 in the refuge (%)

Table 3. Standard fire conditions for safe evacuation routes

	Evacuation routes		
	Room of origin	Floor of origin	Floor of non-origin
Space of origin	All the spaces which do not fall into the followings: a) No occupant exists in normal use b) Safer than a space for which safety standards are satisfied	All spaces which do not fall into the the followings: a) No occupant who needs to escape exists when a fire occurs in the space b) Possibility of fire occurrence in the space is negligible c) Safer than the case when a fire occurs in a space for which safety standards are satisfied	
Scale of fire	Heat release rate and area of fire source i) Unsprinklered spaces: specified as in Figure 6 according to the type of space ii) Sprinklered spaces: the smaller of the followings: a) fire source specified by i) b) maximum fire which is unable to activate the sprinklers in the space		i) Area of fire: the same as in the case of refuges ii) Condition of fire: the same as in the case of refuges
Occupnts	i) Number of evacuees: specified in the form of occupants' density or some other ways according to the type of spaces ii) Evacuation ability: specified according to the type of spaces and occupants iii) Evacuation start time: The smallest of the times at which the occupants recognize the danger due to fire by means of: a) Cue by fire, smoke b) Cue by other occupants c) Through the fire detection and alarming systems		

Table 4. Standard safety criteria for evacuation routes

The items to be checked		Evacuation routes		
		Room of origin	Floor of origin	Floors of non-origin
Smoke	thru outdoor	N/A	N/A	any of (3),(4),(5) and (10)
	thru indoor	any of (9),(10)	any of (3),(4),(5),(10) and (11)	any of (3),(4),(5),(9) and (10)
Heat		(12)	(12)	(12)
Flame spread		(13)	(13)	(14)
Collapse of bldg.		N/A	N/A	any of (7) and (8)
Falling objects		functional	functional	functional
Excessive crowding		(15)	(15)	(15)
Geometry, dimension clarity etc.		specification	specification	specification

THE LIST OF STANDARDS IN TABLES 2 AND 4

(1) The refuge is out of the region enclosed by any cone having the apex on the opening of the fire room and extend upward with the angle of $\tan^{-1}0.25$ around its axis.

(2) The infiltration of smoke into the refuge is prevented by any means of the followings:

(a) air tight exterior wall which satisfy

$$\frac{\alpha A}{V} < 1.0\text{x}10^{-6} \frac{1}{\sqrt{\Delta P}} \qquad (0< P<60 \ \text{Pa})$$

(b) indoor pressurization of refuge which satisfy

$$60\text{-}P < 6.0\text{x}10^{-12}\left(\frac{V}{\alpha A}\right)^2$$

where V : volume of refuge (m^3)
αA : area of leakage potentially exposed to smoke (m^2)
ΔP : pressure difference (Pa)
P : relative pressure of refuge (Pa)

(3) The fire products entered in the refuge are diluted to satisfy

$$C < (1/200)C_0$$

where C : fire product concentration in refuge
C_0: fire product concentration in the room of origin

(4) Smoke transported through indoor space is released at a point between the space to be protected(refuge, evacuation route) and the room of origin to an open air having no obstacle which may prevent free rise of plume in the region enclosed by the following surfaces:

(a) plane which contains the opening ejecting smoke

(b) two plane at right angle to (a) of which the distance from the edge of opening x_1 is given as

$$x_1 = 0.20Z$$

(c) a curved surface of which the distance from (a) x_2 is given as

$$x_2 = 0.6H^{2/3}Z^{1/3} + 0.20Z$$

where H : height of opening (m)
Z : height from the bottom of opening

(5) Smoke transport is prevented between the spaces to be protected(refuge, evacuation route) and the room of origin by any means of the followings:

(a) air tight partition which satisfy

$$\frac{\alpha A}{V} < 8.0\text{x}10^{-3} \left(\frac{1}{t_s \sqrt{\Delta P}}\right) \qquad (0< P<H_1)$$

(b) building up pressure difference(positive at refuge side) which satisfy

$$\Delta P > 1$$

(c) keeping smoke layer bottom at the height s (m) which satisfy

$$s > h + 0.1(H_2 - h)$$

where H_1 : height of non-airtight vertical shaft (m)
H_2 : ceiling height of the space at fire side of the partition (m)
h : height of opening or leakage on partition (m)
ΔP : pressure difference (Pa)
t_s : time of stay in the space (s)

(6) Thermal environment which satisfy

$$\int_0^{t_s} (\Delta T - 10)^2 dt < 4.0 \times 10^4 \qquad (\text{if } (\Delta T-10)<0,\ (\Delta T-10)^2)=0)$$

where ΔT : temperature rise in refuge (K)
t_s : time of stay (s)

(7) Fire resistant building prescribed in the Building Standard Law.

(8) Building which satisfy the relevant standards given by Fire Resistant Design Method.

(9) Smoke layer bottom is kept at height s (m) which satisfy

$$s > 1.6 + 0.1(H - h)$$

where H : ceiling height (m)
h : height of the floor of evacuation route (m)

(10) The smoke to which evacuees are exposed satisfy

$$\int_0^{t_e} (\Delta T)^2 dt < 4.0 \times 10^3$$

where ΔT : temperature rise (K)
t_e : time during which evacuees are exposed to smoke (s)

(11) Outside of the region enclosed by the surfaces defined as
(a) plane which contains the opening ejecting smoke
(b) two vertical planes at right angle to (a) of which the distance from the edge of opening is 0.4 (m)
(c) plane parallel to (a) whose distance from (a) x (m) is given as

$$x = 0.6H^{2/3}Z^{1/3} + 0.20Z \qquad (Z=1.8-Z_n \text{ or } 1.8-0.3H)$$

where H : height of opening (m)
Z_n : height of neutral plane at opening (m)

(12) Incident radiation heat flux r (kW/m^2) to evacuees satisfy

$$\int_0^{t_e} (r - 2)^2 dt < 10 \qquad (\text{if } (r - 2)<0,\ (r - 2)^2=0)$$

where t_e : evacuation time (s)

(13) The interior lining materials do not induce the combustion which violates the safety criteria of 1. Safety from smoke and 2. Safety from heat during the time of evacuation.

(14) The interior lining materials do not burn during the time of evacuation

(15) Unless in space specially protected, crowding at any opening on evacuation routes satisfy

$$n < 120$$

where n : number of evacuees in crowding per unit width (person/m)

PAPERS NOT PRESENTED

Development of a Method for Predicting the Fire Risk of Products

Frederic B. Clarke, III
Benjamin/Clarke Associates, Inc.
Kensington, Maryland 20895
U.S.A.

Abstract

A method of predicting risk is described which uses prototype product and occupancy characteristics as a basis for calculating fire hazard by deterministic modeling. Reported fire experience is then applied to predicted hazard to yield prediction of fire risk. Some results of the method's application to residential furniture are described.

1.0 Introduction

This paper describes the work of the National Fire Protection Research Foundation's Project on Fire Risk. The objective of the project is to develop a quantitative method for predicting the expected life safety risk associated with the use of new and existing products. "Product" is defined as an item capable of being evaluated by laboratory-scale fire performance tests and therefore generally does not include building design features. Fire death is the measure used to quantify life safety risk. In practical terms, the method seeks to predict the fire death rate associated with classes of items amenable to laboratory fire testing and for which the experimental fire experience associated with their use is reported.

In the following sections, the logic and design of the method will be described, followed by a brief description of results applied to a test case: residential upholstered furntirue.

2.0 Description of the Method

2.1 Overall Logic

Reported fires incidents and fire deaths can be classified by scenario, i.e., by commonalities of item ignited, ignition source, etc. The number of fire deaths associated with each fire scenario involving a product in an occupancy is:

D_i (number of deaths) = n_i (number of fires of scenario type i) x d_i (average number of deaths per fire in scenario i)

The total number of deaths is then the sum over all scenarios involving the product. The method attempts to predict D_i for the important scenarios by calculating D_i, the deaths per fire, a severity measure which can be in principle determined by the fire properties of the product, the environment in which it burns, and the capabilities of those expsoed to the fire. The method does not attempt to predict n_i, but uses fire experience.

The scenarios must be formulated in a manner which corresponds to the terminology used in fire statistics. Fire statistics almost never report the performance of a single product, but the performance of an entire class of item-first-ignited. In the absence of knowing the type and frequency of occurrence of each type of product included in a given class, some estimate must be made of the composite, or average, properties of products now in use. If this estimate can be made, and if a hazard calculation using these properties reproduces the number of deaths per fire actually observed, this is evidence that the hazard prediction method for the produce is reasonable. Once a tested hazard prediction is in hand, it can be used to predict how much improvement or deterioration in life safety is associated with products having a given set of fire properties, using the level of risk associated with existing products (and properties) as a reference.

2.2 Steps in the Process

2.2.1 Step 1 - Choice of Product and Occupancy

Some products and occupancies are more likely to give satisfactory results than are others. The product of study must have an analogue in current use, from which it may differ in fire properties and size, but not in intended use or location. It should appear specifically or be contained within the list of items-first-ignited used as a basis for categorization in NFPA 901.

The first case chosen was residntial upholstered furnishings. Specifically, the effort is confined to furnishings in one- and two-family dwellings. This case was chosen first because, upolstered furniture fires have been relatively well-studied in the laboratory, and test methods have been developed which address specifically their burning characteristics. Second, there exist relatively abundant data on which to attempt to validate the finished assessment.

2.2.2 Step 2 - Fixing the Occupancy Characteristics

The result of this step is to identify, and describ for fire-modeling purposes, one or more prototype occupancies in which the fires involving the product will occur. The first task in this step is to decide on the number of prototypes needed. For example, housing statistics show that about 70% of 1 and 2 family housing had the living space on one floor and almost all the rest were two-storied, so two prototypes were thought necessary to represent fire buildup in residences. The information needed to model residential occupancies, the source of the informtion and the rationale for the many estimates which had to be made in the absence of data, are all compiled in brief in Table 1.

2.2.3 Step 3 - The Scenario Generator - Expressing the Scenarios in Fire Reporting Terms

To relate to fire experience, severity must be calculated for scenarios for which the numbers of fires are reported. Fires are characterized in the NFPA 901 Reporting System (as well as national systems used in many other countries) by item-first-ignited. The severity of a reported fire is classified by one of fire levels of flame spread: confined to the object of origin; extending beyond the item of origin in the immediate area of origin; extending beyond the area but not involving the entire room; spreading beyond the room of fire origin; and, finally, spreading beyond the floor of origin.

The extent of flame spread is used to infer quantitative information. Conditions for facile flame spread beyond the object of origin can be viewed as requiring some minimum level of radiatn heat flux imposed by the hot upper layer of the room, approximately 1 kW/m^2, which requires an upper layer temperature in the room of approximately 100°C thus, spread confined to the object of origin will produce conditions below this level. The method defines fires in which the flame spread is confined to the area of origin to be receiving radiant flux of aobut 3kW/m^2, which corresponds to an upper layer temperature of about 200°C. At radiance levels in the neighborhood of 15 kW/m^2, remote ignition of combustibles begins to occur, and this is defined as the onset of spread throughout the room of origin: an upper layer temperature of 450°C corresponds to this radiance level. Similarly, spread beyond the room of origin occurs between 450°C and 700°C.

Relating upper room temperature to the extent of spread provides a crosswalk between four spread classifications and the estimates of fire size. If the fire is curtailed by extinguishment, or by its own failure to spread, then its temperature profile in the room is described by the curve at the left in Figure 1. The height to which it grows is the temperature it reached before declining. The maximum temperature a reported fire reaches is taken to be 100, 200, 450, or 700°C, depending on whether the fire is confined to the object, the area, the room, or goes beyond the room, of fire origin. Using the results of room fire modeling (1), it is possible to define a heat release curve with a shape which produces the temperature profile required in each scenario. The slope of the heat release rate curve is controlled by the fire buildup properties of the product ignited and the other combustibles in the room. Its peak is the size it reaches before the room temperature exceeds the criteria just discussed. For fires leaving the room of origin, the maximum rate of burning is defined by the size of the doorway; the duration of burning is controlled by the room's fire load. The four heat release curves, one for each degree of spread allowed in the scenarios, are also illustrated in Figure 1. Since scenarios described this way are associated with a reported number of fire incidents, the result is a way to marry frequency with severity - i.e., a way to calculate risk.

2.2.4 Step 4 - Designing the Fire Model

1. General Considerations

Several relatively versatile, well documented, compartment fire models now exist, and the one used in this work is FAST (Fire And Smoke Transport) model developed by the Center for Fire Research, National Institute of Standards and Technology (2).

The FAST model uses the heat release rate curve for the room of fire origin developed in Step 3. The model calculates the temperature and flows in a compartment network of specified dimensions, geometry and heat transfer properties. In addition, smoke characteristics in the network, such as toxicity and obscuration, are estimated if the heat of combustion smoke toxic potency and smoke mass optical density are provided for the materials burning. The input data needed to construct the room heat release rate curve and determining tenability are listed in Table 2.

The fire scenarios discussed previously have all presupposed that the product immediately begins to flame once ignited. This need not be true of upholstered furniture which, if directly ignited by a cigarette, can undergo smoldering combustion. Smoldering scenarios were modeled by attaching a smoldering period of this duration tot he beginning of the burn curve.

The parameters needed to specify furniture's contribution to fire growth are: its resistance to cigarette ignition (presently a pass-fail determination); the rate of fire buildup determined by the method of Babrauskas using the cone calorimeter (3); the heat of combustion and the peak heat release rate of the material, the mass optical density of the smoke produced; and the toxicity of the smoke.

To deal specifically with the scenarios in which the upholstered furniture is secondarily ignited from another item, the average distance that the furniture would be from other sources of ignition (i.e. other items first ignited) was estimated by a panel of fire experts. The ignitability of the furniture, also determined from the cone calorimeter, is used to determine the flux needed to ignite the product. Once these data are provided, it is possible to define heat release curves for all room fires in the scenarios where upholstered furniture will be involved. The FAST model then computed the temperature movement of smoke throughout the prototypical residences as a function of time. From these considerations subsequent portions of the method can determine the effect of the fire on residential occupants.

The fire load commonly found in residential occupancies is more than sufficient to carry to flashover any room in which upholstered furniture is likely to be found. Furthermore, the size of the overall residence is sufficiently small that, once a fire reaches flashover, lethal conditions throughout the house are quickly reached. Therefore, it is unnecessary in this particular case to describe the fire in detail once it spreads beyond the room of origin.

2.2.5 Step 5 - Describing Escape Capabilities of Occupants

The characteristics of occupants likely to be found in a given structure are used to construct occupant sets. Each occupant set is one possible population of the structure. Describing the occupants in terms of the speed at which they move, their capacity for unaided escape, and the ease with which they are alerted; the various sets are weighted based on their probable occurrence in the building population. The characteristics of family and non-family households with up to seven members is available from census reports (4). In addition, occupant sets have been adjusted to reflect the likelihood of one or more such people being temporarily incapacitated by drugs or alcohol. In total, over 200 different occupant sets have been identified to help describe the makeup of American residences.

The actual escape capabilities of these occupants from the residences was modeled using an existing evacuation model, EXITT developed at the National Institute of Standards and Technology.

2.2.6 Step 6 - Evaluating Effect of Fire Conditions on Occupants

The method uses three criteria for the cessation of further unaided efforts to escape: accumulated temperature exposure which incapacitates the victim, sufficient heat flux to cause severe thermal injury, and inhalation of a lethal dose of smoke, based on its $L(Ct)_{50}$, or smoke potency.

Each occupant is followed through the occupancy and the temperature, radiant heat flux and smoke concentration to which the occupant is exposed is continuously recorded. When one of the criteria for cessation of escape is exceeded, escape is stopped.

The smoke toxicity of the product is an input to this model. In many fires, material in addition to the product is burning, and for such materials the toxicity of the smoke is assumed to be 900 mg minutes per liter. The photometrically determined smoke obscuration, (the optical density of the smoke) is used in the residential evacuation model to slow down or stop efforts to escape, but is not in itself a criterion for fatality. Tenability criteria do not change from case to case.

2.2.7 Calibrating the Model - The Base Case

The computational method is first used to predict fire experience for the version of the product now in use - the "base case". One or more prototype products must be identified which represent what appears in the present environment and thus has determined present fire experience. The estimated product characteristics which control the fire behavior of the upholstered furniture now in use are listed in Table 3. Most of the values were assigned by an expert panel drawn from the advisory committee, using values obtained by Babrauskas (4) and market survey information compiled by the Consumer Product Safety Commission. According to the survey, about 60% of existing furniture is of "older" manufacture-cellulosic upholstery, cotton batting and urethane or latex foam cushioning. Furniture which is covered with thermoplastic fabric - some 40% of existing stock - does not usually ignite by cigarette, but when alight, it grows rapidly and has a high peak heat release rate. Benchmark values of fire properties are simply a weighted average of the two types.

2.2.8 Step 8 - Prediciting the Fire Risk for a New Product

Once a satisfactory representation of the base case has been obtained, the same hazard model can be used to predict the risk associated with a product of any specified set of fire properties. This is accomplished by replacing the properties of the prototype base case product with those representing the new or test product and carrying out the same calculations, leaving unchanged the balance of data used (see Table 1) prediction is the risk associated with the changed set of fire properties.

3.0 Results and Discussion of Residential Furnishings

3.1 General Observations and Simplifications

For residential furnishings, a complete analysis requires simulating fires within the following combinations:

> Employing 2 types of residences - a one story ranch house and a two-story occupancy; starting the fires in 5 different rooms - living room, bedroom, kitchen, dining room and storage area; drawing four kinds of heat release curves - fires in which the furniture was the first item ignited from a flaming sources, from a smoldering source, fires where the furniture was the second item ignited (9 possible fire growth patterns) and fires where the furniture was present but did not ignite unless the fire involved the whole room (9 possible fire growth patterns)

This gives a total of 200 modeling runs for the base case. Each fire was subdivided into four levels of spread, effectively producing 800 fire scenarios. Each of 220 occupant sets is evaluated for escape from each fire. Thus, a total of over 160,000 outcomes are possible. In addition, escape was evaluated both in the presence and the absence of working smoke detectors.

As a practical matter, not all of these fires are of equal importance in fire deaths. Computation was confined to those rooms and those fire types which fire experience identified the major actual contributors to fire death. About 50% of the total number of possible calculations have been performed, but they account for over 90% of the reported.

3.2 Results

Upholstered furniture is categorized by sequence of ignition - first or second item ignited. The results for items first ignited are presented in Tables R1-a and b. The severity of smoldering fires is slightly under predicted while the impact of flaming is over predicted. The most apparent explanation for this fact is that only cigarette ignitions are classified as smoldering ignitions, when in fact it is known (see Babrauskas) that cellulosic furniture stock often burns in a smoldering or semi-smoldering mode, even when ignited by a flaming source. Also, smoldering ignitions are probably under-reported.

The under-prediction of smoldering risk could also be due to two factors: too high a $L(Ct)_{50}$ in the base case or too short a smolder time. Changing the $L(Ct)_{50}$ to a lower value, however, would be both arbitrary and probably have more effect on the mode of death than the number of deaths. This is because incapacitating temperature, depleted oxygen and accumulation of a fatal smoke dose all occur fairly close together in time.

Table R1-b classifies the results further by time of day. The reported numbers indicate 60% of deaths occur at night while the method predicts 90%. This result certainly is an effect of the location and behavior distribution of the different occupant types. For example, the method assumes all occupants are awake during the day; only the elderly are asleep during the evening; and all occupants are asleep at night. In fact, many children and some adults are asleep during the day, and vice-versa.

Prediction for furniture that is secondarily ignited are similar. Table R3-a indicates more deaths calculated than reported due to flaming and the reverse trend for smoldering. However, this time the difference is substantial - calculations are off by 50 to 70%. Three of the night living room scenarios. These three scenarios which represent fast and medium fire growth at the onset account for half of the deaths in Table R3a. A total of 164 deaths are expected from statistics while 643 were calculated. If some of the first-items ignited are mis-classified and in a category where their burn characteristics are less intense, or the categories are clumsily formulated, the predicted deaths would be too high.

The possibility that that some of the furniture fire growth rates are chosen too high dramatically illustrates the sensitivity of the situation to the fire growth rate of the item ignited. Since most people require an irreducible minimum amount of time to escape, any fire which produces untenable conditions in a time comparable to that needed escape time is very dangerous. A small increase in buildup rate can mean a big change in lethality. If the onset of lethality moves from "just after" to "just before" escape is accomplished, a large difference in deaths per fire is observed.

3.3 Residential Upholstered Furniture Sensitivity Studies

Once the base case for upholstered furniture was established, several studies were performed to test modeling parameters and assumptions.

In the base case, a person reaching a window was assumed immediately to escape through the window. Alternative assumptions build in a delay time before evacuating and permit rescue 10 minutes after the first person evacuates. Results indicate a 40% (720 vs. 624) increase (over the base case) in deaths due to flaming ignition and 6% (488 vs 460) for smoldering ignition when a delay time in escaping through a window is added. Almost no additional effect is seen even when rescue is available. Early escape (perhaps through a window) is more crucial to survival than being rescued later on.

According to the method, a person who is asleep may become aware of a fire because of smoke detector actuation, smoke layer height, or the smell of smoke. The base case uses a layer height of 0.9 meter as an initial trigger. The alternative examines the effect of higher smoke level (1.2m) (i.e., earlier notification).

Not surprising, the total death numbers are lower when persons are alerted at a higher smoke level, Table S1-b. However, the effect is only noticeable (an increase of 7%) for smoldering fires. Flaming fire deaths were essentially not affected.

In the base case, the occupants who are intoxicated by alcohol are asleep in the living room at night. The alternative places them in the bedroom. This produces a decrease in smoldering deaths due and an increase due to flaming fires but, the net result is that the total deaths are virtually unchanged (622 vs. 624).

Houses where fires occur frequently are small. The base case ranch house contains six rooms. To observe the effect of smaller house the house volume was reduced by 10%. The effect is an increase in the total number of deaths, due to a 30% increase in deaths due to smoldering. Reducing the house volume effectively increases the smoke concentration, so for smoldering fires, where smoke quantity is an important factor more deaths can be expected in a smaller house.

An open window intensifies the fire. In the base case windows remain closed at flashover. The effect of opening a window at a heat flux of 2.5 watts/cm² is negligible. This is because, by flashover, survival is minimal, so aggravating the fire condition at that point has very little effect.

The under-prediction of smoldering fire deaths in the base case prompted a test of the results when the smolder period was extended to 3 hours. With a 3 hour smolder period alone, three additional deaths are predicted. All the deaths are in the bedroom and are caused by smoke toxicity.

The $L(Ct)_{50}$ value (900 mg-min/l) that was used in the base case is not well-established. If it is too high deaths due to smoldering ignitions would be under predicted, so a test of the effect of decreasing the product dose to 90 mg-min/l was made such a decrease leads to a 45% increase in total deaths. The effect is similar for both smoldering and flaming fires. The majority of the deaths (about 96%) are due to smoke toxicity compared to zero percent in the base case.

4.0 General Discussion and Outlook

The risk method described here is an attempt to direct the enormous amount of fire science and technology developed in recent years to help describe fire hazard to predicting fire risk. The approach chosen is to view the world as if it were made up of a few kinds of fire, each occurring many times, which produce observed fire experience. This assumption may not be correct: it is possible that a small fraction of "bad actors" actually accounts for a disproportionately large share of losses. To the extent that his bias does exist it makes the method "conservative" because an acceptable model must produce real fire experience from the benchmark product. It will make a new product's performance appear somewhat worse than it really is - - and will make a product with the properties of the "bad actors" appear awful.

However, the effects of such a possibility are reduced because of the use of expert panels that includes fire professionals. This group would see the bad actor more often than often it actually occurs in the marketplace, so its properties implicitly color their view of the "average" product.

The other fact arguing against a badly-skewed base case calculation is the fact that fire experience shows that losses come disproportionately from the larger fires. These almost always involve more than the preoduct alone, so its effects are felt as part of the total burning assemblage.

Another key assumption is that it is possible to predict fire experience based on a probabilistically weighted set of deterministic models. It is assumed that fire deaths are caused by the effects of average, typical or "composite" products. The reason deaths per fire are relatively low, then, is that the fires these products produce rarely are encountered by someone with the vulnerability to succumb. For example, in residences none of the fire scenarios, even the most severe, always kills everyone in the house: only those who are warned too late or unable to escape unaided. The sensitivity of the model in predicting death therefore depends not only on the ability to correctly model the fire's physical characteristics, but also on the refinement of the occupancy sets - the more detailed they are, the more "sensitivity" the method has. The prediction method works less well if less is known about the makeup of occupants.

Resolution can be improved by doing either or both the following:

Postulating scenarios, which are more unlikely but at the same time more severe in the fire environment they provide;

Building more detail in occupancy sets; for example, by describing those who are in the building out of working hours, those who are disabled, etc.

The limitation on these two efforts is that the data needed to assign probabilities to such scenarios and occupancy sets are not readily available, and it is laborious to collect them. However, one can use the method to estimate how changes in the product would impact risk by identifying the product characteristics which would be needed to raise the fire risk above zero. Obviously, how sensitively the method does this would still depend on its ability to discriminate effects.

Thus, the method can be applied most easily to occupancies about which much is known - - both as respects fire experience and occupant capabilities.

This is not to say that the method is not just as useful (or even more useful) for other occupancies, but making it useful to predict risk takes data which may be harder to find.

References

1. c.f., McCaffrey et al, Estimating Room Temperatures and the likelihood of flashover using fire test data correlations, Fire Technology, 17, 198 (1981).

2. Jones, W., "A Multicompartment Model for the Spread of Fire, Smoke and Toxic Gases," Fire Safety Journal, 9, pp. 55-79 (1985).

3. Babrauskas, V., Krasny, J., "Fire Behaviour of Upholstered Furniture," National Bureau of Standards, Gatihersburg, MD, November 1985.

4. U.S. Bureau of the Census, Current Population Reports, Series P-20, No. 411, Household and Family Characteristics: March 1985, U.S. Government Printing Office, Washington, D.C., 1986.

TABLE 1

Occupancy Characteristics Needed for Risk Analysis Method

Information Needed	Source of Data or Basis for Estimate	Rationale for Estimate or Assignment
Number of prototype occupancies	Expert panel identified two prototypes-single and 2-story house; census data provides population in each prototype	Movement of smoke and heat between rooms may be slow in comparison to its movement up a stairway. Residents trapped on second floor may have to use windows for escape; those on single floor can use doors as well.
For each prototype: Floor area, size and layout of roo	Housing census/expert panel	Housing data gives number of rooms, panel estimated room size of each
For each prototype: Number of floors	Housing census	Almost all 1 and 2 family dwellings are 1 or 2 floors; single apartments not part of analysis, those outside of dwelling unit are not at risk.
For each prototype: Location and number of exits	Expert panel identified single exit from ground floor of house	Most of population lives in dwellings with one or two exits on ground floor. Preliminary calculations show that escape of occupants is relatively insensitive to presence of a second exit. Use of windows as exits and possibility of rescue was not estimated, but examined as a sensitivity issue.
For each prototype: Location and number of windows	All windows to vent fire and smoke assumed closed	Although windows will break in fire room, this will generally occur after lethal conditions are reached. Flow of smoke into rest of structure is relatively unaffected by window status.
For each prototype: Whether doors between compartments are open or closed	All doors between compartments assumed to be open	No good basis for assigning door status. Sensitivity analysis carried out for residences shows that closed doors have little impact on fire deaths.

FIGURE 1
Room temperature showing
cutoff levels for limited spread

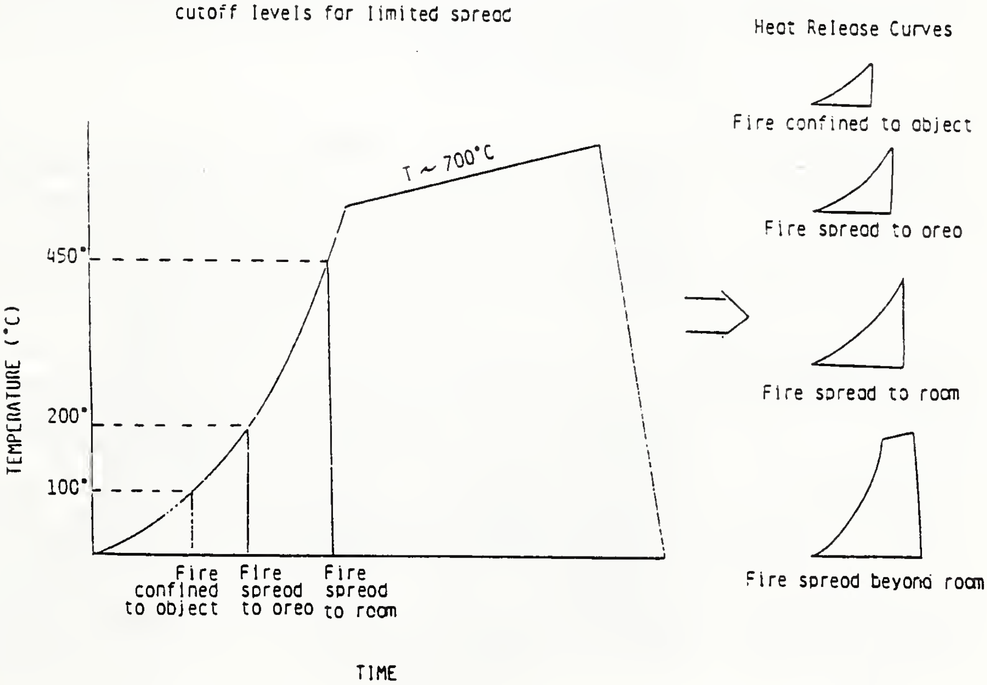


TABLE 2

Input Deta Needed for FAST Fire Model

A. For Construction of Room Heet Releesa Rete Curva		
Quantity Needed	Significance	How Obtained
1. Mese of Product	Determines length of time product burns, and its total contribution to heat raleese	Meaeurement
2. Ignitability: Resistance of product to cigerette ignition	Detarmines whether product will appear in ecenerios whera cigarette is ignition source	Measurament
3. Ignitability: Resistence of product to flaming ignition	Detarminas whathar product will ignite secondarily in scanarioe when it is not firet item to ignite	Measurement - minimum flux for ignition via cone calorimeter or LIFT apparatus
4. Rete of incraase of heat release rate of product	Determines how fest room heet release increeses due product's contribution	Direct measurement using rete of heet releese apparetus. Rete fitted to e quedratic expreesion, i.e., heet releeee proportional to squere of tima. In smoldering scenarios, a rate of smoldering is aleo raquirad, as well as a smoldering time
5. Rete of increasa of heat releaee for all other iteme first ignited except product	Detarminae room haat raleaee rete and when product will be ignited when it ie not first item to ignite; ueed with A-3	Assignment to one of three categories slow, medium or fast - by expert penel
6. Peek heat relaase rate of product	Determinas product's meximum contribution to room haat releese reta	Measurement in furniture calorimeter or calculetion from eurface erea and measured heet releese/unit erea
7. Peek haat release of ell items first ignited except product	Determines room haet relaase rate at eerly stege of fira when product may not ba involvad	Assignment to one of three categories - low, medium, or high - - by expert panel
8. Rete of increasa for heet releese rate for items ignited by product, or by other items first ignited	Determines room heet release rata at latter steges of fire	Assigned to be e universel value of 11 kW/sec^2, and ellowed to continue to grow until room fully involved This cruda epproximation ie justifiable in ceses where product is no longer important sourca of fire and whera no better information ie available.
9. Distence of product from other items first ignited in room	Determinee when, in combination with A-3 and A-5, product receives sufficient radiant haat to ignita	Estimated by expert panal
10. Room fire loed, excluding product	Determines how long room fire burns	Estimeted from published sources
11. Heet of combustion of product	Determinas how much smoka produced per joula of product anergy	Measurement by integreting heat release rets curves over time
12. Heat of vaporization of other items, not product	Determines balance of smoke produced by materials other than product	Assigned a valua of 5 MJ/kg, which ie typical of a 50-50 cellulosic-synthetic mix

B. For Determining Tenability end Predicting Escape of Occupents		
Quantity Needed	Significance	How Obtained
1. Smoke potency of product	Determines how much of product must burn before lathal smoke conditions produced	Measurement as L(Ct)50 or analysis of toxic combustion casas using N-gas methodology
2. Smoke potancy of other itams, not product	Determines contribution of other fuels toward buildup of lethal conditions	Assigned an L(Ct)50 value of 900 mg-min/l, typical of wood or polyurethane
3. Specific smoke extinction area (maes optical deneity) of product	Determines product's contribution to smoke obscuretion, end thus speed of escepe of occupants	Measurement by cone calorimeter modified NIST smoke box, or similer apparetus
4. Specific smoke extinction area of other itams, not product	Determinee contribution of other fuels to smoke obscuration	Assigned e universal value of 300 m^2/kg

Table R1-a

Calculated vs. Reported Deaths
(Scenarios where furniture is the item first ignited)

	Flaming	Smoldering	Total
Reported	145	498	643
Calculated	164	460	624

Table R1-b

Breakdown of Calculated vs. Reported Deaths by Time of Day
(Scenarios where furniture is the item first ignited)

	Day	Evening	Night	Totals
Reported	180	83	379	643
Calculated	52	20	552	624

Table R3-a

Calculated vs. Reported Deaths
(Scenarios where furniture is secondarily ignited)

	Flaming	Smoldering	Total
Reported	617	153	770
Calculated	1050	80	1130

Table S1-a

Sensitivity Results for Evacuation Alternatives

Deaths	No rescue, no window delay (Base Case)	No rescue; window delay	Rescue, window delay
Total	624	720	716
Smoldering	460	488	485
Flaming	164	232	231

Table S1-b

Sensitivity Results for Waking Cues

Deaths	0.9 Meter (Base Case)	1.2 Meter
Total	624	595
Smoldering	460	431
Flaming	164	164

Table S1-c

Sensitivity Results for Placement of Intoxicated Persons

Deaths	Living Room (Base Case)	Bedroom
Total	624	662
Smoldering	460	449
Flaming	164	173

Table S1-d

Sensitivity Results for Decreasing the House Volume

Deaths	Base Case	Smaller House
Total	624	762
Smoldering	460	599
Flaming	164	163

Table S1-e

Sensitivity Results for Decreased $L(Ct)_{50}$ Value

Deaths	$L(Ct)_{50}$ = 900 mg-min/l (Base Case)	Bedroom
Total	624	909
Smoldering	460	671
Flaming	164	238

NOTE: 1. Cause of death in New Product Case is 96% smoke toxicity, 4% convected heat

2. Cause of death in Base Case is 100% convected heat

EXIT89
An Evacuation Model for High-Rise Buildings

RITA F. FAHY
National Fire Protection Association
Quincy, Massachusetts 02269 USA

1. BACKGROUND

EXIT89 is an evacuation model that was developed for use as part of a software package called HAZARD I. HAZARD I, which was developed by the National Institute of Standards and Technology Center for Fire Research (NIST/CFR), includes programs that model fire growth and smoke spread in a building, the evacuation of occupants, and the impact of combustion products on the occupants as they move through the building. This package's applicability is limited to one- and two-family dwellings at least in part because of the limitations of the evacuation model currently used.(1)

The need for a model that can handle the evacuation of a high-rise became obvious during some other project work being done at NFPA. Some of the capabilities of HAZARD I's evacuation model, especially its ability to track individuals along their routes out of the building, needed to be available in the high-rise model.

Existing evacuation models are either behavioral or network flow models. The first type can be used to track individuals in small buildings such as dwellings, but they do not address queueing. The second type can handle large buildings but use queueing methods that cannot treat occupants individually. This paper describes a PC-based evacuation model for high-rise buildings that can track the movement of individuals from time of awareness of a fire until escape from the building, or entrapment. This model, call EXIT89, was designed to replace the evacuation model in HAZARD I, and so allow that package to be applied to high-rise buildings.

2. INTRODUCTION

HAZARD I can be used as a tool to evaluate the fire hazard of a dwelling. The components of HAZARD I that relate to building evacuation are FAST, EXITT and TENAB. FAST, which stands for Fire And Smoke Transport, models the conditions throughout a dwelling during a user-specified fire. Inputs to the model include the geometry of the rooms, the size and location of connections between rooms, the burning properties of the walls, floors and ceilings, the burning rate of the fire and generation rates for combustion products. The output for the model includes the changes in temperature and levels of combustion products throughout the building during the fire.

EXITT, which was written by Bernard M. Levin, formerly of NIST, is the evacuation model used in HAZARD I. It requires for input a network description of the building, the geometry of the rooms and descriptions of the occupants. It also reads in from the FAST output file the smoke density of the hot upper layer in each room and the height from the floor of the cooler lower layer. EXITT takes into consideration the behavioral characteristics of the occupants. It attempts to realistically reflect the actions of family members, including investigation of the fire by capable adults, the rescue of small children by adut females and the varying degree of difficulty waking sleeping adults. The movement of people, however, is deterministic. All individuals within an occupant class will behave in the same way and at the same speeds. Actions of occupants will not vary from run to run, or from individual to individual, as they would in a probabilistic model. EXITT's output includes the actions and locations of the occupants as they evacuate along optimal escape routes. The model is currently limited to 12 rooms and 35 nodes.

TENAB uses output from FAST and EXITT to estimate the hazard to occupants of their exposure to combustion products from the fire as they move along their escape routes. When those hazards reach certain levels defined for each combustion product, the person is considered incapacitated or dead.

HAZARD I is the best tool available for evaluating the fire risk of a building, but EXITT is of limited use beyond dwelling fires. Aside from the fact that it is limited to 12 rooms, it requires so much bookkeeping to keep track of each occupant's characteristics, capabilities, location and motivation for his or her actions that it can run very slowly. It requires too much detail on each individual to be used in an analysis of high-rise evacuation. It also recalculates escape routes throughout the entire building each time a room or node is blocked by smoke, which would be an extremely time-consuming exercise for a large building. In addition, it has no provision for queueing effects, which would be a requirement for any model applicable to large buildings.

The model discussed in this paper was designed to use the same smoke input as EXITT and to output the information needed by TENAB so as to function as a replacement module in HAZARD I for EXITT.

3. PROGRAM DESCRIPTION

EXIT89 requires as input a network description of the building, geometrical data for each room and for openings between rooms and smoke data if the effect of smoke blockages is to considered. The model will be described in detail in this paper, but the following is a brief overview.

It first calculates the shortest route from each building location to a location of safety (usually outside). It moves people along the calculated routes until a location is blocked by smoke. Affected exit routes are recalcualted and people movement continues until the next blockage occurs or until everyone who can escape has reached the outside.

Evacuation can begin for all occupants at time 0 or can be delayed. Smoke data can be used to predict when the activation of a smoke detector would occur and evacuation will begin then or after some user-defined delay beyond that time. The program is written is BASIC.

4. CHARACTERISTICS AND ASSUMPTIONS OF EXIT89

At a minimum, an evacuation model that could serve as a substitute for EXITT in high-rise applications needs 1) to be able to handle a large occupant population; 2) to be able to recalculate exit paths after rooms or nodes become blocked by smoke; 3) to track individuals as they move through the building by recording each occupant's location at set time intervals during the fire; and 4) to vary travel speeds as a function of the changing crowdedness of spaces during the evacuation, i.e., queueing effects.

The model has a local perspective rather than a global one. People will move to what looks like the closest exit, even though the total length of the path to the outside might be longer than through another exit door. For example, an occupant of a hotel stepping out of his room will head to the closest stairwell even though it may be five flights down to grade level while another stairwell a slightly greater distnace from his room might be only three flights from grade level. A model with a global perspective would move him along the truly shortest path, but that route would not be realistic for a hotel guest who would be unfamiliar with the layout of the building.

Another assumption of the model is that once people enter a stairwell, they will follow it all the way down to the outside unless it becomes blocked by the fire's progress, in which case they will move out of the stairs and onto the nearest floor. In real situations, people may head for the roof or leave the stairs to go onto lower floors for no apparent reason.

EXIT89 does not explicitly include the behavioral considerations that are included in EXITT. These behaviors include investigation of the fire, rescue of small children, alerting or waking other capable aduts and assisting other occupants that may require help. The population of high-rise buildings is too large to handle so much detail for each individual, and behaviors such as investigation or rescue of other occupants are not as relevant in larger, more impersonal, buildings. The model calculates walking speed as a function of density. This calculation will be discussed in more detail later.

5. MODEL INPUTS

The input to the model includes a network description of the building. Nodes can be rooms or sections of rooms or corridors, whichever will result in the most realistic travel paths. If FAST output will be used, the nodes defined for EXIT89 should correspond with the rooms used in FAST.

The definition of each node includes its useable floor area, the height of the ceiling, its initial occupant load, and the number of seconds occupants of that room will delay before beginning evacuation. The definition of each arc includes the distance between nodes and the width of the opening between the nodes. Arcs are bidirectional. Escape via windows is allowed by assigning a very large value as the distance along the arc so that that route will only be used as a last resort.

6. USING THE MODEL

EXIT89 can be used in two different ways. The user can input the names of nodes that become blocked by smoke and the times those blockages occur. Or, the user can use the smoke data output from FAST as input to the model. In the first version, evacuation begins simultaneously throughout the building at time 0, plus any delay time specified at nodes by the user. In the second version, evacuation begins throughout the building when the smoke level reaches that defined for smoke detector activation, plus any delay time specified at nodes by the user. By using the first version and not specifying any blockages, the user can model emergency evacuation of a building with no fire occurring.

The program will print out the movement of each occupant from node to node. It also records the location of each occupant at each time interval so that the output can be used as input to TENAB. TENAB will calculate the hazards to which each occupant was exposed using FAST output for combustion products and will determined when incapacitation or deaths occurs.

7. SHORTEST ROUTE CALCULATIONS

Shortest routes are calculated for each floor, from each node to the stairways or to the outside. The shortest route algorithm used is that described by Hillier and Lieberman as the shortest and simplest of those they reviewed.(2) The algorithm begins by identifying the origin of a network and then fans out from the origin, identifying the shortest routes to all the other nodes until the destination is reached.

The adapted version of the algorithm used in the model calculates the shortest routes on each floor to the stairways or the outside or any other defined locations of safety. Locations of safety can include horizontal exits or areas on the other side of fire doors. The route down each stairway is then established by defining the connected node for each stairway node as the one below it.

One advantage to the approach used in EXIT89 is that the blocking of a node by smoke will only require the recalculation of the routes on that floor, rather than all routes throughout the building. If a stairway node is blocked by fire, the routes on that floor and the floor above will be recalculated. This will cause occupants in the stairway on higher floors to move out of the stairway when they reach the node above the smoke-blocked node.

Another advantage of this approach is that it more closely approximates the local perspective of an occupant in the building. Other shortest route routines see all possible routes to the outside and so they make decisions based on information not available to a real person.

8. CALCULATION OF WALKING SPEEDS

EXIT89 uses walking speeds calculated as a function of density based on formulas from Predtechenskii and Milinskii.(3) Repeatedly calculating velocities using these equations for every occupant througout a fire simulation would be extremely time-consuming. Fortunately, tables of velocities by density were given for normal, emergency and comfortable movement along horizontal paths, through openings and on stairs. EXIT89 assumes that people are aware of the fire emergency when they evacuate, so only the velocities for emergency movement are included in the current version of the model.

Initially, the program was coded the way the formulas were given; that is, the density was based on the area of the stream -- the width of the doorway by the length of the stream of people. This resulted in reduced velocities even when only two people were in a room, and could noticeably decrease walking speed when, say, six people were in even a fair-sized room. People do not necessarily line themselves up so closely when evacuating through rooms. They can spread out and so maintain a more rapid, free-flowing walking speed. The formulas used in the model now calculate densities based on the floor area of the nodes. For travel along corridors, the useable floor area and the area of the stream as calculated by Predtechenskii and Milinskii will be very close, if not identical.

This model does not yet simulate people crawling through smoke.

9. MOVING THE OCCUPANTS

The initial shortest routes throughout the building are calculated before any smoke data is read in. The model begins by calculating, based on the initial distribution of occupants, how long it would take to travel from each occupied node to its connected node. Then for each occupant, it looks at how long that occupant has been at that node and how long it takes to traverse the arc. If the occupant has been waiting long enough to traverse the arc, the occupant is moved to the next node, and the waiting time at that node is set to 0. Waiting times are actually portions of the arc traversal times. If there are still occupants in the building, the model recalculates time to traverse arcs based on the updated densities at nodes.

The sequence is repeated until the time is reached when a node is blocked by smoke. At that point, the affected node is removed from the network, any occupants at that node are counted as trapped and shortest routes are recalculated for the affected floor (or floors if the node is in a stairway). People movement is then resumed until the next blockage or until everyone is either out of the building or trapped.

Queueing is handled by the decreased walking speeds that result from increased densitites as more occupants move into a room or stairway. The program does not currently allow occupants to select less crowded routes. They simply join the queue at nodes along the shortest route.

10. LIMITATIONS OF THE MODEL

The model in its current form does not include any explicit behavioral considerations. Occupants who are aware of the fire do not assist other occupants or travel to other nodes to alert them. This may be realistic in an office environment where everyone should be awake but may be less so in a hotel. Once an occupant begins evacuation, s/he does not stop unless blocked by smoke. Behavioral considerations can be handled implicitly by incorporating time to perform investigation activities or to alert others before evacuating in the delay times that the user specifies for the occupants of each node. The model will be modified to allow occupants to be defined as assisters or assistees. Due to the degree of impersonal-ness of large buildings, assistance will be limited to others at the same node, e.g, family groups in hotel rooms or a handicapped person's coworkers.

Another behavior that is not yet incorporated in the model is the tendency of able-bodied adults in the presence of other able-bodied adults to ignore early warning of the presence of a fire. This diffusion of responsiblity has been observed in actual incidents and needs to be added to this model.

Walking speed is calculated as a function of densitites and is based on tables of values from Predtechenskii and Milinskii. The model does not yet simulate crawling through smoky rooms by reducing walking speeds, or reversing direction where possible to use a less smoky, though longer escape route. These changes would not be difficult to incorporate.

One of the program's inputs is the capacity of nodes. The reason for including this value was to allow evacuees to avoid nodes that were already crowded if alternate routes are available. This would prevent occupants from queueing at one stairway while the other section or sections of the floor emptied out into less busy stairways. That logic also has not yet been written.

11. CONCLUSION

EXIT89 is still in a developmental stage. Additional testing and validation of the model are required. Some of the current limitations of the model, and the actions needed to address them, have been presented. The structure of this model allows those changes to be incorporated, resulting in a model that will be able to substitute for EXITT and still include essential human behaviors and interactions, but be able to handle much larger buildings efficiently and realistically.

12. REFERENCES

1. R.W. Bukowski, et al., "HAZARD I - Volume 1: Fire Hazard Assessment Method," National Institute of Standards and Technology Center for Fire Research, NBSIR 87-3602, July 1987.

2. F.S. Hillier and G.J. Lieberman, Introduction to Operations Research, third edition, Holden-Day, Inc., Oakland, California, 1980.

3. V.M. Predtechenskii and A.I. Milinskii, Planning for Foot Traffic Flow in Buildings, Amerind Publishing Company, Inc., New Delhi, 1978.

DEVELOPMENT OF A LABORATORY RADIANT COMBUSTION APPARATUS FOR SMOKE TOXICITY AND SMOKE CORROSIVITY STUDIES

PRESENTATION TO
11TH JOINT MEETING OF THE
UJNR PANEL ON FIRE RESEARCH AND SAFETY
October 19-24, 1989

ARTHUR F. GRAND
SOUTHWEST RESEARCH INSTITUTE
P. O. Drawer 28510
San Antonio, Texas 78228-0510

A new laboratory apparatus has been developed and been shown to be useful for evaluating either the toxicity or corrosivity of the smoke produced from actual products. The apparatus features radiant heat combustion of the specimen and collection of all of the smoke produced. Three important fire parameters may be determined using this apparatus. They are: 1) time to ignition, 2) rate of smoke evolution, and 3) characterization of the smoke (e.g., toxicity or corrosive effects). These may be evaluated as a single, measured test parameter or determined independently and then combined mathematically. The parameters determined in this test method may be used to help estimate the hazard of a product in an actual fire scenario by using computer fire models.

The apparatus is shown schematically in Figure 1. It is an improvement on an earlier radiant furnace smoke toxicity test device (1), which was a modification to the NBS (now NIST) "cup" furnace toxicity test apparatus (2). The unique aspects of this apparatus compared to others currently in use may be summarized as follows:

1. A relatively large size specimen can be used and radiant heat of up to 70 kw/m^2 is applied to the top face of the specimen, permitting testing of actual products (even composite products) in addition to raw materials.

2. An enclosed combustion/exposure system permits collection of the total amount of smoke produced from the specimen.

3. Continuous mass-loss measurements are obtained.

4. The radiant heat system permits essentially instantaneous heat radiation to the specimen and adds a minimal amount of heat to the enclosed chamber.

5. The combustion atmosphere may be modified before or during the combustion and/or exposure phases of an experiment (e.g., by controlling the oxygen concentration).

6. The combustion cell can be isolated from the exposure chamber by a shutter in order to terminate the combustion phase of an experiment. Thus, the smoke becomes isolated from (and therefore is no longer influenced by) the specimen residue or the hot combustion cell.

7. The smoke in the exposure volume is available for:
   a. analytical measurements, including those requiring a long sampling time and large sampling volume;
   b. toxicity determinations, including those under "steady state" smoke conditions;
   c. corrosivity measurements, even those utilizing large or multiple targets; and
   d. almost any other physical or chemical characterization of an accumulated quantity of smoke.

A plot of a typical smoke concentration vs. time curve (in this case, Douglas fir) is presented in Figure 2. The processes that occur during the test procedure are illustrated in this figure. At zero time, the radiant lamps are turned on to irradiate the specimen, which is located on the sample platform within the combustion cell. After some period of time, the specimen ignites (t_{ig}). Generally, the mass loss rate is not very high until ignition. After some predetermined time interval, the radiant lamps are turned off and the smoke shutter is closed. This is the "irradiation time" (IT). From that point on, the smoke concentration (and that of any non-condensible gases) remains essentially constant until the end of the test (e.g., 30 minutes).

The three key parameters determined in this test method are illustrated in the figure. The time to ignition is shown. The mass loss rate is illustrated by the slope of the line of smoke (or gas) concentration for the time between ignition and the stopping of combustion (generally at the irradiation time). Characterization of the smoke is conducted on the quantity of smoke or gas evolved.

A test method may be conducted in this apparatus under at least two different procedures. In one, a fixed quantity of specimen (e.g., 7.5 cm x 12.5 cm, 3 in. x 5 in., which is the largest practical size) is used, with a variable irradiation time (IT). Combustion is generally stopped at relatively short IT's (anywhere from one minute to perhaps 10 minutes). This smoke may represent the "early" smoke produced from a specimen under this test. In another procedure, the quantity of specimen is varied and the IT is fixed (e.g., at 15 minutes). This procedure tends to bake small specimens for a longer time than in the other procedure and the smoke would be a mixture of all products produced from the specimen over the time duration.

A hazard "index" for the first test procedure could be reflected by the IT required to produce an atmosphere that gives a set response (e.g., a particular toxic or corrosive end point). An alternative method, applicable to either test procedure would be to develop independently the three primary variables developed in this test procedure: ignition time (t_{ig}), mass loss rate (MLR) and a number characterizing the smoke (SC for "smoke characterization," e.g., an LC_{50} for toxicity measurements or some corrosive end point). These three may be combined mathematically to produce a simplified index of toxic hazard, such as the following equation:

$$\text{Toxic Hazard Parameter} = \text{Function of } [MLR/(T_{ig} \times SC)].$$

The full potential for this apparatus has not been examined experimentally. The apparatus offers the unique ability to control the atmosphere (oxygen concentration) during the burning process in an enclosed system. The ability to stop combustion at any time during the burning in order to examine the smoke produced (or even to isolate a quantity of smoke in the middle of the burning process) is a further very desirable feature. Physical collection of the smoke, without having to resort to synthesizing the total smoke volume, along with knowing the mass of that smoke, is important for physical, chemical or biological characterization of the smoke.

The question still remains whether or not one can simulate a realistic large-scale fire environment in this (or in any) laboratory apparatus. There is a tendency to believe that application of a relatively high heat flux, such as produced in large scale fires, will automatically simulate that particular large scale fire environment. In fact, when smoke toxicity considerations are paramount to the testing, the oxygen availability may be a more critical factor than the applied heat flux.

REFERENCES

1. Alexeeff, G. V., and S. C. Packham, "Use of a Radiant Furnace Fire Model to Evaluate Acute Toxicity of Smoke," J. Fire Sciences, Vol. 2, July/August 1984, pp. 306-320.

2. Levin, B. C., A. J. Fowell, M. M. Birky, M. Paabo, A. Stale, and D. Malek, "Further Development of a Test Method for the Assessment of the Acute Inhalation Toxicity of Combustion Products," National Bureau of Standards (U.S.), NBSIR82-2532 (1982).

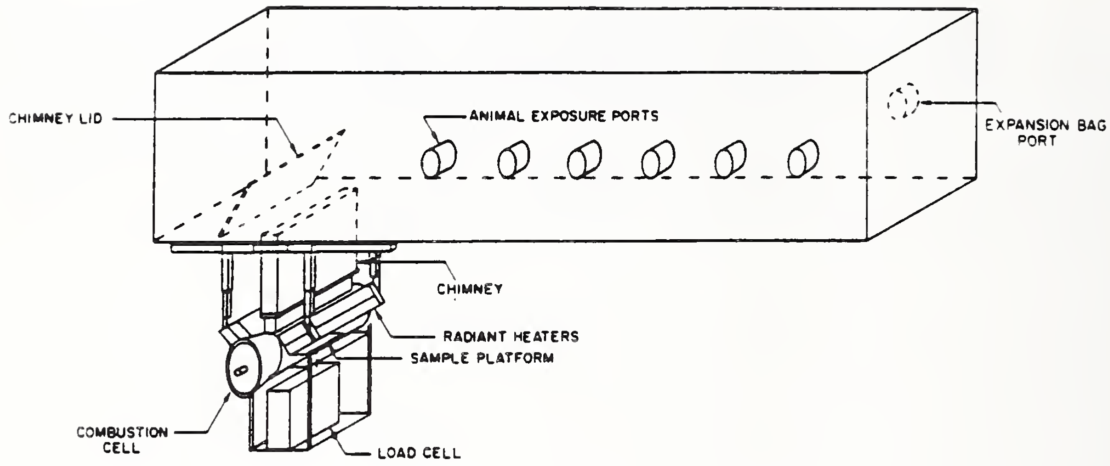


Figure 1. Schematic Drawing of Radiant Combustion/Exposure Apparatus

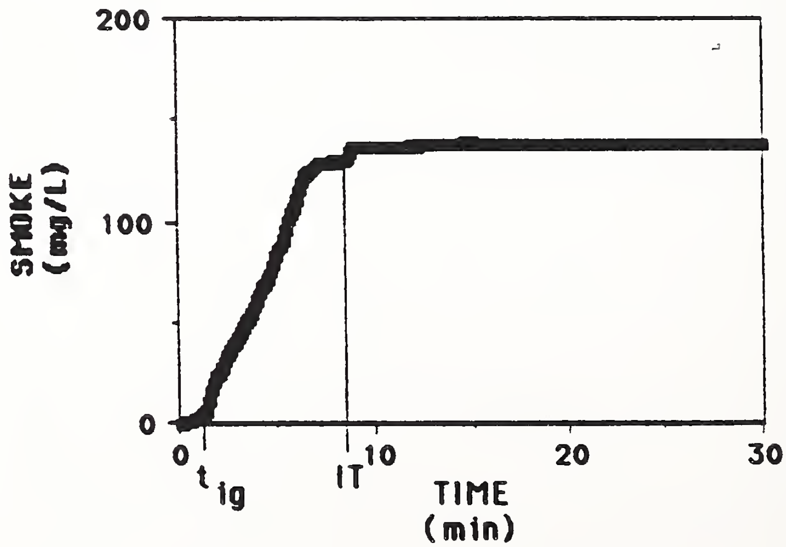


Figure 2. Typical Smoke Concentration - Time Curve

DISCUSSIONS

OPEN TECHNICAL SESSION

[Questions for W. Pitts Paper, R. Gann Presenter]

PROF. ZUKOSKI:

I'd like to make one comment. I'm concerned with your vitiated test in the cone apparatus in the sense that we think that having the two layers is a very important part of this. If we go and look at a single layer with a flame completely in a vitiated layer, it just goes out when you get down to 10 or 12 percent oxygen. At least with a simple gas like methane, we don't make anything wild, and so I don't quite know what you're going to get out of that. I think the two-layer part of the thing is important, and I think it's a very tough, tough problem.

Let me just add one thing. We've recently tried to understand the differences between several sets of our tests, and we conclude that the temperature of the gas in the upper layer is more important than we thought; that if we have low enough temperature we end up even with very rich mixtures, we end up with 3 or 4 percent oxygen. If we get the temperature up to, say, 500 or 600° Kelvin, the amount of oxygen left over gradually goes down and eventually vanishes about 600° Kelvin.

[Answer by R. GANN]

. . . the importance of the upper layer and the reduced scale experiments are one more geometry to do the kind of thing you've been doing. However, we ran some preliminary tests last year in the cone for a small number of materials--solids and liquids--and we varied independently the oxygen percent and the air flow rate. We found, much the way you did, that if one decrease the oxygen, the carbon monoxide doesn't change a lot, and the flame eventually goes out.

However, when we decreased the flow rate, we saw massive increases in carbon monoxide. So this is a small amount of data, and we need more to bracket any correlation.

PROF. PAGNI:

Can we get away with CO equilibria, or are kinetics required? That is, if I take a simple flame, and assume for the moment that we can deal with flames, and perhaps the difficulty is that isn't sufficient. We also have to deal with surface reactions. And if I trace an element through the reaction zone, is it possible to simply have equilibria at each point along that zone, and then from the fluid mechanics added to that chemical equilibrium only worry, determine the amount of CO? Or, do I need to get into the problem, with a big "P", of the kinetics involved in the particular system that I'm dealing with? I think that's a critical question to ask an answer.

Because if we can answer that, then it throws the ball back into the hands of people like Zukoski, who are doing the fluid mechanics, and if they tell us what the composition is, and what the temperature is, and what the flow is at any point in the field, we could calculate CO for comparison with our tests. But I think, until that question is answered, I'm a little worried about charging off and doing all this testing.

[Answer by R. GANN]

The simple answer--there are three, at least three combustion zones where carbon monoxide can be formed or destroyed. The first is in the plume above the burning material itself. The second is the volume between that plume and, let's say, the door. Generally, in a zone model we call that the upper layer. And third, it can be created or destroyed if there is burning outside the door. Each of those represents a challenge to a correlation approach or a straight chemical approach. We are, based on the expertise that we consulted, we're putting our money on the fact that some sort of correlation is going to work to a reasonable degree. That is why the plan is worded the way it is.

That is, that if we use correlations in the plume, correlations in the upper layer, correlations outside the room that, in principle, we should be able to predict the yield of carbon monoxide. If we firmly believed that, that would be the only part of the plan. But we have engineers over here, and we have scientists over here, and the scientists, quite correctly, have identified a number of reasons why that correlation will not be sufficiently general.

PROF. PAGNI:

I agree with the direction you went in. I agree with your answer. The correlations, I think, would be great for those three zones you talked about. But I think those are perturbations to the problem. I think the essence is back in the flame. We need to know the answer to the question: Does equilibria suffice or not to produce the CO in the first place?

If I went to my computer and worked very hard, and we studied simple enough systems so that I could tell you the local temperature and the local species everywhere in the flame, would that suffice, without any consideration of reactions and their rates, but only the equilibria, would that suffice to give me the source term for the CO?

Your answer addressed the questions of what happened to it later, but I don't think that's the critical part of the problem. (But I may be missing it.) The critical part of the problem is in the flame, the local conditions. It's like. . . .

The best analogy I can think of is the NO problem. We've got all this air pollution work in automobiles, and we find out there that what matters is that equilibria of the NO at the peak temperature. Is there a similar simple idea for CO? And we ought to nail that down before we work on what I think are going to be secondary effects in the plume, in the room, and outside. Let's get back to the flame and talk about the production term. And I won't ask any more questions.

[Answer by R. GANN]

I respectfully disagree with your presumption. Nitrogen oxide chemical kinetics have a much, much stronger temperature dependence than either the CO formation reactions or the CO further oxidation and reduction. So my suspicion is that in the flame zone, it's the perimeter of the flame rather than the core of the flame that matters, and that, as Ed has shown, even the lower temperature region in the upper layer can still have some effect. Therefore, it's critical that the experiments be done in which the variables are separated to find out whether Pitts or Pagni walk off with the red rose.

DR. JIN:

You mentioned that CO is the major hazardous thing, but other toxicants are also produced in the flame. So, from the hazardous point of view, more total review not only of CO, but of the other toxicants must be included.

[Answer by R. GANN]

Tomorrow I will be Dr. Babrauskas, and I will describe a project that addresses exactly what you are talking about.

[Questions for H. Suzuki Paper]

DR. SNELL:

Now, I certainly agree with the objective. The 64-dollar question is how to do it. You must have some thoughts.

[Answer by H. SUZUKI]

We don't know at the momert, so how can we do it? We are thinking about that. How can we do that? Because the latest method proposed at ISO meeting, and after many discussions, but only a few committees agreed over adopt the standard.

From the point of view of scientists, it maybe not too difficult, but if we include the political or administrative, it may be difficult.

DR. SNELL:

It was my observation that one of the major driving forces in the U.S. is litigation. There is a factor other than the test methods themselves. That is, if you can show the consequences of a fire were a result of the performance of a product, using the scientific methods, it's almost immaterial what the test methods used for approval were. Now, that complicates this picture somewhat, but it suggests to us a choice. Either we, together, select a test method to improve or introduce, for example, for wall linings, or we, together, look to improve our ability to demonstrate the connection between product design and fire outcome and pursue that route to a change in ISO.

PROF. FERNANDEZ-PELLO:

I think that this picture has brought a very interesting point, in my point of view, the introduction between the tests viewed from a scientific or technological point of view and facts of life. We often look at tests, whether it is an ignition test or a flame spread, from the point of view of is this material going to ignite or not, or how much heat is released. But maybe, if we are aware that the consumer is going to buy a certain product in any case, maybe the tests should consider those facts and address more the consequences or address aspects that should be considered in the design or implementation of the product rather than what we are doing right now of just determining whether it ignites or not, or if the flame spreads or not. I think, at least for me, it is very interesting.

[Answer by H. SUZUKI]

. . . so I said for one kind of material, the test method should be maybe double or triple--I don't exactly the number of test methods, but for tests at each stage of fire, the developing fire and the fully developed stage of fire. Then, first data will give the spread of fire along the material itself. The later data will give the potential energy of the material which was involved in the fully developed fire, I think. Dr. Snell said it's very complicated to introduce a new test method. I actually agree with him, and I am thinking, what is the direction to our real target, and it may be very, very difficult. We think we have to make effort for our real target.

DR. KASHIWAGI:

This question is maybe following Carlos' question, Carlos Fernandez-Pello. In the United States, some of the material--this is not flammability--but like water heater to car mileage, in some things, their performance is specified, and the consumer decides what they want to have. So, rather than this case, the engineer or scientist decides what it should be, but the consumer decides what they want to have or maybe what they want to risk. So that might be one possibility.

[Questions for R. Gann's Paper]

PROF. FERNANDEZ-PELLO:

Well, I think that this project is a wonderful opportunity to see how one of these operations will work out, and the comment that I have is that if we had a fundamental knowledge of how a fire retardant acts, it would certainly simplify this project tremendously since I think that part of the problem is that we don't understand very thoroughly how the suppressants work. So in these kinds of projects, there are a lot of trial and error. That's what makes it so long. I think it will be fascinating to see the progress of this type of project through the years.

[Answer by R. GANN]

There is a sizeable amount of chemistry and physics for flames and flame extinction in the program. So if the sponsors will pay for that, then the flame science that you are interested in will, in fact, get done.

PROF. ZUKOSKI:

Do you understand how the stuff works now from an engineering point of view? I mean, you don't have to go away and do a lot of studies on these two things, do you?

[Answer by R. GANN]

Prof. Pagni would question whether I understand anything from an engineering point of view. Halon 1301 is a gas. It's dispersed as a gas, and it is entrained into the flame, and we think we understand the chemical interaction with the flame. Halon 1211 is a liquid and is thrown at the fire from a distance as a liquid, and there are very, very interesting fluid mechanical issues. The droplet's penetration of the flame may be more important than the chemical activity, and that we don't understand.

DR. DING:

Some people say that halide will be produced, a toxic, so if the answer is positive, halide could be used in basement, enclosure basement of a building. In what type of occupancies is halide best used?

[Answer by R. GANN]

. . . especially Halon 1301 in places where people must stay in the room, and exposure to 5%, which is the design number, for several minutes is not a real problem. Longer is probably okay, but NFPA 12A allows 5% for approximately 10 minutes.

DR. DING:

Is there any upper limit?

[Answer by R. GANN]

Not that I know of. Economists and lawyers want to know why I just can't go back 30 years to the first work that was done and take the second-best compound and substitute it for CF_3Br. Thirty years ago, a small number of compounds like these, all very similar, were tested for flame inhibition effectiveness using the explosion burette--a totally invalid way of measuring fire suppression. Butane is an excellent fire suppressant based on the explosion burette. Of course, nobody uses butane to put out fires. The results from these two and five or so more totally halogenated compounds looked sufficiently good that people immediately went to medium and large-scale testing and found that they still worked. So what started out as a exploratory research program immediately went to testing and code qualifying, so no more real research was done.

About 15 years later, a small number of people--Forman Williams, Bob Fristrom, Joan Viordi, and myself--started looking at "could one do better than these?" And that was the answer was, "How can you do better than perfect?" The net result is that there is very little literature on compounds that are reasonable flame suppressants that are chemically different from these. The program, that very wide funnel, includes every chemical entity that we can think of that should be able to inhibit a flame.

[Questions for T. Kashiwagi's Paper]

PROF. FERNANDEZ-PELLO:

A comment: You brought a very important point from the point of view of testing that melting or motion of the material is going to influence the type of test or the results of the test.

Your results will depend strongly on the orientation. For example, the ignition results you have, instead of feeding horizontally, the feed is vertical. You have different results. We can never ignore in our testing in that the definition of our testing apparatus is the possibility of melting.

[Answer by T. KASHIWAGI]

At this moment, we have a tendency to neglect or ignore this drippiness, and one difficulty is we see that phenomena, but we don't have a good tool yet to quantify that effect. Another real question is: how does that affect hazard?

Fire and Toxicity Chemistry Session

[Questions to R. Gann on V. Babrauskas' Paper]

PROF. ZUKOSKI:

I wonder why you think that you'd get the same species in two different full-scale tests? It's clear that the production of CO is very dependent on where the interface between the hot layer and the cold layer and that. . . . I don't think there is any reason to expect that you'd get much better correlation if you did three or four different full-scale tests, that really exercise the variables that you're interested in.

[Answer by R. GANN]

A very good question. The expectation is that early pre-flashover, that is, while the combustibles are still almost in a free-burning mode, it should be possible to simulate some of the combustion physics and combustion chemistry in a small-scale apparatus. As the multiple stage combustion in the room becomes important, the expectation is any small-scale apparatus will fail most of the time. When one gets to post-flashover conditions, once again the possibility exists that there are some points of similarity which can be captured at small scale.

Should this simplification hold, then the critical factor is that the intermediate region that you were just describing that I'm hoping is unimportant because it is extremely geometry and material dependent, the hope is that that accounts for a relatively small fraction of the time-integrated toxic product production.

If the accuracy level of small-scale devices is only a factor of five in replicating large-scale results, then the way that we think about regulation on the basis of toxic potency of smoke needs to be modified considerably.

DR. FRIEDMAN:

In regard to the question of whether other toxicants could be hoped to track the carbon monoxide, surely the HCl would not do so, would it?

[Answer by R. GANN]

I would be very surprised if it did.

FIRE AND SMOKE PHYSICS SESSION

[Questions for Dr. Hasemi's Paper]

DR. HESKESTAD:

You have a burner that's four and a half meters in diameter, is that correct?

[Answer by Y. HASEMI]

Yes.

DR. HESKESTAD:

And that's a gas burner?

[Answer by Y. HASEMI]

Yes.

DR. HESKESTAD:

That's fantastic. Could you show the principle of its construction?

[Answer by Y. HASEMI]

Basically, it consists of two burners. If you want, I will send you something about this.

DR. HESKESTAD:

Yes, thank you.

PROF. PAGNI:

Is it possible that the radiation is responsible for the differences you observed between the methane and the propane, because the flame height perhaps is measured as a function of the visible flame?

[Answer by Y. HASEMI]

Yes.

[Questions for Hasemi's Paper]

DR. QUINTIERE:

In your experiment, it is always difficult to measure upward spread rate, and a more easily sort of discernible piece is the flame height. So, in that regard, it might be useful to extend your wall beyond the specimen, so that you can measure the flame height continuously. We've used this, I think, as you know with the work of Kulkarni. Maybe you haven't seen it plotted that way. But recently, he has presented his data in terms of flame height or energy release as a function of time. If you know flame height, it's related to energy release.

[Answer by Y. HASEMI]

We are going to major flame height, so it is a good idea to extend the backward support for the wall. But I think it is easy to estimate flame height from heat release rate, but it is difficult to estimate heat release rate from flame height. We are not so successful in estimating of heat release rate.

PROF. ZUKOSKI:

If we consider the results of the last paper before you which indicated that turbulence might have a substantial effect. It might be interesting in all of these experiments to measure the turbulence level properties because they will be different in different laboratories, and this might have a substantial effect on the flow.

MR. NELSON:

I would strongly urge that you try to get at least one screening test across a very broad sample, so that we get some advance consideration whether or not this will work on laminates, whether it will work on a wide variety before you invest totally understanding PMMA and plywood. Again, I would suggest a screening view across Saito's entire line, and it would give you an advance idea of whether this is a usable regulatory device or engineering data. If it looks successful, I suggest you apply this test also to furniture material so that we have some common understanding between the various things that burn in a room.

[Answer by Y. HASEMI]

The only reason why I selected PMMA and plywood is that we have much data of these properties. So we want to start with this PMMA and plywood, and next year probably we can do various materials.

DR. QUINTIERE:

Are you proposing this as a test method, or are you doing these experiments just to get some data, and then the test method may be other devices that give you the information to make predictions? Which of the two?

[Answer by Y. HASEMI]

I think this process to be a standard test.

PROF. PAGNI:

It also would be interesting to compare your test results with the first model available from NIST, as well as the OSU model.

MR. NELSON:

. . .the rate of heat release, you have to put that as an input.

PROF. PAGNI:

Not necessarily. One of the two options is to include it as input, and the other is to let it grow.

MR. NELSON:

Try it on a vertical input.

PROF. PAGNI:

Okay.

[Questions for J. Shaw's Paper]

MR. SHAW:

Maybe this would be a good opportunity to clear something up. My understanding is that the OSU model is the only model that's really designed to handle the fire growth of wall lining materials. Now, if there is input contrary to that, we're certainly anxious to hear it because the OSU model does have certain limitations. It's based on the E-906 apparatus, which exposes a 6" x 6" sample. It is difficult to get the flame spread rate from that kind of exposure.

I should point out in relationship to that that Mark Janssens at NIST is working with the LIFT apparatus and that data, as well as cone calorimetry data and is attempting to use that input in lieu of the rate of heat release apparatus input that Professor Smith uses, and that we have been using. So we're actually getting a comparison of flame spread and rate of heat release, empirical data, from two different sources and being able to compare that. I should also point out that Mark Janssens also predicted this room fire and was also very close in terms of his prediction of the flash-over time. So one would expect that his curves would look very similar to these.

PROF. PAGNI:

. . .and he responded that he thought the OSU model was the only one that could handle vertical growth of a fire.

I asked if the first model at NIST could also be used to model the experiments.

PROF. WILLIAMSON:

First of all, there is a very good corner test model that Michel Curtat has written; it's at CSTB in France, and he has modeled very successfully room corner performance. But, let's go back to your curves. I don't think it's much of a prediction to predict that a room will flashover when you switch from a 40 kilowatt fire to 150, and you'll see that today in the experiment we're going to run at the field station.

I think it would be a much better test of the models if you would run it at either 150 or some intermediate value from the beginning because it obviously isn't going to flashover at 40, and then you go to 150. At that time, it's preheated, and it's just going to go right up. So, I would say either one or the other. Either use a different ignition source program that might hold steady, or don't try to claim too much of a correlation between the two.

[Answer by J. SHAW]

We're curious. We did see flashover under the 40-kilowatt exposure in the first 5 minutes with the OSB panel, and we did not see any flashover in the full 15-minute test with the fire retardant treated wood. So, we do see some differentiation of flammable materials in this particular model. The two materials on the extremes, the one with the low flame spread, did not flashover in the full 15-minute test, even with a 160-kilowatt exposure. Whereas, there was one wood material, the oriented strand board with the higher flammability characteristic which did flashover under a 40-kilowatt exposure only in the first 5 minutes of the test. So, we do see some range there and we're very anxious to see what the model will do with that. It very definitely should be able to handle that. If not, then it's back to the drawing board and definitely some modifications to the model.

MR. NELSON:

This just a curiosity. If you put that slide up where you had the American words and mix them all up, you'll get the same sense. If you put "hazard" where you've got "danger" and "risk" where you've got hazard, most Americans use them interchangeably.

This paper is absolutely right; a more universal protocol has to be developed. I believe that to use the word "risk" or "hazard" out of a complete sentence is like using a value without dimensions. You must say, "The risk of something, given something," so that the listener understands how you are using it, which is, I expect, the way the Japanese must use the word "kiken", if I'm pronouncing it correctly.

[Questions for R. Friedman's Paper]

DR. GANN:

In comparing the free-standing jet with the slot burner up against the wall, do you use the same flame temperature in the calculation?

[Answer by R. FRIEDMAN]

In the data I showed, I don't think there was a calculation. These were measured quantities.

DR. GANN:

Significantly different flame detectors might explain the different radiant fractions.

[Answer by R. FRIEDMAN]

That might well be. It's almost certainly so.

DR. QUINTIERE:

In the flame spread problem, the total heat flux and its extent is really a key factor, and I wonder if you're measuring the total heat flux as well? Because one of the comments you made about expecting that the radiated fraction should be a critical parameter and results highly sensitive to it, I could almost see the opposite coming about in that if something radiates more, it's radiative heat flux might be high, but it's flame temperature is likely to go down. Its convective heat flux would be lower. So, it's a compensation between these two heat flux modes, thereby suggesting that maybe the total flux may not change significantly. I wonder if you've measured the total flux and can speak to variations?

[Answer by R. FRIEDMAN]

Yes. We have measured the total heat flux, and no, I'm not prepared to speak on it. I don't have the facts.

I neglected to say that there were more experiments up afar. I neglected to say that I only gave what I thought were some interesting abstracts of what was done. We actually studied four geometries. One was a turbulent jet flame --axisymmetric. Second was a slot burner out in the open. Third was a slot burner pushed up against a wall, a solid wall. And fourth is a porous wall where the fuel was coming out through the. . . . We're doing all four. We realize they're all different.

[Questions for Chief J. McMullen Presentation on Earthquake Damage and Response of Fire Fighters]

[Answer by CHIEF McMULLEN]

Well, I can't speak too much for Japan, but it was my understanding that the Japanese population as a whole is generally more concerned with disaster than the American population. However, what I can tell you about is the American population.

The American population is almost, in my judgment, at an information overload. We say: "Be prepared for earthquake." "Be fire safe." I have just rented 90 billboards throughout the state that say seven words. You'll see them as you're cruising around California, and they say: "Is yours working? Smoke detectors save lives."

This is a natural spin-off of our 10-year-old campaign we used to have where we said, "Smoke detectors save lives." We have 80 percent of our nation now protected by smoke detectors. Ten years later, several things have occurred. They don't work. A third of them are not operating from either batteries or just simply shelf life. A 10-year-old smoke detector may have exceeded its shelf life. Or, they've been put in by someone who knows nothing about them. Back in the days when we were promoting them, the same folks were putting them in.

We're trying to educate the public, and we're adding a little Madison Avenue approach. "Is your working? Smoke detectors save lives." So the maintenance of smoke detectors. . . .

We're competing against "Say no to drugs," child abusers, and many other things from AIDS, and all these things we're competing against at the American population to get their attention.

On the tape, you will see where several citizens were there helping to fight the fires. Citizens of this country volunteering to help "any way I can" as well as Fire Chiefs of Washington, DC and Houston offering help.

The trouble is how do you manage all this resource? You have to have it in some kind of a controlled manner, such as the Red Cross, the Salvation Army, or these volunteers that work for the military or through the fire departments or some such. Yes, there were a lot of offers of help. But are we prepared? No.

Should we be? Yes.

[Questions for G. Heskestad's Paper]

<u>DR. QUINTIERE</u>:

It wasn't obvious to me whether the height of the facility entered into it, particularly when you had the ceiling vent? Did it enter in, and if didn't, why didn't it?

[Answer by G. HESKESTAD]

It would enter into it in the sense that if there were non-uniformities in the temperature distributions over scales comparable to the size of the vent, then if there were non-uniformities on that scale, it would be important. Evidently, there was. . . . We didn't see any effects.

DR. GANN:

Would you roll back the slides to the one where you had the Froude number plotted as a function of the Grashof number? You said that at the higher Grashof numbers that the Froude number was approaching an asymptote, the basis for that was the one full-scale test that was at the same value as the intermediate range small-scale tests. The presumption then is that all the physics that are represented in those two combined numbers are preserved between the large and the intermediate scale. If that is not true, then clearly there is no basis for the asymptote. Can you comment on how strong your conviction is that those are, in fact, the same data set?

[Answer by G. HESKESTAD]

I am strongly convinced that they belong to the same phenomenon. As we increase the Grashof number, turbulence approaches an asymptotic structure in the large scale; not in the small scale, on the large scale. We typically expect an asymptotic range at high Grashof numbers, which in forced flow situations correspond to Reynolds numbers. So, I'm very convinced that it's the same phenomenon represented along the entire lower asymptote.

DR. ZUKOSKI:

In some work with Dunn in this area using salt water modeling, we found that the depth of the wall that formed the ceiling when you had the hole in the ceiling was an important parameter, or it seemed to be to us in the salt water modeling, that the depth of that hole as you went from a very thin ceiling to a very thick one, that it made a difference. Can you comment on that?

[Answer by G. HESKESTAD]

I have examined the data for such effects, but I have not seen any, and I think primarily because the depth of the hole compared to the width of the hole were all small in the sense that you speak of.

DR. KASHIWAGI:

The opening is on the wall and then in another case on the ceiling. Suppose both are the same sized opening area. What physical process affecting this different value of "C"?

[Answer by G. HESKESTAD]

We think the physical processes are much different, wall aperture flow versus ceiling aperture flow. I think the wall aperture flow is fairly easy to understand in the sense of the simple theory that I mentioned. The ceiling aperture flow is extremely complex and is an entirely different kind of phenomenon, and that's probably why we're seeing that the turbulence or the Grashof number is a very important factor in that case, but we are quite ignorant about what goes on in the ceiling aperture.

DR. KASHIWAGI:

The second question: "is the shape of the flame very important?" In your case, you assumed a pure cylinder. However, the results seem to agree reasonably well.

[Questions for Klote Paper Presented by J. Quintiere]

PROF. ZUKOSKI:

Is it possible that the CO went up because the interface came down like in our experiments with methane?

[Answer by J. QUINTIERE]

In the case of the smoke control?

PROF. ZUKOSKI:

Without the smoke control, most of the flames were burning in above the interface. Did you have any idea where the interface was?

[Answer by J. QUINTIERE]

I would think that the interface with that small opening would be pretty near the floor.

PROF. ZUKOSKI:

I see.

[Answer by J. QUINTIERE]

And even if an interface is sort of an idealized phenomena. There would be a lot of mixing, I think, for that kind of case, and there would be a stratifying, I think, of oxygen.

[Questions for M. Tsujimoto's Paper]

DR. GANN:

In both sets of tests, it looked like the room was wider than it was tall.

[Answer by M. TSUJIMOTO]

Right.

DR. GANN:

When I think of an atrium, I think of taller than it is wide (limited experience, I guess). Would you expect your same scaling relationships to hold for that other kind of aspect ratio?

[Answer by M. TSUJIMOTO]

Oh, very much so. I didn't make experiments about the ratio of the height because of this, so I'm not sure, but I think I can use these theories to use the type of these relationships.

PROF. ZUKOSKI:

If you look at the early work of Martin and Turner, they concluded that if the aspect ratio of the height to the width was big enough, that they got quite a different filling. So that's something you might want to look at.

[Answer by M. TSUJIMOTO]

Yes.

DR. QUINTIERE:

If you had the main layer of smoke, and then down in the lower left there was some mixing that seemed to be occurring. Could you explain what that was due to? Was it due to the wall effect or the opening effect? It wasn't clear.

[Answer by M. TSUJIMOTO]

I'm not sure. When we used a motor to make some like a experiment, there is no mixing, or it is not usual to see the mixing. But when we used the slow burn or the air, we always see some type of disturbance under the layer of the smoke. I cannot explain reason why.

DR. QUINTIERE:

Did it occur in the cases without the opening as well, or did it occur just in the opening cases?

[Answer by M. TSUJIMOTO]

I'm not sure.

[Questions for T. Yamada's Paper]

DR. GANN:

The agreement that you find between the experimental and the calculated numbers is very good. I expect that much of the difference is due to limits of accuracy in the measurement, not the model, and errors of plus or minus 10 or 15 percent are probably unimportant. Very useful results.

[Answer by T. YAMADA]

Thank you.

[Questions for H. Nelson's Paper]

DR. HESKESTAD:

I think that the interesting part of the scenario that you have described is that a fire that is vented at a window can develop high CO concentrations at remote points in the building. Now, we know from experience way back that a fire that is vented at the window--a ventilation controlled fire--will develop high CO_2 concentrations in the fire room.

Is it correct, do you think, to consider the remote location in this case as part of the fire room?

[Answer by H. NELSON]

Realistically, the only reason I say "no" is because I've used this, and then I've used some simpler models I've been trying to work on. And if I treat it as a single room, I don't get the right answers. I have to vent the gases through the door. But the main point is that I'm not sure that using a zone model for a corridor or transportation mechanism is going to remain valid.

Ken Steckler has put together a zero corridor algorithm that we are going to try to test against the data that we got in the fire in Norfolk. But if I try to treat it as one large room and use zone models--now maybe if I'd used the field model it would be different--but if I tried to do it as a zone model, I get answers that are not realistic. They don't match the fires at all.

DR. ZUKOSKI:

There's a hall flow, a hallway flow. Mixing is very, very weak, and you transport the material without much dilution. We don't know what happens in a stairway, and that's something that needs to be looked at. How does the gas get upstairs, and what is the degree of mixing that occurs there? And that nobody, as far as I know, has done any very helpful work on.

[Answer by H. NELSON]

Unfortunately, when I got rushed out here for the earthquake, it disappeared; it's somewhere.

DR. ZUKOSKI:

I see.

[Questions for O. Sugawa's Paper]

DR. HESKESTAD:

You referred to von Karman vortex, which produced a fire whirl. To me, von Karman vortex implies cyclic shedding of vortices. Did you mean to imply that these fire whirls were cyclic?

[Answer by O. SUGAWA]

We set the fire source inside the light setting, but we observed that two peaks on both sides of that down-wind side. It's just an opening. So the double, twin vortex, would appear.

DR. HESKESTAD:

So there was a steady state, more or less?

[Answer by O. SUGAWA]

Not so steady, but it's dropped for a minute or so.

DR. HESKESTAD:

But it did not alternate back and forth.

[Answer by O. SUGAWA]

In the experiment, it's not alternating. It appeared twin.

PROF. ZUKOSKI:

Did the extension of the building help as far as protecting the upper stories?

[Answer by O. SUGAWA]

Yes, I think so, because we could have a stand-off from the wall.

PROF. ZUKOSKI:

Yes.

[Answer by O. SUGAWA]

It's very effective to protect that second floor or more higher.

[Questions for P. Pagni's Paper]

PROF. WILLIAMSON:

When does the glass fall out of the frame? What are your plans to approach that problem?

[Answer by P. PAGNI]

I think I need to do some experiments in the lab and see what the phenomena are. The simplest approach would be to calculate this time and then say, "Twenty percent more time, and it's all gone." I'd love to be able to do something like that, but I don't know yet just how it will work.

DR. GANN:

Some of the glass has to fall out. That's the assumption in your mind. If you assume it's an expansion process and it cracks, there's only one way to release it from tension.

[Answer by P. PAGNI]

I think it's safe to say that some flow occurs. It may, you know, hang by an edge somehow, resting against another piece of glass. But I'm sure that at the time we calculate cracking, there will be some flow.

PROF. ZUKOSKI:

But the strains are 0.0005, and it doesn't take much to support a structure.

[Answer by P. PAGNI]

We'll look at this video tape again, and you can see how much the opening has occurred. Another fascinating problem is once you've got some opening, what fraction of the flow do you get that you would have gotten if you had a full opening.

DR. GANN:

That's a full opening?

[Answer by P. PAGNI]

Yes.

DR. KASHIWAGI:

This cracking one, that depends on how the window is supported at the edge?

[Answer by P. PAGNI]

Yes.

PROF. ZUKOSKI:

If you look at a modern building, the glass is supported so that it will stand an earthquake, and that means that it's a fairly flexible support.

[Answer by P. PAGNI]

Yes. In fact, they constructed some glass in our building, and I watched very carefully, and every side, two sides, always had a gap as they put it together.

PROF. ZUKOSKI:

With rubber grommets. . . .

[Answer by P. PAGNI]

In addition to the rubber grommet, there was a literal gap.

MR. NELSON:

Again, being an applied engineer, not a scientist, I have a problem. Incidentally, all my problems come from the Eastern United States, and I don't know if they leave those gaps or not. However, I just mentally ran through three health care fires that I have run analyses on, each one of which had the fire actually in the bed adjacent to the window. And each one, if I believed the models, would not have flashed over if the window had broken out. This was a fast-rising but limited, maximum energy fire. So, I have to assume that the window stayed in until the fire reached a condition of flashover bringing remote items in to raise the energy. I have a problem of matching my limited experience of reality with the early glass breakage assumption in the fires I've investigated.

[Answer by P. PAGNI]

Let me say that I was saving that for Washington. We've got to save something to say there that's a little bit different next week, two weeks from now. Aruna Joshi has done this analysis. Charlie Fleischmann is working on the problem of, even in those cases, I think, of letting the room fill with the excess pyrolozates, imagine your bed, a mattress and it's pouring out this stuff, and it's forming a layer, and pretty soon--I think earlier even than the glass breaking--the fire enters that vitiated layer, so that there is a lot of accumulated burnable material. And then the glass breaks, and then the flame--well, there's an intermediate step where there is a layer formed that is burnable that moves it back to the flame. Once it hits the flame, that layer gets ignited, and then the fire flashes through the whole room. I think that's the phenomena that we call flashover by a different mechanism than the one that has been studied so much in the past. But, we'll have time maybe in Washington.

CLOSING REMARKS

DR. SNELL:

I would like, in closing, to make an observation about where we have been and where we are going. In a sense, you might call this a charge from the Chairman to the new committee that will develop the program for our 12th meeting in Tsukuba.

It seems to me that we need a road map. Pagni-san was very careful to make sure that we knew the way to his house. In fact, he gave us a concise map. As I listened to the papers, I thought about the objectives of our collaboration and I wonder where is our map?

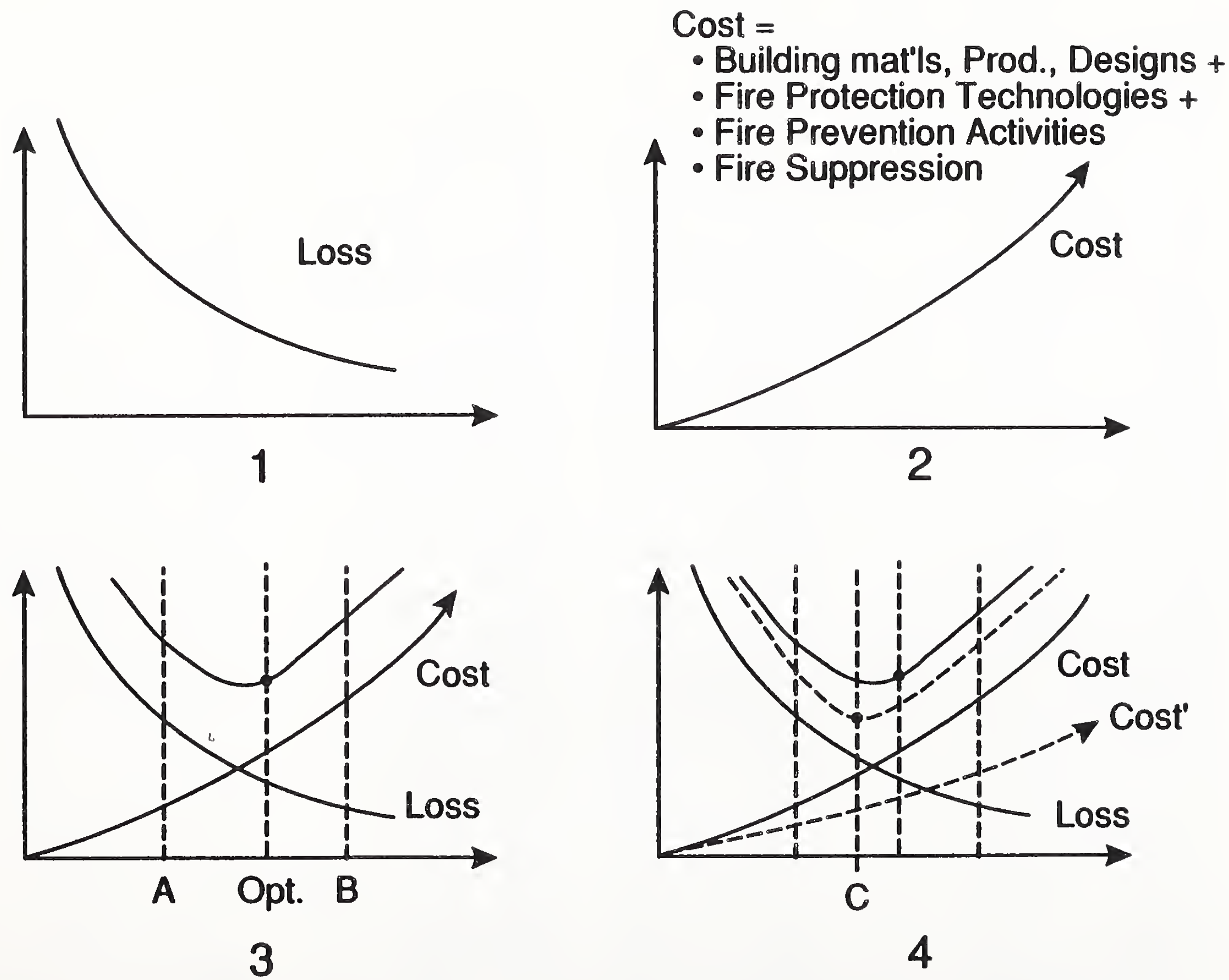
Now, it's clear to me, we have come a long way in our journey in these first 11 meetings of our collaboration. So, I am convinced we are going in the right direction. But, it is not clear, yet, that we know how to get to our destination. It seems to me, that if you look over the years of this collaboration and the work of the participating organizations, the nature of the work has changed significantly. In the beginning, papers were largely empirical, and there was still much emphasis on tests and indices.

In this meeting, we have heard almost none of that. The focus of the collaboration now is almost entirely on understanding and prediction, and I think that is very good.

Several years ago, we added as an objective for the collaboration, work towards development of the technical basis for a performance fire code. Now, none of us yet has a clear concept of exactly what that is. Tanaka-san perhaps is closest with the paper that he has presented, on the system that he helped develop in Japan, but it still is very rough in its substance. In the same sense, the HAZARD I method and the risk methodologies that were reported are part of what is necessary to have a performance code, but they are not sufficient. Clearly, this is an important step on our journey, but we still need a map.

Now, I don't have the map, but I have some thoughts about what might be necessary to find our way. Our motivation for fire research has, for the most part, been to reduce the loss or costs of fire, see Figure 1. And indeed, Tanaka's presentation includes some such presentation. We can use deaths, injuries or $ loss as a measure, etc. and use such a curve as a means of showing what happens by increasing performance. For example, by increasing ignition temperature, or maybe the inverse of peak rate of heat release, or whatever. In any case, we are trying to drive down some such curve. But, how far do we go, and where are we trying to get?

If we reflect on Tanaka's paper, and the new Japanese system, they talk about loss and cost. Certainly, for any given technology, as we push that technology out to a higher level of performance or do much of it, the cost of providing that is going to increase, and it is going to increase it at some increasing rate simply due to economies, see Figure 2.


Loss
1
Cost =
• Building mat'ls, Prod., Designs +
• Fire Protection Technologies +
• Fire Prevention Activities
• Fire Suppression
Cost
2
Cost
Loss
A
Opt.
B
3
Cost
Cost'
Loss
C
4

If we had the capability of putting these together so we could look at the total loss and cost as shown on Figure 3, we could identify the optimum condition, the best possible level of fire safety performance for our society. But to do this, we need a map.

Where are we now on this Figure? At A where losses are excessive, or B where costs are excessive? Some of us feel that many of our fire safety provisions are excessive, that the costs are such that we could reduce requirements and still be okay. But, we must be very careful for to do that would be to, perhaps, result in some increase in loss.

To go back to what I said a minute ago, the economist would draw this sort of a curve with the assumption that everything else is fixed, or this is a supply/demand, production/demand curve for a technology. What we want to do is to use our understanding and use our predictions to change the cost curve, to bring this curve down here to cost so that we get both lower costs and lower loss, or a lower loss at a lower cost to the community, point C on Figure 4.

The economists would tell us to do that requires new technology. Clearly, it seems to me, why else should we be pursuing understanding and the ability to predict, but to use that knowledge to introduce a new generation of fire safety technology.

Now, when we think about next generation fire safety technology, we may think about many different things. We may think about new materials or products--wall lining materials that do not burn the way the ones we saw yesterday do; or maybe glass fixtures that do not break; products that when they are cooked do not give off the same kinds of highly flammable pyrolysis products that we see today, more efficient designs.

Or, we may think about new active technologies and major advances in the performance or reliability of smoke detectors, sprinkler systems, alarms, warning systems, exit way systems, and the like.

Alternatively, we may think about new technologies for fire prevention within the community, as substitutes for public information and those things, and for the fire fighting forces.

This diagram is a very broad map, too broad. It does not denote a route; this is the whole continent. Clearly, if we want to reduce loss and costs, we need something other than more of the past solutions. It means doing things differently and doing them more efficiently. For example, it is not clear, even with the changes taking place in the Japanese economy and demographics, that persuasion is as effective a strategy for fire safety as it used to be. Certainly, it is not very effective in this country.

Reliance on the public information side of fire prevention is difficult. Ideally, perhaps, prevention technologies may be the way to go. But it excited me, even though I was unable to participate in the last meeting of this collaboration, to see "new technologies" added as an objective of our cooperation because I think we are at the point where the knowledge base is such that we can begin to use that knowledge to focus on safer products, next generation protection, and prevention technologies for reducing the loss and costs of fire.

So, I would challenge us all to consider, in the time between now and the next time we meet again, to think about how we get to where we are going. How collectively, we can bring ourselves from the current levels of effort, costs and losses, to a much higher level of effort which would greatly increase the benefits of community investment in fire safety. Otherwise, our research is of little value in society.

Let me put it positively. The challenge to us is to demonstrate the value of our research as a means of achieving that higher level of impact. We must draw attention to the potential impact of our work.

Now, let me shift gears and resume the closing. Prof. Pagni has made outstanding arrangements for this meeting. He got a superb translator for us, and only the earthquake damage to her own house prevented her from coming. At the slightest mention of her difficulty and her need, a collection has been made so that we are in a position now, as a result of the generous contributions from Japanese side and provision made on U.S. side to forward Ms. Nariko Abe an amount very nearly equal to that she would have received, had she been with us this entire week. It is wonderful. Thank you.

Obviously, this has been a very busy week for Drs. Gann and Suzuki as they were kept running with schedule changes. Ms. Cramer and Ms. Grant have served us very ably and more will be said about this when they are with us at the reception downstairs.

Prof. Pagni's students have been abundantly apparent and helpful. But, I'm not sure how he is going to deal with his students now that they must go back to their studies.

There is no question that the courage award for this meeting of our joint panel must go to the Japanese side. After all, all of them came here! If half of the Americans didn't come to San Francisco from the East Coast because of an earthquake on the West Coast, what would we do if there was an earthquake in Japan? Go to London? Please, do not put us to that test.

The other courage award goes to those on the Japanese side, that rugged contingent from BRI, who took to the high seas on Saturday for a bracing sail. The majority of us survived. I hope all found that a rewarding experience.

We have during this week, between BRI and CFR, signed a cooperative research agreement to highlight and accelerate the excellent cooperations that have begun through this panel, and we look forward to more such cooperations in the future.

It has been a week of unforgettable moments for us all. You have your special memories, I have mine. Mine include sailing under the Golden Gate Bridge. They include Inga's excellent tour at Christian Brothers, as she told us how to savor wine and chocolate at the same time. Mine include the magnificent dinner at Inglenook and an unforgettable evening at Pagni's house, and the lovely ambience of lunch today at the Women's Faculty Club. Mine also include the unforgettable experience of walking through the Marina District to see the earthquake damage, not to mention the outstanding technical quality of the papers and the presentations at this meeting.

So, I go away from this Eleventh UJNR Meeting a little bit tired, very much mellowed, and with many unforgettable memories, and I very much look forward to our next meeting in Japan. Thank you.

DR. TSUKAGOSHI:

Thank you very much, Dr. Snell. I think, it is not easy to find the map you needed, but we should make the effort to find it. I would like to ask Prof. Pagni to take the roster for this meeting.

PROF. PAGNI:

One of the few times I get the last word over Dick Gann. I'd like to thank my California colleagues and, of course, my wife, and also Professor Zukoski, who jumped right in and helped us here in Berkeley as if we were at his own institution. I appreciate that. I would like to thank Professor Fernandez-Pello and Professor Williamson for their contributions to this meeting. I must thank you. I have had a dream. That dream began after either the second or the fourth UJNR Meeting in the cafeteria at NIST. I remember a fall day, and I was listening to Professor Emmons and Dr. Lyons describe their recent trip to Japan, and they were so impressed with the level of preparation of each individual Japanese person in fighting fire. I remember the description of the special buckets that kept all the water from going out as you threw it on the fire, and I remember thinking, what a wonderful idea, that faced with the same serious problems of fires, we should explore the solutions that separate cultures have developed.

I was hoping that as a young researcher some day I would have the pleasure and honor of serving on the Panel. Shortly after that, I think, possibly--I've never known--due to the suggestion of the late Irwin Benjamin, I was invited to be an Associate Member of the Panel, and for the Fifth Meeting I showed up early and Dr. Clarke and I got to guide our guests through the Smithsonian Institute in Washington.

DR. TSUKAGOSHI:

I look forward to the next meeting in Tokyo and Tsukuba in 1992!

RESOLUTIONS

October 24, 1989

RESOLUTIONS

The members of the United States-Japan Conference on Development and Utilization of Natural Resources' Panel on Fire Research and Safety are quite pleased with the results of the 11th Joint Meeting, held at the University of California in Berkeley, October 19-25, 1989. We wish to thank the University of California, Berkeley for their outstanding efforts in hosting this meeting in the face of the disruption from the great earthquake. The following resolutions summarize the consensus reached.

It is hereby resolved that:

1. The objectives of the meetings of this panel remain to:

   (a) exchange the latest technical information;

   (b) promote cooperative research on Fire Safety Science;

   (c) encourage the innovation necessary for the development of new testing methods, designs and standards;

   (d) form a multi-national consensus in the field of computer based fire modeling;

   (e) explore the possibility of developing performance fire codes;

   (f) develop new fire protection and prevention technology appropriate to modern products and designs.

2. The next (12th) meeting of UJNR Panel on Fire Research and Safety will be held in Autumn of 1992 at Tokyo and Tsukuba in Japan.

3. A committee composed of two members from each country, chosen by the chairmen, shall provide the chairmen with a suggested format and topics for the 12th Panel Meeting agenda by the Summer of 1991. The chairmen will then set the detailed agenda by consensus. The discussion of each topic should begin with an outline of progress made in each field between meetings by both Japan and the United States.

4. We are pleased with the collaborations between Drs. Sekizawa and Hall; Drs. Mulholland, Koseki and Jin; and Drs. Hasemi and Quintiere. Emphasis should be placed on further Cooperative Fire Research Programs. These are especially valuable where the facilities are somewhat different in our two countries. The four member committee, described in resolution number three, will identify appropriate joint research programs and propose them to the chairmen within six months. In addition, the exchange of working personnel should continue to be pursued vigorously. During the past year, Drs. G. Mulholland and W. Parker, NIST employees, each spent a valuable month in BRI and FRI. Drs. Yamada, Yusa, Nambu, and Kushida are now conducting useful research projects in the United States. Dr. Kanemaru has already completed his project.

5. Panel Members are encouraged to exchange information of interest through the respective chairmen between meetings. Research reports issued in each country should be exchanged as soon as they are available. The titles of these reports will, in each country, be sent to the panel members who can identify the ones they would like to receive from their chairmen. It is important that all the relevant reports for the next meeting be sent in time to be received in the other country at least two months before the 12th meeting.

AUTHOR INDEX

S

T

U

W

Y

Z

NIST-114A (REV. 3-89)

U.S. DEPARTMENT OF COMMERCE
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY

BIBLIOGRAPHIC DATA SHEET

1. PUBLICATION OR REPORT NUMBER
NISTIR 4449

2. PERFORMING ORGANIZATION REPORT NUMBER

3. PUBLICATION DATE
October 1990

4. TITLE AND SUBTITLE

Eleventh Joint Panel Meeting of the UJNR Panel on Fire Research and Safety

5. AUTHOR(S)

Nora H. Jason and Deborah M. Cramer, Editors

6. PERFORMING ORGANIZATION (IF JOINT OR OTHER THAN NIST, SEE INSTRUCTIONS)

U.S. DEPARTMENT OF COMMERCE
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
GAITHERSBURG, MD 20899

7. CONTRACT/GRANT NUMBER

8. TYPE OF REPORT AND PERIOD COVERED

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (STREET, CITY, STATE, ZIP)

10. SUPPLEMENTARY NOTES

[ ] DOCUMENT DESCRIBES A COMPUTER PROGRAM; SF-185, FIPS SOFTWARE SUMMARY, IS ATTACHED.

11. ABSTRACT (A 200-WORD OR LESS FACTUAL SUMMARY OF MOST SIGNIFICANT INFORMATION. IF DOCUMENT INCLUDES A SIGNIFICANT BIBLIOGRAPHY OR LITERATURE SURVEY, MENTION IT HERE.)

The 11th Joint Meeting of the United States-Japan Panel on Fire Research and Safety was held on the campus of the University of California, Berkeley, October 19-24, 1989. Some disruption of the meeting resulted from the October 17 earthquake. The epicenter was about 60 miles southeast of San Francisco, in the Loma Prieta mountains near Santa Cruz. Thus, some of the papers were not presented, but are included in this volume.

This volume comprises a total of 6 progress reports and 30 supporting papers in 3 areas: Risk, Hazard and Evacuation; Fire and Toxicity Chemistry; and Fire and Smoke Physics. The next Panel Meeting will be held in Japan in the autumn of 1992.

12. KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)

building fires; building materials; combustion toxicology; compartment fires; computers; halons; hazard assessment; oil spills; polymers; pool fires; risk analysis; smoke

13. AVAILABILITY

36

[X] UNLIMITED

[ ] FOR OFFICIAL DISTRIBUTION. DO NOT RELEASE TO NATIONAL TECHNICAL INFORMATION SERVICE (NTIS).

[ ] ORDER FROM SUPERINTENDENT OF DOCUMENTS, U.S. GOVERNMENT PRINTING OFFICE, WASHINGTON, DC 20402.

[ ] ORDER FROM NATIONAL TECHNICAL INFORMATION SERVICE (NTIS), SPRINGFIELD, VA 22161.

14. NUMBER OF PRINTED PAGES

15. PRICE

ELECTRONIC FORM