NIST HANDBOOK 146, Volume II

Technical Reference Guide for the HAZARD I Fire Hazard Assessment Method

Richard W. Bukowski
Richard D. Peacock
Walter W. Jones
C. Lynn Forney

NIST United States Department of Commerce
National Institute of Standards and Technology

The National Institute of Standards and Technology[1] was established by an act of Congress on March 3, 1901. The Institute's overall goal is to strengthen and advance the Nation's science and technology and facilitate their effective application for public benefit. To this end, the Institute conducts research to assure international competitiveness and leadership of U.S. industry, science and technology. NIST work involves development and transfer of measurements, standards and related science and technology, in support of continually improving U.S. productivity, product quality and reliability, innovation and underlying science and engineering. The Institute's technical work is performed by the National Measurement Laboratory, the National Engineering Laboratory, the National Computer Systems Laboratory, and the Institute for Materials Science and Engineering.

The National Measurement Laboratory

Provides the national system of physical and chemical measurement; coordinates the system with measurement systems of other nations and furnishes essential services leading to accurate and uniform physical and chemical measurement throughout the Nation's scientific community, industry, and commerce; provides advisory and research services to other Government agencies; conducts physical and chemical research; develops, produces, and distributes Standard Reference Materials; provides calibration services; and manages the National Standard Reference Data System. The Laboratory consists of the following centers:

- Basic Standards[2]
- Radiation Research
- Chemical Physics
- Analytical Chemistry

The National Engineering Laboratory

Provides technology and technical services to the public and private sectors to address national needs and to solve national problems; conducts research in engineering and applied science in support of these efforts; builds and maintains competence in the necessary disciplines required to carry out this research and technical service; develops engineering data and measurement capabilities; provides engineering measurement traceability services; develops test methods and proposes engineering standards and code changes; develops and proposes new engineering practices; and develops and improves mechanisms to transfer results of its research to the ultimate user. The Laboratory consists of the following centers:

- Computing and Applied Mathematics
- Electronics and Electrical Engineering[2]
- Manufacturing Engineering
- Building Technology
- Fire Research
- Chemical Engineering[3]

The National Computer Systems Laboratory

Conducts research and provides scientific and technical services to aid Federal agencies in the selection, acquisition, application, and use of computer technology to improve effectiveness and economy in Government operations in accordance with Public Law 89-306 (40 U.S.C. 759), relevant Executive Orders, and other directives; carries out this mission by managing the Federal Information Processing Standards Program, developing Federal ADP standards guidelines, and managing Federal participation in ADP voluntary standardization activities; provides scientific and technological advisory services and assistance to Federal agencies; and provides the technical foundation for computer-related policies of the Federal Government. The Laboratory consists of the following divisions:

- Information Systems Engineering
- Systems and Software Technology
- Computer Security
- Systems and Network Architecture
- Advanced Systems

The Institute for Materials Science and Engineering

Conducts research and provides measurements, data, standards, reference materials, quantitative understanding and other technical information fundamental to the processing, structure, properties and performance of materials; addresses the scientific basis for new advanced materials technologies; plans research around cross-cutting scientific themes such as nondestructive evaluation and phase diagram development; oversees Institute-wide technical programs in nuclear reactor radiation research and nondestructive evaluation; and broadly disseminates generic technical information resulting from its programs. The Institute consists of the following divisions:

- Ceramics
- Fracture and Deformation[3]
- Polymers
- Metallurgy
- Reactor Radiation

[1]Headquarters and Laboratories at Gaithersburg, MD, unless otherwise noted; mailing address Gaithersburg, MD 20899.
[2]Some divisions within the center are located at Boulder, CO 80303.
[3] Located at Boulder, CO, with some elements at Gaithersburg, MD.

NIST HANDBOOK 146, Volume II

Technical Reference Guide for the HAZARD I Fire Hazard Assessment Method

Richard W. Bukowski
Richard D. Peacock
Walter W. Jones
C. Lynn Forney

Center for Fire Research
National Engineering Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899

June 1989

U.S. Department of Commerce
Robert A. Mosbacher, Secretary

National Institute of Standards and Technology
Raymond G. Kammer, Acting Director

Library of Congress Catalog Card Number: 89-600740

National Institute of Standards and Technology Handbook 146, Volume II
Natl. Inst. Stand. Technol. Handb. 146, Vol. II, 323 pages (June 1989)

CODEN: NIHAE2

U.S. Government Printing Office
Washington: 1989

DISCLAIMER

The Department of Commerce makes no warranty, express or implied, to users of the HAZARD I Fire Hazard Assessment Method and associated computer programs, and accepts no responsibility for its use. Users of HAZARD I assume sole responsibility under Federal and State law for determining the appropriateness of its use in any particular application; for any conclusions drawn from the results of its use; and for any actions taken or not taken as a result of analyses performed using HAZARD I.

Users are warned that HAZARD I is intended for use only by persons competent in the field of fire safety and is intended only to supplement the informed judgment of the qualified user. The HAZARD I software package, used outside of the broader HAZARD I Fire Hazard Assessment Method, is a computer model which may or may not have predictive value when applied to a specific set of factual circumstances and which could lead to erroneous conclusions if not properly evaluated by an informed user.

INTENT AND USE

The algorithms, procedures, and computer programs described in this report constitute a prototype version of a methodology for predicting the consequences to the occupants of a building resulting from the involvement of particular products in a specified fire. They have been compiled from the best knowledge and understanding currently available, but have important limitations which must be understood and considered by the user. The hazard analysis method is intended for use by persons competent in the field of fire safety, and with some familiarity with personal computers. It is intended as a decision-making tool, but the scope of its use is exploratory.

Acknowledgments

A large number of people assisted in the development of the HAZARD I methodology. V. Babrauskas and B. C. Levin developed the tenability criteria for heat flux, temperature, and smoke obscuration. B. C. Levin provided data for tenability limits for toxic gases. B. M. Levin developed the first version of the evacuation model. E. Braun wrote FIREDATA and provided the basis for the database portions of the methodology. A. J. Fowell provided guidance in the overall logic of the hazard assessment methodology. S. W. Stiefel contributed to the development of the fire statistics documentation. N. Breese, C. Arnold, A. B. Fadell, A. J. Shibe, and P. Martin assisted in the software development.

The expertise of the Fire Services Panel and the Building Configuration Panel was key in providing an unbiased and representative set of example cases to test the HAZARD I methodology. The authors are indebted to the Joint Council of Fire Service Organizations, the American Institute of Architects, the Building Officials and Code Administrators International, the International Conference of Building Officials, the National Association of Home Builders, the National Fire Protection Association, the Southern Building Code Congress International, and the individual panel members who volunteered their time and effort which added to the success of the project.

Ninety-three organizations participated in the beta test of HAZARD I. Their interest, time, and careful critique of the pre-release version of HAZARD I led to many enhancements to the final version.

The authors wish to express their appreciation for the contributions of all those involved in the development effort.

CONTENTS

FIGURES

TABLES

For technical support on the HAZARD I software, contact

Fire Hazard Analysis
Center for Fire Research
National Institute of Standards and Technology
Gaithersburg, MD 20899

R. W. Bukowski (301) 975-6881
R. D. Peacock (301) 975-6664
W. W. Jones (301) 975-6887
C. L. Forney (301) 975-6663

CHAPTER 1. OVERVIEW

This report describes a prototype method to assess the relative contribution of specific products to the overall hazards of fire and smoke in buildings. Although this initial version is focused on single-family residential occupancies, it is potentially of use for other occupancies. It is intended that this prototype method will be used by those with experience in the field of fire safety to enable it to be tested widely. Constructive feedback from its initial use will better define its usefulness and limitations and will help to foster needed improvements. Users should exercise sound technical judgment in applying the algorithms and computer programs described herein.

1.1 The Need for Quantitative Hazard Analysis

Public fire safety is provided through a system of fire and building codes which are based on the judgment of experts in the field, and which incorporate test methods to measure the fire properties or performance of materials and products. These codes generally prescribe the construction methods and materials considered acceptable in various classes of occupancy, which are defined on the basis of use and the assumed capabilities of the users. They rely heavily on the concepts of compartmentation and the provision of duplicate, protected paths of egress. A number of active fire protection systems are also required, including various combinations of detection/alarm, suppression, and smoke control/management systems. These systems work together with the passive measures to provide additional time for safe evacuation of the affected area and reduction of the fire impact on the structure and its occupants.

This system of fire and building codes works to provide a reasonable level of safety to the public. However, existing codes need continual revision as new materials or design and construction techniques are introduced. Quantitative tools for fire hazard analyses can provide the code official with ways of addressing such developments consistent with the intent of the code. The flexibility provided by these quantitative tools can help to ensure the safe and rapid introduction of new technology by providing information on the likely impact on fire safety before a performance record is established through use. Similarly, these methods can be of value to product manufacturers in identifying the potential fire safety benefits of proposed design changes.

Figure 1-1 illustrates the elements and interactions which need to be considered in performing a quantitative fire hazard analysis. Experimental measurements of the burning behavior of materials of interest and details of the building in which they burn are needed to define the fire in terms of its release of energy and mass over time. The transport of

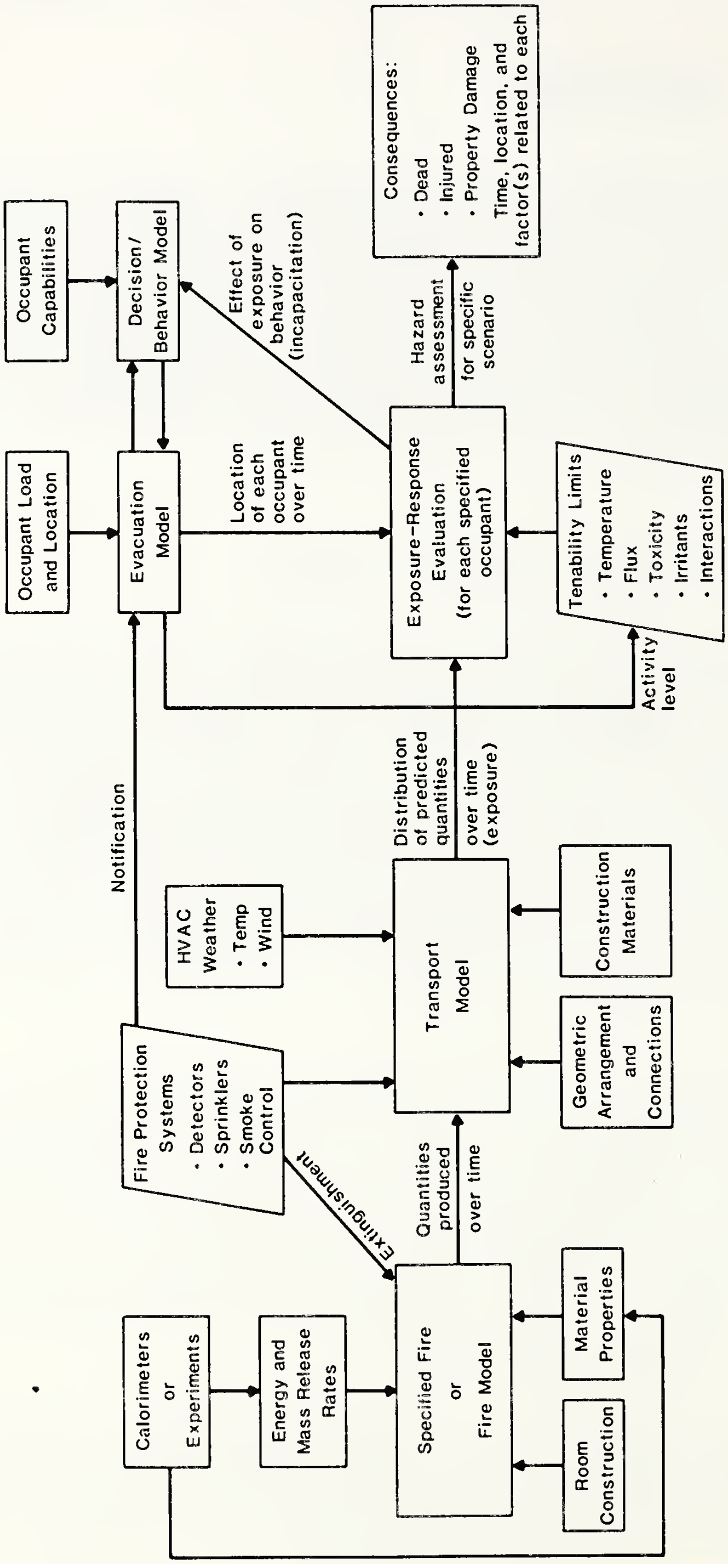


Figure 1-1. Interrelationships of major components of a fire hazard model.

this energy and mass through the building is influenced by its geometry, the construction materials used, and the fire protection systems employed. The response of occupants and the consequences of the fire depend on when the occupants are notified, their physical capabilities, the decisions they make, and their susceptibility to the hazards to which they are exposed.

Tools for fire hazard analysis make it possible to evaluate product fire performance against a fire safety goal. For example, a goal of fire safety has always been to "keep the fire contained until the people can get out." The problem is that it is very difficult to keep the "smoke" contained. Quantitative hazard analysis allows the determination of the impacts of smoke, such as toxicity, *relative* to the impact of other hazards of fire for a prescribed building and set of occupants and determines if the time available for egress is greater than the time required; and if not, why not. Time is the critical factor. Having 3 minutes for safe escape when 10 minutes are needed results in human disaster. But providing 30 minutes of protection when 10 are needed can lead to high costs. A hazard analysis method can help prevent both types of problem from occurring.

Quantitative hazard analysis techniques have the potential of providing significant cost savings. Alternative protection strategies can be studied within the hazard analysis framework to give the benefit-cost relation for each. In addition, measures are evaluated as a system with their many interactions, including the impact of both structure and contents. Providing these alternatives promotes design flexibility which reduces redundancies and cost without sacrificing safety. New technology can be evaluated before it is brought into practice, thus reducing the time lag currently required for code acceptance. Thus, quantitative hazard analysis is a powerful complement to existing codes and standards and a useful tool in evaluating improvements to them.

1.2 Overall Approach

HAZARD I is a set of procedures combining expert judgment and calculations to estimate the consequences of a specified fire. These procedures involve four steps: 1) defining the context, 2) defining the scenario, 3) calculating the hazard, and 4) evaluating the consequences. Steps 1, 2, and 4 are largely judgmental and depend on the expertise of the user. Step 3, which involves use of the extensive HAZARD I software, requires considerable expertise in fire safety practice. The heart of HAZARD I is a sequence of procedures implemented in computer software to calculate the development of hazardous conditions over time, calculate the time needed by building occupants to escape under those conditions, and estimate the resulting loss of life based on assumed occupant behavior and tenability criteria. These calculations are performed for a specified building and set of fire scenarios of concern.

The buildings and scenarios of interest to the user of a fire hazard assessment will depend on the purpose of the assessment. For example, product manufacturers generally will not be concerned with a particular building but rather with any scenarios significantly involving their products in all the building types they may be used. The interest of fire investigators will be with specific fires in specific buildings, since they are reconstructing incidents which have occurred.

A set of reference examples has been compiled to assist the user through the process, and to demonstrate the capabilities of the procedure. These include sets of prototypical residential buildings and common fire scenarios. The method described in this report allows the user to substitute his product for that in one of the examples using one of the prototypical buildings or scenarios, or perform an analysis on a different building or scenario provided, of course, that the phenomena involved are not beyond the technical capabilities of the models.

Not every situation merits a complete or new set of hazard calculations. For example, the user may find that his questions can be answered simply by estimating or inferring the expected performance of his product from review of the provided matrix of preworked examples. Obviously, over time as the number of preworked examples increases, many users will find the results they need simply by looking up estimated performance from such files. Alternatively, the potential user of HAZARD I may find that his concern involves situations beyond the current capabilities of the system, in which case he must revert to traditional approaches, i.e., some combination of experience, judgment and/or small- or full-scale fire tests. The third alternative is that the user chooses to run through a complete set of new calculations for his problem situation. The flow chart, figure 1-2 illustrates these three alternatives for the potential user of HAZARD I.

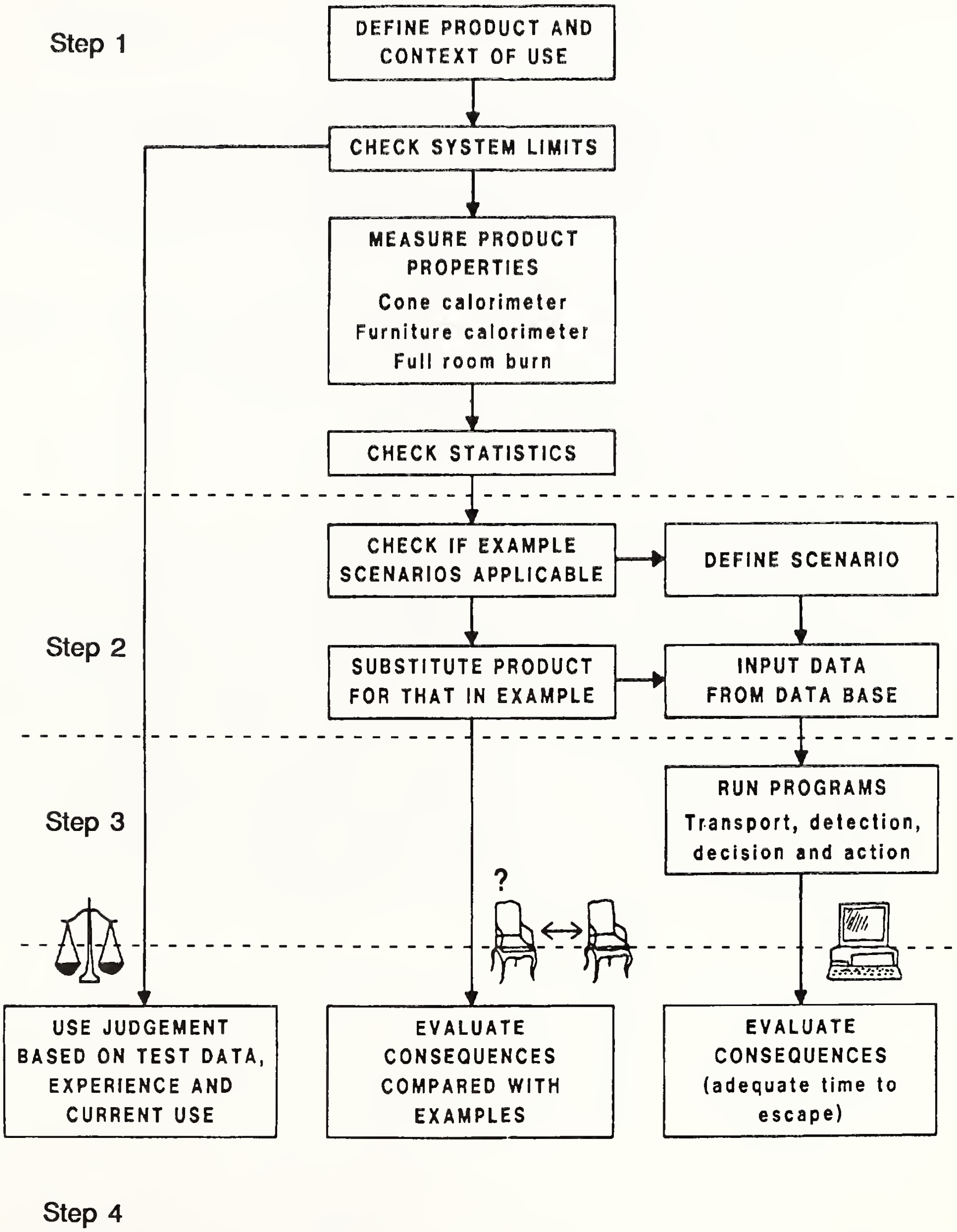


Figure 1-2. The overall method.

1.3 Overview

The material contained in these three volumes encompasses the first version of the HAZARD I Fire Hazard Assessment Method. The set of computer disks contains the software necessary to conduct hazard analyses of products used in residential occupancies. All of the software provided will operate on any IBM[1] PC (XT, AT, or PS/2) or compatible MS-DOS computer with the following minimum hardware configuration:

- 640 k memory
- graphics card (IBM CGA, EGA, or VGA; or Hercules compatible)
- hard disk drive (about 2 Mb required for the files)
- math co-processor (8087, 80287, or 80387)
- printer (with graphics capability)
- MS-DOS 3.0 or higher

The organization of the HAZARD I software package is shown in figure 1-3. It includes an interactive, user interface program for entering data into the fire model (FAST_in); a database program (FIREDATA) including files of thermophysical, thermochemical, and reference toxicity data; the FAST model (version 18) for multi-compartment energy and mass transport; a graphics utility for plotting data (FASTplot); a detector/sprinkler activation model (DETACT); an evacuation model which includes human decision/behavior (EXITT); and a tenability model (TENAB) which evaluates the impact of the predicted exposure of the occupants in terms of incapacitation or lethality from temperature or toxic gases or incapacitation by second degree burns from radiant flux exposure. In addition to this **Technical Reference Guide**, the accompanying **HAZARD I Software User's Guide** includes detailed instructions for the use of the software, the form of the data provided to each of the modules, and examples of the use of the software.

---

[1] The use of company names or trade names within this report is made only for the purpose of identifying those computer hardware or software products with which the compatibility of the programs of HAZARD I has been tested. Such use does not constitute any endorsement of those products by the National Institute of Standards and Technology.

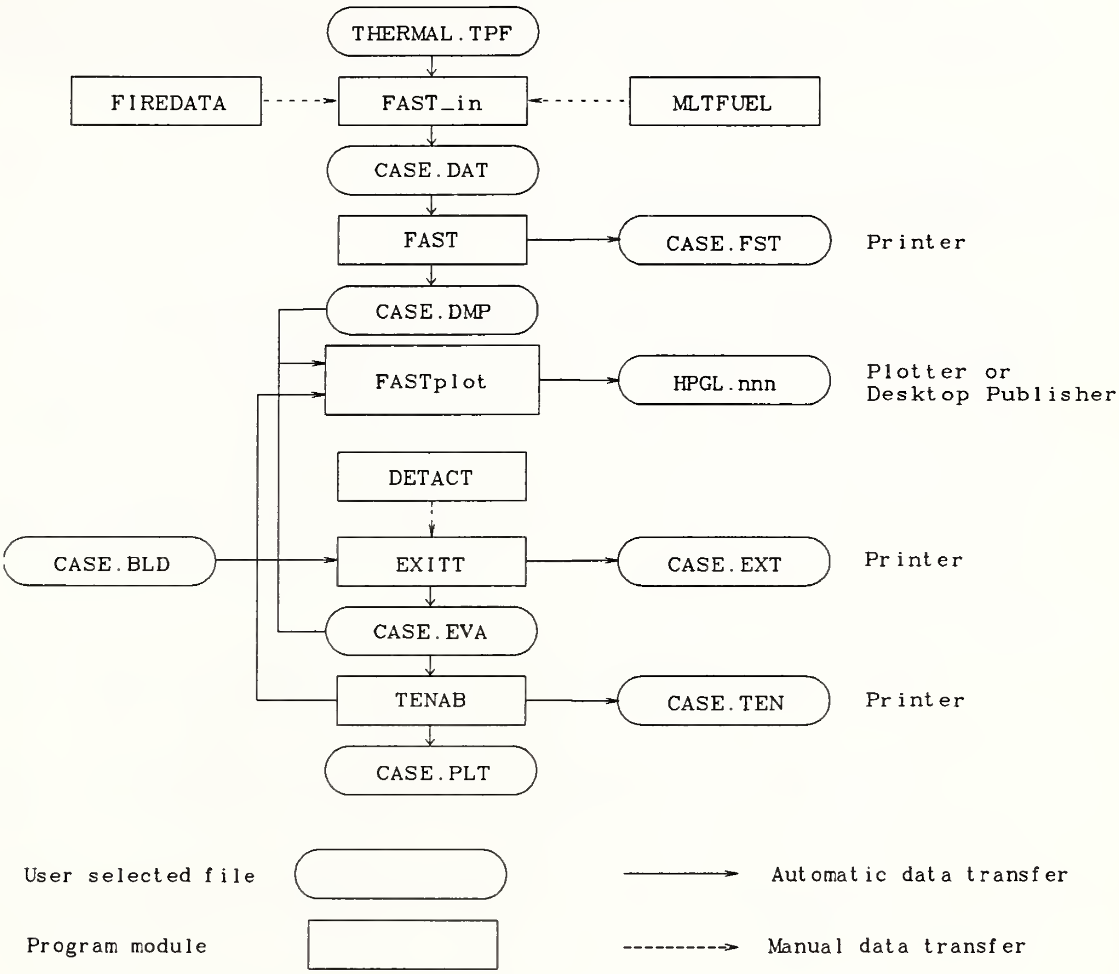


Figure 1-3. HAZARD I software.

A set of eight representative example cases of typical residential fires, established by two panels of outside experts, is also included in the documentation. Details of the fires were specified by a panel composed of representatives of the major fire service organizations. The three single-family residences were verified as representing typical homes by a panel from the model code and architectural communities. A description of the process of developing these cases and a complete set of the output produced from each (input data file listings, program outputs and graphs of selected variables) are provided in the HAZARD I Example Cases volume.

While the scope of this first hazard assessment method is limited to residential occupancies, our goal is to extend it to other occupancy classes. Such an extension would be made in parallel with the improvements identified through user feedback.

1.4 Assumptions and Limitations

General: HAZARD I is a set of procedures combining expert judgment and calculations to estimate the consequences of a specified fire. These procedures involve four steps: 1) defining the context, 2) defining the scenario, 3) calculating the hazard, and 4) evaluating the consequences. Steps 1, 2, and 4 are largely judgmental and depend on the expertise of the user. Step 3, which involves use of the extensive HAZARD I software, requires considerable expertise in fire safety practice. The HAZARD I software consists of a collection of data, procedures, and computer programs which are used to *simulate* the important time-dependent phenomena involved in residential fires. The major functions provided include calculation of:

- the production of energy and mass (smoke and gases) by one or more burning objects in one room, based on small- or large-scale measurements,

- the buoyancy-driven transport of this energy and mass through a series of user-specified rooms and connections (doors, windows, cracks, etc.),

- the resulting temperatures, smoke optical densities, and gas concentrations after accounting for heat transfer to surfaces and dilution by mixing with clean air,

- the evacuation process of a user-specified set of occupants accounting for delays in notification, decision making, behavioral interactions, and inherent capabilities, and

- the impact of the exposure of these occupants to the predicted room environments as they move through the building, in terms of the expected fatalities, and the time, location, and cause of each.

As can be seen from this list, the hazard analysis involves an interdisciplinary consideration of physics, chemistry, fluid mechanics, heat transfer, biology, toxicology, and human behavior. In some areas, fundamental laws (conservation of mass, energy, and momentum) can be used, whereas in others empirical correlations or even "educated guesses" must be employed to bridge gaps in existing knowledge. The necessary approximations required by considerations of operational practicality result in the introduction of uncertainties in the results. The user should understand the inherent assumptions and limitations of the procedures and programs, and use them judiciously - including sensitivity analyses for the ranges of values for key parameters - in order to make estimates of these uncertainties.

Scope: The scope of HAZARD I has been limited to one- and two-family residential structures. Models of the complex flows of heat and smoke through the HVAC systems and up the tall stairwells found in other occupancies are not yet sufficiently refined to include them in HAZARD I. Similarly, the focus has been on the inclusion of "rules" for the behavioral interactions of people within family units in the EXITT model. Large-building evacuation models, which include phenomena such as congestion in and around stairwells and behaviors typical of people in other occupancies, have not yet been incorporated into HAZARD I.

Since the majority of U.S. fire losses are in one- and two-family residential structures, this occupancy was selected for the first hazard system. The scope will be broadened in subsequent versions of the system.

Programs and procedures: Figure 1-3 presents the HAZARD I software package developed to implement the assessment of hazard. Of the eight programs shown, three (FIREDATA, FAST_in, and FASTplot) perform utility and user interface functions only.

The principal current limitation of FIREDATA is that data are provided for only a small set of example products. Data provided in the cone and furniture calorimeter files are measured values from individual samples tested in these devices under a specified set of conditions. While the materials are identified generically, it should be understood that such data are not necessarily representative of the behavior of that generic material. Some variation would be expected, even on a set of samples from the same lot, and no attempt was made to obtain representative samples for test. Also, data in the thermophysical properties file were taken either from manufacturers' data or from literature sources with no attempt to verify values or to determine if they are the most representative values. Finally, the data in the toxicity file are published values from the sources indicated. Only some of the sources provide confidence intervals for these data. The material identifications are those provided in the sources.

Specified fire: An important limitation of HAZARD I is the absence of a fire growth model. It was not practical to adapt currently available fire growth models for direct inclusion in HAZARD I. Therefore, the system utilizes a user specified fire, expressed in terms of time specified rates of energy and mass released by the burning item(s). Such data can be obtained by measurements taken in large- and small-scale calorimeters, or from room burns. Their associated limitations are as follows:

1. For the Furniture Calorimeter, a product (chair, table, bookcase, etc.) is placed under a large collection hood and ignited by a 50 kW gas burner (simulating a wastebasket) placed adjacent to the item for 120 s. The combustion process then

proceeds under assumed "free-burning" conditions, and the release rate data are measured. Potential sources of uncertainty here include measurement errors related to the instrumentation, and the degree to which "free-burning" conditions are not achieved (e.g., radiation from the gases under the hood or from the hood itself, and restrictions in the air entrained by the object causing locally reduced oxygen concentrations affecting the combustion chemistry). There are limited experimental data for upholstered furniture which suggest that prior to the onset of flashover in a compartment, the influence of the compartment on the burning behavior of the item is small. The differences obtained from the use of different types or locations of ignition sources have not been explored. These factors are discussed in reference [1].

2. Where small-scale calorimeter data are used, procedures are provided to extrapolate to the behavior of a full-size item. These procedures are based on empirical correlations of data which exhibit significant scatter, thus limiting their accuracy. For example, for upholstered furniture the peak heat release rates estimated by the "triangular approximation" method averaged 91% (range 46% to 103%) of values measured for a group of 26 chairs with noncombustible frames, but only 63% (range 46% to 83%) of values measured for a group of 11 chairs with combustible frames [2]. Also, the triangle neglects the "tails" of the curve; these are the initial time from ignition to significant burning of the item, and the region of burning of the combustible frame, after the fabric and filler are consumed.

3. The data and procedures provided relate directly only to burning of contents items initiated by relatively large flaming sources. Almost no data are currently available for release rates under smoldering combustion, or for the high external flux and low oxygen conditions characteristic of post-flashover burning. While the program MLTFUEL allows multiple items burning simultaneously to be converted to a single "equivalent" specified fire, it does not account for the energy interchange of such items. Thus, for other ignition scenarios, multiple items burning simultaneously (which exchange energy by radiation and convection), combustible interior finish, and post-flashover conditions, the procedures provided give estimates which are often nonconservative (the actual release rates would be *greater* than estimated). At present, the only sure way to account for all of these complex phenomena is to conduct a full-scale room burn and input the release rates to the transport model. Subsequent versions of the hazard system will include detailed combustion models such as those in HARVARD V [3] or FIRST [4] which can be used as the source fire.

Transport: The distribution of energy and mass throughout the rooms included in the simulation is done in the model FAST, which is a zone (or control volume) model. The basic assumption of such models is that each room can be divided into two or more zones, each of which is internally uniform in temperature and composition. In FAST, all rooms have two zones except the fire room, which has an additional zone for the fire plume. The boundary between the two layers in a room is called the interface.

It has generally been observed that in the spaces close to the fire, buoyantly stratified layers form. While in an experiment the temperature can be seen to vary within a given layer, these variations are small compared to the temperature difference between the layers.

Beyond the basic zone assumptions, the model typically involves a mixture of established theory (e.g., conservation equations), empirical correlations where there are data but no theory (e.g., flow and entrainment coefficients), and approximations where there are neither (e.g., post-flashover combustion chemistry) or where their effect is considered secondary compared to the "cost" of inclusion. An example of a widely used approximation is to ignore the variation of the thermal properties of structural materials with temperature. While this would be fairly simple to add to the computer code, data are scarce over a broad range of temperature even for the most common materials, and the estimated error from this assumption is small.

With a highly complex model such as FAST, the only reasonable method of assessing impacts of assumptions and limitations is through the verification and validation process, which is ongoing at the Center for Fire Research (CFR). Until the results of this process are available, the user should be aware of the following:

1. Within FAST, the user can elect to have burning constrained by the available oxygen. This "constrained fire" (type 2) is not subject to the influences of radiation to enhance its burning rate, but is influenced by the oxygen available in the room. If a large mass loss rate is entered, the model will follow this input until there is insufficient oxygen available for that quantity of fuel to burn in the room. The unburned fuel (sometimes called excess pyrolyzate) is tracked as it flows out in the door jet, where it can entrain more oxygen. If this mixture is within the user-specified flammable range, it burns in the door plume. If not, it will be tracked throughout the building until it eventually collects as unburned fuel or burns in a vent. The energy released in the fire room and in each vent, as well as the total energy released, is detailed in the output of the model.

2. Similarly, an oxygen combustion chemistry scheme is employed, only in constrained (type 2) fires. Here user-specified hydrocarbon ratios and species yields are used by the model to predict concentrations. A balance among hydrogen, carbon, and oxygen molecules is maintained. Under some conditions, low oxygen can change the combustion chemistry, with an attendant increase in the yields of products of incomplete combustion such as CO. Guidance is provided on how the user can adjust the CO/CO_2 ratio. However, not enough is known about these chemical processes to build this relationship into the model at the present time.

Some data exist in reports of full-scale experiments (e.g., [5]) which can assist in making such determinations.

3. The entrainment coefficients are empirically determined values. Small errors in these values will have a small effect on the fire plume or the flow in the plume of gases exiting the door of that room. In a multi-compartment model such as FAST, however, small errors in each door plume are multiplicative as the flow proceeds through many compartments, possibly resulting in a significant error in the furthest rooms. The data available from validation experiments [6] indicate that the values for entrainment coefficients currently used in most zone models produce good agreement for a three-compartment configuration. More data are needed for larger numbers of rooms to study this further.

4. In real fires, smoke and gases are introduced into the lower layer of each room primarily due to mixing at connections between rooms and from the downward flows along walls (where contact with the wall cools the gas and reduces its buoyancy). Doorway mixing has been included in FAST, using an empirically derived mixing coefficient. However, for wall flows the associated theory is only now being developed. Thus the lower layer can accumulate smoke and gases. This may produce an underestimate of the lower layer concentrations.

5. Energy (heat) gains in the lower layer result only from convective heating from the floor and lower walls. It is assumed that the lower layer does not absorb energy by radiation from the upper layer. This may produce an underestimate of the lower layer temperatures resulting in an overestimate of the upper layer temperatures.

6. The only mechanisms provided in zone models to move energy and mass into the upper layer of a room are two types of plumes; those formed by the burning item(s) in the fire room, and those formed by the jet of upper layer gases flowing through an opening. Thus, when the model calculates the flow of warm, lower layer gases through a low opening (e.g., the undercut of a door) by expansion, they are assigned to the lower layer of the room into which they flowed where they remain until the upper layer in the source room drops to the level of the undercut and the door jet forms. Thus, for a time the receiving room will show a lower layer temperature which exceeds that in the upper layer (a physically impossible condition). However, no hazard will exist during this time as the temperatures are low, and no species produced by the fire are carried through the opening until the upper layer drops to the height of the undercut.

Occupant behavior and evacuation: The EXITT model is a fairly straightforward "node and arc" evacuation model to which an extensive series of behavioral rules has been added. The assumptions of interest are thus inherent in these rules, and the limitations are associated mostly with behavior not yet included. For example, the model does not have people re-entering the building, as they sometimes do. In addition, the current model is completely deterministic - a specific set of circumstances always results in a specific action. The data on which the rules were based sometimes identifies several potential actions (e.g., under this condition, 60% of the time they do A and 40% of the time they do B). To model such behavior properly, the program would have to employ probabilistic branching.

Within the current model, some of the rules are qualitative (e.g., a man's first action is to investigate) and some are quantitative (e.g., a woman between the ages of x and y walks at z meters per minute). The assumed values in quantitative rules are called parameter values, and the documentation for the model identifies each, the reason for assigning that value, and how the user can change it (allowing a sensitivity analysis to be performed on those parameters for which the user might feel that the supporting data are weak).

Activation of thermal devices: The activation of smoke detectors, heat detectors, or sprinklers is handled in the program DETACT. The report (included as Appendix D of this **Technical Reference** volume) describes the underlying theory and assumptions used. The basic assumption is one of quasi-steady ceiling layer gas flow under an unconfined ceiling (no walls). It is consistent with the experimental study [7,8] done by Factory Mutual Research Corp. for the Fire Detection Institute (FDI) and on which the NFPA 72E [9] Appendix C methods were developed. As such, the assumptions employed in this program are those commonly used by the engineering and code communities and represent the current state-of-the-art. Smoke detectors are only crudely treated as heat detectors with an activation temperature of 13 °C above ambient based on recommendations contained in the FDI study.

Tenability criteria: The impact of exposure to the occupants is evaluated in the program TENAB. Individual determinations are made for both incapacitation and lethality from temperature and toxicity, along with potential incapacitation from burns due to flux exposure. No interactions are currently included (e.g., temperature exposure does not change rate of uptake of toxic species). The basis for the threshold values used and the derivation of the equations on which the toxicity calculation is based are provided in this **Technical Reference** volume in the chapter on Tenability Limits, which contains an extensive list of references. For all cases except flux exposure, the user can easily change the limit values used (and is encouraged to do so as a sensitivity test). Also, the method of presentation of the output of TENAB facilitates the observation of the sensitivity of the result to the limiting value selected.

The limiting values of temperature exposure are based on the general literature, which includes some human data. The flux criterion comes from work done with pig skin, which is generally considered to be very similar to human skin. The toxicity data, however, are from the combustion toxicology literature which is based entirely on animal exposures (primarily rodents for lethality studies and nonhuman primates for incapacitation studies). Thus, the model assumes that humans will exhibit a similar physiological response.

A toxicity parameter, Ct (concentration multiplied by exposure time, often referred to as "exposure dose") is used to indicate the toxic impact of the smoke without differentiating the constituent gases or the possibility of diminished oxygen. This is a broad assumption. Another toxicity parameter, FED (the fractional effective dose), is also introduced. This represents the fraction of the lethal dose that has been accumulated by an individual over time. The FED parameter combines the effects and interactions of the gases CO, CO_2, and HCN along with the effect of diminished oxygen. The model on which the FED calculation is based, referred to as the N-Gas model [10], is under continuing development, and additional gases will be added as the data are obtained. It is expected the first irritant gas (HCℓ) will be included in the next version.

1.5 References

[1] Babrauskas, V.; Lawson, J. R.; Walton, W. D.; Twilley, W. H. Upholstered furniture heat release rates measured with a furniture calorimeter. Natl. Bur. Stand. (U.S.) NBS-IR 82-2604; 1982 December. 73 p.

[2] Babrauskas, V.; Krasny, J. F. Fire behavior of upholstered furniture. Natl. Bur. Stand. (U.S.) Monogr. 173; 1985 November. 101 p.

[3] Mitler, H. E.; Emmons, H. W. Documentation for CFC V, the fifth Harvard fire code. Natl. Bur. Stand. (U.S.) NBS GCR 81-344; 1981 October. 187 p.

[4] Mitler, H. E.; Rockett, J. A. Users' guide to FIRST, a comprehensive single-room fire model. Natl. Bur. Stand. (U.S.) NBSIR 87-3595; 1987 September. 138 p.

[5] Lee, B. T. Effect of ventilation on the rates of heat, smoke, and carbon monoxide production in a typical jail cell fire. Natl. Bur. Stand. (U.S.) NBSIR 82-2469; 1982 March. 80 p.

[6] Peacock, R. D.; Davis, S.; Lee, B. T. An experimental data set for the accuracy assessment of room fire models. Natl. Bur. Stand. (U.S.) NBSIR 88-3752; 1988 April. 120 p.

[7] Heskestad, G.; Delichatsios, M. A. Environments of fire detectors - phase 1: effect of fire size, ceiling height, and material, Volume 1 - Measurements. Natl. Bur. Stand. (U.S.) NBS GCR 77-86; 1977 May. 206p.

[8] Heskestad, G.; Delichatsios, M. A. Environments of fire detectors - phase 1: effect of fire size, ceiling height, and material, Volume 2 - Analysis. Natl. Bur. Stand. (U.S.) NBS GCR 77-95; 1977 July. 129 p.

[9] Anon., Standard for the installation, maintenance and use of automatic fire detectors, National Fire Protection Association Standard 72E. NFPA, Quincy, MA; 1975.

[10] Babrauskas, V.; Levin, B. C.; Gann, R. G. A new approach to fire toxicity data for hazard evaluation. Fire Journal 81(2): 22-28; 1987 March/April.

CHAPTER 2. BACKGROUND

2.1 Summary of Developments to Date

The CFR project to develop a quantitative hazard assessment method was initiated following the NBS Workshop on Combustion Product Toxicology held in 1982 [1]. In this workshop, papers were presented in which some of the initial concepts of hazard analysis were discussed. The general approach for the hazard analysis capability was discussed in the *Journal of Fire Science* early in 1983 [2]. Later that year, NBS made a commitment to produce a practical hazard assessment method in 3 to 5 years [3]. HAZARD I and the accompanying software and documentation is a prototype of this method.

In February 1984, the National Fire Protection Association (NFPA) sponsored a two-day workshop on "Practical Approaches for Smoke Toxicity Hazard Assessment" [4] involving groups of leading toxicologists, fire protection engineers, fire scientists, fire modelers, and code and fire service representatives. Later in 1984 the Toxicity Advisory Committee of NFPA proposed a simple four-step procedure [5] derived from the workshop's efforts. As the project progressed, papers were published which discussed the evolving philosophy and structure of the hazard assessment methodology (e.g., [6,7]). These papers, and the growing questions regarding combustion product toxicity, stimulated some early hazard analyses using both hand calculated estimates and some of the available fire models. None of these analyses involved explicit predictions of the impact of the calculated occupant exposures in terms of incapacitation or lethality as is done in HAZARD I.

2.1.1 Hand Calculations

In May of 1984, the Toxicity Advisory Committee of the National Fire Protection Association published a procedure for providing "order of magnitude estimates" of the toxic hazards of smoke for specified situations [8]. In this report, Bukowski based the estimating procedure on a series of algebraic equations, which could be solved on a hand calculator. Individual equations were provided to estimate steady-state values for such parameters as upper layer temperature, smoke density, and toxicity; and graphical solutions were provided for room filling time. This work was followed by the more extensive compilation of such equations for use by the U.S. Navy for use in assessing fire hazards on ships [9].

Subsequently, the Toxicity Advisory Committee was asked by the National Electrical Code Committee for assistance in addressing a toxicity hazard question regarding PTFE plenum cables. In providing that help, a hand calculated analysis was performed [10]. This paper concluded for a single, specified scenario, that the size of room fire needed to cause the decomposition of the cable insulation would itself cause a toxicity hazard in an adjacent space before the cable would become involved.

It should be noted that, while suitable for estimating, algebraic equations are limited to steady-state analyses, and cannot deal consistently with the transient aspects of fire behavior. To obtain a complete answer then, requires a computer to solve the differential equations which describe these transient phenomena. This is the role of computer fire models.

2.1.2 Computer Models

The computer models currently available vary considerably in scope, complexity, and purpose. Simple "room filling" models such as the Available Safe Egress Time (ASET) model [11] run quickly on almost any computer, and provide good estimates of a limited number of parameters of interest for a fire in a single compartment. A special purpose model can provide a single function, e.g., COMPF2 [12] calculates post-flashover room temperatures. And, very detailed models like the HARVARD 5 code [13] predict the burning behavior of multiple items in a room, along with the time-dependent conditions therein.

In addition to the single-room models mentioned above, there are a smaller number of multi-room models which have been developed. These include the BRI (or Tanaka) transport model [14] which is similar to the FAST model, and the HARVARD 6 code [15]; a multi-room version of HARVARD 5. All of these models are of the zone (or control volume) type. They assume that the buoyancy of the hot gases causes them to stratify into two layers; a hot, smokey upper layer and a cooler lower layer. Experiments have shown this to be a relatively good approximation.

While none of these models were written specifically for the purpose of hazard analysis, any of them could be used within the hazard framework to provide required predictions. Their applicability depends upon the problem and the degree of detail needed in the result, as will be shown later in this chapter.

2.1.3 Measurement Systems

The development of predictive methods, from algebraic equations to computer models, has created a need for data. Traditional test methods were generally designed as pass/fail or ranking category systems which do not yield quantitative information or if they do, it is not usually in a form which is usable in calculations. To fill this gap, a number of new measurement methods have been developed which are specifically intended to produce such data.

2.1.3.1 Cone Calorimeter

The Cone Calorimeter [16] is one of a number of devices which measure rate of heat release using the oxygen consumption technique. This refers to the indirect measurement of energy release by measuring the mass of oxygen consumed as a material burns. Huggett reported that the ratio of oxygen consumed to energy released is almost constant for nearly all materials [17]. This fact makes the oxygen consumption calorimeter significantly less complicated and more accurate than traditional calorimeters measuring sensible heat. In addition, the burning material need not be encumbered by an enclosure which affects its burning. Combined with the instrumented exhaust system, the apparatus easily lends itself to the measurement of other needed parameters such as sample mass loss rate, effective heat of combustion, and yields of various chemical species of interest.

2.1.3.2 OSU Calorimeter

The Ohio State University (OSU) Calorimeter (ASTM E906) was originally a sensible heat calorimeter which was later modified to include an oxygen consumption operating mode. Of particular interest to this discussion is the fact that its developer, Prof. E. Smith, has developed a fire growth model specifically for use with the data produced by this device. This model [18] is then used to extrapolate the test data to the predicted results of a room fire involving that material.

2.1.3.3 Factory Mutual Flammability Apparatus

Dr. A. Tewarson of Factory Mutual Research Corp. (FMRC) has been a prolific producer of material property data for use in predictive methods. These data are produced in calorimeters of several sizes, some capable of evaluating materials under controlled, vitiated burning conditions [19]. In addition, work on scaling effects on the measured properties have been published [20]. Finally, a new approach to predicting the required combustion properties for families of polymeric materials based on a soot point apparatus has recently been developed [21]. Time and resource constraints prevented the inclusion of much of this data into the prototype data base supplied with this report. Ultimately, all such data needs to be accessible to users of fire models.

2.1.3.4 Lateral Ignition and Flamespread Test (LIFT)

Another source of data for predictive methods is the Lateral Ignition and Flamespread Test developed at NBS by Quintiere and Harkleroad [22]. It developed from an analysis of the flame spread results from a potential test method apparatus currently under consideration by the International Maritime Organization (IMO) [23]. This device measures lateral flame spread velocity and ignition time as a function of irradiance, and critical (minimum) flux values for ignition and for spread. In addition, effective values for thermal inertia ($k\rho c$) at elevated temperature, ignition temperature, and a parameter related to flame temperature are derived from the measured data.

2.1.3.5 Large-Scale Calorimeters

There are a number of large-scale calorimeters using the oxygen consumption technique. Here, large-scale means that the calorimeter is large enough to burn a complete item (e.g., sofa, bookcase, or desk). At CFR, the furniture calorimeter has a maximum energy release rate limit of about 0.7 MW. The "Large Combustion Products Collector" at Factory Mutual Research Corp. is rated about 10 times higher. Other than size, their function is similar to the Cone Calorimeter.

2.1.3.6 Standard Room

The ASTM is developing a test method for conducting room fire tests called the "Standard Room" [24]. This uses an 8 x 12 x 8 foot room with a single door opening, which is directly below a large hood. This hood is equipped for oxygen consumption and chemical analyses. The room test is particularly suited to evaluating (and producing data on) interior finish materials in their normal configuration. Since mass loss data are important for predictive methods, the ASTM room at CFR has been suspended on load cells so that the entire room can be weighed throughout the experiment.

2.1.4 Applications to Date

Over the past few years, models began to be used within a hazard analysis framework to address questions of interest. In 1984, Nelson published a "hazard analysis" of a U.S. Park Service facility which used a combination of models (including ASET) and hand calculations [25]. The calculations were used to determine the impact of various, proposed fire protection additions (smoke detectors, sprinklers, lighting, and smoke removal) on the number of occupants who could safely exit the building during a specified fire incident.

In 1985, Bukowski conducted a parametric study of the hazard of upholstered furniture using the FAST model [26]. Here, the model was used to explore the impact of changes in the burning properties of furniture items (burning rate, smoke production, heat of combustion, and toxicity) on occupant hazard relative to the random variations of the different houses in which the item might be placed. These latter variables were room dimensions, wall materials, and the effect of closed doors. The conclusion was that reducing the burning rate by a factor of two produced a significantly greater increase in time to hazard than any other variable examined. So much so that the benefit would be seen regardless of any other parameter variation. Results such as this can show a manufacturer where the greatest safety benefit can be achieved for a given investment in re-design of his product.

A more recent example of a hazard analysis application is the elegant work of Emmons on the MGM Grand Hotel fire of 1980. This work, conducted during the litigation of this fire was only recently published [27]. Using the HARVARD 5 model, Prof. Emmons analyzed the relative contributions of the booth seating, ceiling tiles and decorative beams, and the HVAC system, all in the room of origin, on the outcome of the fire.

Another recent example is the report of the National Academy of Sciences [28] which contains two hazard analysis case studies; one making use of the HARVARD 5 model and the other using experimental data. The cases deal with upholstered furniture and a combustible pipe within a wall, respectively.

2.1.5 HAZARD I Prototype Evaluation

In July of 1987, the prototype software for the HAZARD I Fire Hazard Assessment Method was approved for limited release. The intent was to conduct what, in the software business, is known as a beta test. That is, a formal evaluation of the software by persons representative of the intended users.

In all, 93 registered beta testers were invited to examine the software package. Written comments were eventually received from half of these. These comments and suggestions, along with those from our staff, had a substantial influence on the general release version presented herein. A copy of the complete report on the beta test is included as Appendix A of the **Technical Reference** volume.

2.2 References

[1] Snell, J. E.; Levin, B. C.; Fowell, A. J. Workshop on combustion product toxicology, summary of presentations. September 10, 1982. Natl. Bur. Stand. (U.S.) NBSIR 82-2634; 1982 January. 65p.

[2] Snell, J. E. Hazard assessment - challenge to fire science. J. Fire Science 1: 4-8; 1983 January/February.

[3] Lyons, J. W. Statement of Dr. John W. Lyons before the Senate Committee on Labor and Human Resources, hearing on fire safety issues, July 19, 1983.

[4] Anon. Proceedings of NFPA toxicity advisory committee workshop on practical approaches for smoke toxicity hazard assessment. NFPA, Quincy, MA; 1984 February.

[5] Snell, J. E.; et al. Summary preliminary report of the advisory committee on the toxicity of the products of combustion. NFPA, Quincy, MA; 1984 June. 1-24.

[6] Bukowski, R. W.; Jones, W. W. The development of a method for assessing toxic hazard. Fire Journal 79(2): 24-26, 28-29, 82; 1985 March.

[7] Bukowski, R. W. Quantitative determination of smoke toxicity hazard - a practical approach for current use. Grant, C. E.; Pagni, P. J. ed. Fire safety science - proceedings of the first international symposium, Hemisphere Publishing Corp., NY; 1986 October. 1089-1100.

[8] Bukowski, R. W. Strawman procedure for assessing toxic hazard. In Summary preliminary report of the advisory committee on the toxicity of the products of combustion. NFPA, Quincy, MA.; 1984 June.

[9] Lawson, J. R.; Quintiere, J. G. Slide-rule estimates of fire growth. Natl. Bur. Stand. (U.S.) NBSIR 85-3196; 1985 June. 56 p.

[10] Bukowski, R. W. Toxic hazard evaluation of plenum cables. Fire Technology, 21(4): 252-266; 1985 November.

[11] Cooper, L. Y. A mathematical model for estimating available safe egress time in fires. Fire and Materials 6(3) and 6(4): 135-144; 1982 September/December.

[12] Babrauskas, V. COMPF2 - A program for calculating post-flashover fire temperatures. Natl. Bur. Stand. (U.S.) Tech. Note 991; 1979 June. 76p.

[13] Mitler, H. E.; Emmons, H. W. Documentation for CFC V, the fifth Harvard computer fire code. Natl. Bur. Stand. (U.S.) NBS GCR 81-344; 1981 October. 187 p.

[14] Tanaka, T. A model of multiroom fire spread. Natl. Bur. Stand. (U.S.) NBSIR 83-2718; 1983 July. 175p.

[15] Gahm, J. B. Computer fire code VI, volume I. Natl. Bur. Stand. (U.S.) NBS GCR 83-451; 1983 December. 116p.

[16] Babrauskas, V. Development of the Cone Calorimeter - A bench scale heat release apparatus based on oxygen consumption. Fire and Materials 8(2): 81-95; 1984 June.

[17] Huggett, C. Estimation of rate of heat release by means of oxygen consumption measurements. Fire and Materials 4(2): 61-65; 1980 June.

[18] Smith E. E.; Satija, S. Release rate model for developing fires. J. Heat Trans. 105: 281-287; 1983 May.

[19] Tewarson, A.; Lee, J. L.; Pion, R. F. The influence of oxygen concentration on fuel parameters for fire modeling. Proceedings of the eighteenth symposium (international) on combustion; 1980 August 17-22; The Combustion Institute; 1980.

[20] Tewarson, A.; Newman, J. S. Scale effects on fire properties of materials. Grant, C. E. and Pagni, P. J. ed. Proceedings of the first international symposium on fire safety science; 1985 October 7-11; New York: Hemisphere Publishing Corp.; 1986. 451-462.

[21] Tewarson, A. Prediction of fire properties of materials, part 1. Aliphatic and aromatic hydrocarbons and related polymers. Natl. Bur. Stand. (U.S.) NBS GCR 86-521; 1986 December. 60p.

[22] Quintiere, J. G.; Harkleroad, M. New concepts for measuring flame spread properties. T. Z. Harmathy, ed. Fire safety: science and engineering. American Society for Testing and Materials ASTM STP 882; 239-267.

[23] Robertson, A. F. A Flammability test based on proposed ISO spread of flame test, third progress report. Intergovernmental Maritime Consultative Organization, IMCO FP/215; 1979.

[24] Anon. Proposed method for room fire test of wall and ceiling materials and assemblies. 1982 Annual Book of ASTM Standards, Part 18, 1618-1638.

[25] Nelson, H. E. Jefferson National Memorial historical site analysis of impact of fire safety features. Natl. Bur. Stand. (U.S.) NBSIR 84-2897; 1985 March. 40p.

[26] Bukowski, R. W. Evaluation of furniture fire hazard using a hazard-assessment computer model, Fire and Materials 9(4): 159-166; 1985 December.

[27] Emmons, H. W. Why fire model? The MGM fire and toxicity testing, The 1985 SFPE Guise Award Lecture, Harvard/FMRC Home Fire Project Technical Report No. 73; 1985 July. 24p.

[28] Anon. FIRE & SMOKE: Understanding the hazards. Committee on Fire Toxicology, National Research Council, National Academy of Sciences; Washington DC: National Academy Press; 1986 July. 105-130.

CHAPTER 3. STEP-BY-STEP PROCEDURE FOR CONDUCTING A HAZARD ANALYSIS

3.1 The Logic of the Procedure

Initially, the context of use and scenario(s) of concern (steps one and two of the hazard analysis method) for the product in question are established, and compared against the matrix of example cases provided. If it is determined that the application falls within the scope and capabilities of HAZARD I but the examples are insufficient to answer the questions of the relative hazard posed by the product, then a new hazard analysis calculation (step three of the process) is needed. The purpose of this chapter is to guide the user through the process of using the HAZARD I methodology and the models, supporting programs, and data that constitute the HAZARD I software, for step three.

Figure 3-1 outlines the four steps in the hazard analysis method. These steps will be discussed in detail in the remainder of this chapter. The user is strongly cautioned to keep the limitations of the system in mind when conducting and analyzing the results of this procedure. While some studies to validate the models and procedures have been conducted, and the system has been tested both internally by CFR and by selected groups outside of CFR, this system should be considered experimental until it has been successfully applied to a broad range of problems by a number of users. As such experience is gained and flaws are identified and corrected, the level of confidence in the system will be enhanced. This requires that users feed their experiences, both good and bad, back to CFR to enable corrections and improvements to be made.

When proceeding with a hazard analysis, the user should try to understand the method and the reasons for each step. The representative examples should be referred to as a guide to the method and as a database where appropriate. Since the system is considered experimental, the results of any analysis should be challenged by the user's common sense and experience; with any results that violate these, questioned and re-examined.

Throughout the problem definition stage, steps one and two - context of use and scenario selection - the user may find it helpful to refer to the representative example case studies and to the section of the **Technical Reference** volume on scenario data from the NFIRS system. In this section, the NFIRS database information is presented, arranged by product identified as first item ignited. That is, for example, the section on upholstered furniture lists the major data elements (form of heat of combustion, equipment involved,

1. **DEFINE CONTEXT OF PRODUCT USE:**

- What is the problem to be resolved?
- What is the scope or context of product use? - occupancy type(s), building design(s), contents, occupants, etc.
- Who are the key decision-makers?
- What criteria will they use to accept/reject the product?

2. **DEFINE FIRE SCENARIO(S) OF CONCERN:** (A scenario is a specified fire in a prescribed building with well characterized contents and occupants.)

- Examine relevant fire incident experience with same/similar products,
- Identify the likely role/involvement of the product in fire,
- Which fire scenarios do the decision-makers feel are . . .
  most common/likely?
  most challenging?

3. **CALCULATE HAZARDS/OUTCOMES:** for each of the scenarios identified above using the technical reference guide and software provided.

- The major software subroutines are . . .
  "FAST_in" - scenario specification (building, contents, occupants, fire)
  "FAST" - fire and smoke transport calculations
  "EXITT" - prediction of occupant decisions and actions
  "TENAB" - calculation of outcomes, i.e., impacts on occupants

4. **EVALUATE CONSEQUENCES:**

- Examine outcomes for each of the relevant fire scenarios selected in step 2 relative to the decision criteria.
- Establish confidence in the predicted results using sensitivity analysis, expert judgment and, when needed, complementary small or large scale tests.
- Delimit the range of applicability of the results based on the above.

Figure 3-1. Hazard analysis procedure.

material, and area of origin, as well as extent of flame and smoke spread, etc.) by frequency for residential fires, deaths, injuries, and dollar loss. These data can help in establishing frequent scenarios or details to include in one's own scenarios of concern.

3.2 Step 1: Defining the Context

Defining the context requires that an analysis of the product and the details of its use within the occupancy of interest be developed. The context of use of a product (e.g., residential wall coverings or office furniture) often implies characteristics of the occupancy necessary for the next step, scenario selection.

The user should clarify, up front, the basis on which the judgment of the product is to be made. It is preferable to state explicitly the required or desired level of safety the product is expected to meet. For example, an appropriate criterion for a new product may be that its fire safety performance be better than or at least as good as existing products in the same use, or that the product exceed a specified level of performance. For example, the product might be judged to be less flammable, result in fewer losses, reduce the likelihood of ignition, etc.

The procedures to be used in step 3 must measure the impact of the fire scenario in terms of the chosen criteria. For example, if a reduction in life loss is the criterion, the procedures must predict fatalities. It should also be determined if calculation/test procedures are available which deal with key aspects of product performance.

Finally, questions important to verification or acceptance of results should be asked. These include:

- Whose experience should be reflected in the solution?
- Should their inputs regarding criteria for acceptance be obtained?
- How can technical limitations be overcome (sensitivity analyses, testing, expert judgment, etc.)?

3.3 Step 2: Defining the Scenario(s) of Concern

The method used in HAZARD I is outlined in figure 3-1. This is similar to the procedure used for several years by the National Fire Protection Association Toxicity Advisory Committee in assessing smoke toxicity hazards associated with code change

<u>BUILDING DESCRIPTION</u>

1. NUMBER OF ROOMS
2. DIMENSIONS OF ROOMS
3. DIMENSIONS OF OPENINGS BETWEEN ROOMS (DOORS, WINDOWS, PENETRATIONS)
4. CEILING, WALL, AND FLOOR CONSTRUCTION (UP TO THREE LAYERS)
5. PRESENCE AND LOCATION OF DETECTORS OR SPRINKLERS

<u>FIRE DESCRIPTION</u>

1. DESCRIPTION OF ALL COMBUSTIBLE ITEMS IN THE ROOM OF ORIGIN
   - MATERIALS AND WEIGHTS OF EACH
   - DIMENSIONS AND CONSTRUCTION OF EACH ITEM
   - LOCATION OF EACH ITEM WITHIN THE ROOM (ADJUST FOR DESIRED SPREAD)*
2. IGNITION SOURCE
   - DESCRIPTION (MATERIAL AND QUANTITY)
   - LOCATION WITH RESPECT TO THE FIRST ITEM IGNITED
3. EXTENT OF FIRE SPREAD
   - SINGLE ITEM
   - PART OF ROOM
   - FULL ROOM

<u>OCCUPANT DESCRIPTION</u>

1. NUMBER OF OCCUPANTS
2. AGE AND SEX
3. PHYSICAL/MENTAL LIMITATIONS
4. LOCATION AND CONDITION AT TIME OF FIRE

*** Current version requires that pre-flashover fire spread be specified by the user. <u>NFIRS</u> data on extent of fire spread by material and product are provided for guidance. Time to flashover is scenario dependent and will be indicated by the model so that the required adjustments can be made. Future versions will include both pre- and post-flashover fire development predictions.**

Figure 3-2. Scenario description for using the HAZARD I software.

proposals.[2] The procedure consists of four steps. The first is to define the context of product use or simply the problem to be resolved, including the criteria to be used for evaluating results. The second step is scenario selection, that is, identifying the fire scenarios of concern to those making the decision. The third step is to quantify the hazards resulting from each selected scenario in terms of their outcomes, for example, death, injury or extent of damage. The fourth step is to evaluate the consequences of the intended use of the product in question in view of the quantitative results obtained in step three and the criteria for decision.

A significant amount of information can be obtained from historical fire incident experience involving the product or related products. Databases such as the National Fire Incident Reporting System (NFIRS) contain relevant data, normally segregated into specific categories. A more detailed discussion of the kinds of data available in NFIRS is provided in chapter 5.

Also of value are census data and demographic information compiled by industry trade associations. For example, the American Hotel and Motel Association maintains detailed information on occupancy rates and characteristics of guests in member properties.

Next, one scenario is selected for analysis using the HAZARD I software. An outline of the items which need to be specified is given in figure 3-2. Detailed discussion of the inputs required is contained in the **Software User's Guide**. The entire scenario should be developed before data input is begun. If there is more than one scenario of concern, they can all be developed initially, or taken one at a time. Studies of the sensitivity of the results to variations in one or more parameters of the scenario specification are recommended, but these should be decided upon after seeing the results of the first analysis for the baseline scenario.

3.3.1 Building Description

Drawings of the building to be specified should be obtained. Where a "typical" building will suffice, the buildings provided for the examples can be used as representative. The easiest way to use one of the example buildings is to read one of the example case files into FAST_in and change the nonbuilding inputs. In any case, a complete set of floor plan drawings for the building used in the analysis should be made. These drawings will be used extensively throughout the process to locate doors and windows, contents, people, dimensions and distances, etc. For multi-story buildings, a sectioned elevation drawing should also be prepared to locate the elevation of building elements above some reference

[2] Snell, J. E. A Preliminary Report of the NFPA Advisory Committee on the Toxicity of the Products of Combustion. Fire Journal 78(5): 1-24; 1984 September.

elevation. These drawings should be dimensioned and to scale to avoid confusion. All details of construction required as input should be shown on the drawings.

In addition to dimensions, the thermophysical properties of the materials of construction are required. These include the density, thermal conductivity, heat capacity, and surface emissivity. Data for many common materials are included in the database. Where data on the desired materials are not provided (such as for proprietary products), they are often available from the manufacturer. The user is cautioned to be careful to use the required units for these, and all input values.

3.3.2 Fire Description

The fire is specified in terms of heat of combustion, mass loss or heat release rate and the yields of major species over time. The yield of a species is the mass of that species produced per mass of fuel lost. Each of these inputs can vary over user-defined time intervals. The database contains Furniture Calorimeter data on the burning of specific full-scale items obtained at CFR. One should keep in mind that the burning characteristics of these items are not necessarily representative of other, similar products.

The fire description begins with the selection of an ignition source (known in NFIRS as the "form of heat of combustion") and first item ignited. Once these have been decided upon, the arrangement and burning characteristics of the other items in the room of fire origin define the extent and time of fire spread up to the point of flashover. Thus, the user should adjust the arrangement of the other items in the room to obtain the desired (pre-flashover) fire spread based on the NFIRS data or other considerations.

If information on the item or a suitable substitute is not provided in the furniture calorimeter database, the database of Cone Calorimeter data should be consulted for data on the materials of construction of the item needed. These data are on component materials, so the rate of fire development of the entire item must be calculated. The techniques for doing this are discussed in chapter 6.

If the required data are not provided, it may be necessary to have the item or material tested. This would obviously be the case if the performance of a specific item is being analyzed. Large scale oxygen consumption calorimeters are available at many fire research and testing laboratories. Cone Calorimeters are being produced commercially and are operating in many testing laboratories in a number of countries. Measurements using the Cone Calorimeter are detailed in an ASTM draft procedure which will eventually become a standard test method.

Spread to the next item occurs when there is contact by the flame from the first item or by radiant ignition. (Note: Data on radiant ignition of materials is often given for piloted and nonpiloted conditions. The piloted case would yield the more conservative result.) Ignition of a second item depends on the radiative power output of the first item, the separation distance, and an appropriate ease-of-ignition criterion. Once the ignition time is determined, the fire development of the second item is assumed to take place as if it were burning alone except that the time is shifted by the ignition time. This process is repeated with each item until all are burning or until flashover occurs, at which time all combustibles in the room ignite.

The suggested procedure is to decide on the ignition source and first item ignited. Input these into the FAST and run the case. If flashover does not occur, upper layer temperature in the room of origin does not exceed 500 °C, go back and see if any second items would ignite from the first item. If none do, the case is over. If one or more do, include these and run the case again. When enough items are burning to produce flashover, assume all items in the room ignite at that point and run the case with these data. At this point it would be likely that the fire is ventilation limited, and the burning rate will depend on the available air flow rate. The pyrolysis or mass loss rate will depend on the associated heat transfer to all fuel surfaces.

As was stated earlier, the model requires a single set of fire time-dependent inputs (heat of combustion, mass loss or heat release rates, and species yields). Where there are multiple items burning simultaneously or a single item made up of multiple materials, a composite set of values is needed. These can be obtained by using the program MLTFUEL. This is an interactive program which asks for the data from the individual fuels and provides the composite values needed. The only work necessary before running it is to construct a time line for the fuels and establish the time intervals for the composite fire (as illustrated in chapter 3 of the **Software User's Guide**). The program asks for the number of fuel items and the number of intervals and then the data for each fuel and interval are entered in order. Where yields of more than one species are to be used, the effective yield of the first species is calculated in the initial sequence of questions and additional species are calculated one at a time without the need to re-enter the mass loss data.

Obviously, the fire description is a major task requiring considerable time and expertise to insure correctly modeled results. Chapter 6 provides more details and methods for specifying the burning items. In future versions of this system, a fire growth model will be included to predict this spread based on the arrangement specified. If the user has access to a copy of the Harvard or FIRST fire models, these can be used to predict the fire spread for up to five items and the result entered into the FAST model as the specified fire. Also, the data obtained from room fire tests has been used as the specified fire input to FAST by some researchers. This is the best way to include the burning behavior of rooms and contents since all models are limited in the physics and combustion chemistry to some extent. The application of either of these techniques requires familiarity with the models which is beyond the scope of this report.

3.3.3 Occupant Description

The data required for the occupant description are used in the evacuation/behavior model and not in the fire model. Thus a detailed discussion of the data inputs will be made later in this section. The four general descriptors as presented in figure 3-2 should be decided at this point. However, since the location and activity of the occupants may affect the rooms for which calculations are made or whether internal doors are open or closed, these will also influence the results of the fire model.

3.4 Step 3: Calculate the Hazard

The purpose is to provide the best state-of-the-art technical information/estimate of the product's contribution to the overall hazards of fire in general and in particular its smoke toxicity hazard for each scenario of concern. It is preferable for these outcomes to be expressed in deaths, injuries, extent of damage, etc., so they may be related to the criteria established in step one and applied in step four. One should try to go beyond measures such as time to flashover, escape time, peak temperatures, flammability or other indices which leave the decision maker asking "so what?." Also, it may be desirable to obtain results for the fire and occupant exposure conditions in appropriate engineering units for comparisons.

3.4.1 Input Program

Once the detailed problem has been defined, the user interface program (FAST_in) is run. This program creates the input file necessary to run the transport model, FAST. It allows the user to work in either English or metric units, converting to the metric (SI) units required by FAST. The results of FAST are output only in metric units, however.

FAST_in does error checking on the consistency of the data input and advises the user if a problem is discovered. Help screens are provided if the user is unsure of what to enter. Additional details on the input program operation are provided in the **Software User's Guide.**

3.4.2 FAST Model and Its Output

The transport model (FAST Version 18) is run as a "batch" program rather than interactively. The HAZARD Interface Shell (HIS) will assume the name of the file which was created in the previous step, or any other compatible file can be selected. Contrary to its name, the model takes a significant time to execute. The more complex the case, the longer it takes; so be patient.

The model produces a printed output summary at time intervals selected by the user in FAST_in. These tabulated data can be directed to the screen, to a printer, or to a file for later printing. This version of FAST also supports run-time graphics, which are easily activated from FAST_in. The user should remember that you cannot send the printer output to the screen if the run-time graphics is active since one will write over the other. The default plots are upper layer temperature (°C), interface position (the boundary between the layers), oxygen concentration (%) and heat release rate (kW). The plots displayed by the run-time graphics can be customized by editing the graphics specification in the input (.DAT) file with the HIS editor (see Reference chapter of the **Software User's Guide**).

A more detailed (frequent) output is sent to a plot file (called a dump file), also at intervals specified by the user in FAST_in. It should be noted that this is a very large file; 28k per time interval, so it should be verified that there is sufficient disk space available for the dump file before a run is started. A plotting package (FASTplot) is provided to produce graphs and tabular listings of the data. The <save> feature in FASTPLOT will write the data into an ASCII file in columns which can be used with many commercial plotting packages for fancier graphs.

3.4.3 Decision/Behavior Evacuation Model

After obtaining the results of the FAST calculation, the evacuation model EXITT is run. The detailed inputs are discussed in the Reference section of the **Software User's Guide**. They are entered into a file using the editor in the HIS. The room dimensions are taken from the building drawings and the occupant descriptions from the data decided upon in the first step. In addition, the data predicted by FAST for the interface position and smoke density in each room are read directly from the dump file produced by FAST.

The evacuation model will predict the activation time of any smoke detectors based solely on the smoke data (smoke density and layer thickness) read from the FAST dump file, or a time can be manually entered. For heat detector or sprinkler head activation times the model DETACT is provided. The instructions for running it are provided in the **Software User's Guide**. When the activation time is obtained, this time can be specified as an input to the evacuation model and it will be used as the notification time for the occupants. While the DETACT model can be used to calculate the activation time of sprinklers if such are present in the scenario, the current hazard analysis system cannot predict the extinguishment process nor the impact of the spray on the transport or cooling of the gases in the layers. These impacts are thus left to the judgment of the user.

3.4.4 Tenability Program

The results of all of the preceding calculations are now used to evaluate whether or not the occupants successfully escape. If they do not, the user will know whether the limiting condition was heat, smoke, or toxicity, and when this condition occurred. In all cases only physical impacts are predicted, and not impairment of mental processes or judgment.

This is done by executing the program TENAB, which compares the conditions in the building over time predicted by the FAST model and the location of the occupants over time predicted by the evacuation model to the tenability criteria discussed in the section of the **Technical Reference** volume titled TENABILITY LIMITS. If at any time step the interface position in the occupied room is above 1.5 meters, the occupant is assumed to be exposed to the conditions in the lower layer. If the interface is below 1.0 meters, they are assumed to be exposed to the conditions in the upper layer. Between 1.0 and 1.5 meters, TENAB checks the upper layer temperature and selects the upper layer if its temperature is below 50 °C or the lower layer if the upper layer temperature is above 50 °C, assuming that the occupant is bent over or crawling.

Temperature and heat flux are considered limiting conditions and are assumed to have no impact on the occupant until the limit occurs. While this is not explicitly true, the state-of-the-art of toxicity evaluation does not currently account for intermediate effects.

Smoke obscuration and its effect on the ability to escape is accounted for within the evacuation model in that people move faster when exposed to light smoke and slower when exposed to moderate smoke. At a high smoke level, people will not enter the room (route is blocked) and they will find another route or be trapped. Thus, no further accounting for the effect of smoke is necessary.

Toxicity is considered in two ways (in TENAB): (1) using the concentration-time product parameter (Ct), and (2) by the FED method which considers the exposure to hydrogen cyanide and carbon monoxide, accounting for the impact of the simultaneous exposure to carbon dioxide and reduced oxygen. (Note: For a thorough discussion of Ct and FED, and response to other fire products, see chapter 7.) These gas concentration data are produced by the FAST model when yields of these species are specified by the user. For Ct, reference values of 900 g-min/m^3 for lethality and 450 g-min/m^3 for incapacitation may be used where the materials burning are of "ordinary" toxicity. This means that, when tested using an appropriate combustion toxicity screening test, the materials show neither "extreme toxic potency (ETP)[3]" nor an "unusual toxicological response (UTR)[4]". Since this is an approximation of toxicity, it is desirable to determine the sensitivity of the result to the reference value of Ct used. This does not require any additional runs of models, but only the determination of the cumulative value of Ct for each occupant at the time that they exit the building. The reference value given above divided by the maximum accumulated value represents a "safety factor" for the estimate.

The evaluation of the impact of carbon monoxide, hydrogen cyanide, and carbon dioxide along with reduced oxygen, represents the first version of a toxicity evaluation technique referred to as the "N-Gas Model." The equations used by TENAB to make this evaluation are discussed in chapter 7 of the **Technical Reference** volume. When the computed value for FED reaches 1, lethality is assumed to occur; at a value of 0.5, incapacitation is assumed. Another set of tenability criteria are used by TENAB to evaluate incapacitation only. These equations are based on the work of Purser with non-human primates, and are presented in detail in chapter 8 of the **Technical Reference** volume.

For both the Ct and FED approach, the data values used are exposure doses (time integral of concentration) and are thus additive over time. Therefore, the changing exposure of an occupant moving through the building or overtaken by the descending layer are accounted for by adding (integrating) these doses over time in TENAB. For example, an occupant is initially exposed to the lower layer until the interface reaches head height. The time that this occurs is obtained from the interface position data for that room. Thus, the exposure at any time equals the accumulated Ct value up to that time. When moving from room to room, the accumulated dose for each room is computed. The total exposure is the sum of the doses accumulated in each room until the occupant exits the building. The same technique is used for the FED data.

---

[3] The data on the toxic potency of smokes from nearly all materials falls within a nominal range of one to one-and-a-half orders of magnitude. Extreme toxic potency is defined by data falling substantially below this nominal range.

[4] The inhalation of smokes from virtually all materials can cause irritation and damage of the respiratory system along with asphyxiation. Thus an unusual toxicological response is evidenced by 1) respiratory irritation or pathology, or both, which vary significantly from that observed following exposure to smoke and 2) toxic effects influencing tissues, organs, or systems (other than the respiratory system) in a manner not attributable to asphyxiation. Unusual toxicity may also be evidenced by deaths unexplained by the concentrations of the common combustion gases, e.g. CO, CO_2, and HCN.

As a quick, initial check, the impact of the fire can be evaluated and a critical time obtained for each room without running the evacuation model. This would be done by running TENAB with an "occupant" placed in each room (by keyboard entry) at time=0 and never moved. This would represent an occupant of the room who makes no attempt to (or cannot) escape. When run with the dump file from FAST, this gives a set of critical times for each room.

3.5 Step 4: Evaluate the Consequences

In this final step, the results obtained for the product are analyzed using the criteria established in step one. This may involve comparison with accepted practice or baseline data. Sensitivity to key parameters is checked. All scenarios are considered and the final decision(s) are made. It must also be decided if all pertinent scenarios have been considered, whether the results make sense, and if any additional steps (e.g., testing) are required as a result of limitations of the method employed.

While the results of the calculations are in absolute terms (the occupant(s) lived or died) they should only be interpreted in a relative way. That is, since the hazard analysis system is still considered experimental, the impact of methodological errors which may affect the validity of the result may be reduced by evaluating the difference between two calculations. Thus, the system is best used to examine the difference in the result with and without the product in question or where the product is replaced by the traditional alternative. The representative examples provided can be used as baseline cases if appropriate.

In addition, it should be recognized that many of the inputs specified are assumed by the user, and the sensitivity of the results to these assumptions should be examined. If the result is very sensitive to a given input, further study may be necessary to refine the estimate or value used in order to have more confidence in the predicted result.

Finally, as was stated in the introduction to this section, the results of any analysis should be challenged by the user's common sense and experience. Results that violate these should be questioned and resolved. Comparisons should be made to data from similar experiments or actual fires wherever possible. If such data are not available, it may be advisable to conduct verifying tests in situations where public safety is at risk.

CHAPTER 4. MATRIX OF EXAMPLE CASES

4.1 Purpose

The example cases provided with the HAZARD I software serve multiple purposes. First, they represent realistic cases of interest which demonstrate the use of the system. Second, as common scenarios, they provide a baseline against which to compare the relative change in hazard produced by modifications in products or materials. And third, they define typical buildings and fires for a given occupancy which may be suitable for use as representative of that occupancy for other types of analyses and purposes such as education, firefighter training, evaluating the potential impact of code changes, etc.

4.2 Development of the Examples

Since one of the primary purposes of the hazard method is to address product hazard questions, it is critical that the context of the analyses be considered meaningful to the various enforcement authorities responsible for acceptance of the material or product in question. Within the United States, this responsibility is shared by the Fire Services and Building Code Officials through the fire and building codes, respectively.

Two groups were empaneled to develop example case descriptions for inclusion in the matrix of example cases. One, the Fire Services Panel was organized with the cooperation of the Joint Council of Fire Services Organizations, and staffed by representatives of their members. They were assigned the task of developing a set of fire scenario descriptions. The other, the Building Configuration Panel representing the four Model Building Code groups and the architectural community, was asked to produce a set of building descriptions. For each panel, a chairman was obtained from the respective area who helped identify appropriate participants and chaired the working group at the meetings. The CFR role was only as facilitator, providing administrative support and background guidance. No CFR staff were assigned to either panel so that the results of the panel deliberations represented the work of the group and were not biased by CFR influence.

Tables 4-1 and 4-2 list the panel participants and the organizations represented for the first set of meetings. Their first exercise was limited to the development of cases for residential (one- and two-family) occupancies.

Figure 3-2 presents the level of detail to which the panels were asked to describe the cases. The Building Configuration Panel supplied the items under building description and the Fire Services Panel covered the items under both fire description and occupant description. The furnishings selected for the three houses are tabulated in tables 4-3 to 4-5, and the floor plans are shown in figures 4-1 to 4-4. The scenarios for the eight cases are summarized in tables 4-6 to 4-13. And the complete documentation of the calculations is included in the **Example Cases** volume of the **Reference Guide.**

One of the most important questions which was addressed by the panels dealt with the philosophy of the representativeness of the example cases. This was addressed by posing the set of questions listed below:

QUESTIONS TO BE RESOLVED

The purpose of the generic fires and building descriptions is to provide a baseline against which to compare the change in hazard to the building occupants resulting from the use of new or modified products. Since neither the manufacturers of such products nor the code authorities asked to rule on product acceptability know the specific characteristics of the building into which the product will be placed, these generic scenarios are needed to perform an analysis of the potential benefits of new technology.

With this in mind, there are some questions which need to be resolved:

1. Should the building described represent the typical home or the typical home which will experience a (reported) fire?

2. Should either of the above be typical at all, or rather be "marginally" code compliant?

3. Should the fires represent the most common fires (reported or unreported), or most common fatal fires? Should they be matched to the material or product?

4. Should the fires come only from frequency of occurrence or should they attempt to include low frequency, high risk cases?

5. Should the occupants represent the typical family, the typical family who will have a (reported) fire, or include persons known to be at higher risk, such as the very young and old?

All of these questions are really the same. No one expects to eliminate fire losses. The object is to improve safety or at least maintain the status quo at reduced cost. Thus, when attempting to measure the level of safety provided, is it better to do so for a typical case or a minimum acceptable case?

While initially unsure of a response, the groups settled on *typical* homes and occupants with some emphasis on homes that have reported fires. For example, they did include some very young or old people in some scenarios and tried to cover a range of slow, medium, and fast fires which were realistic in their own experience. But they included typical furnishings in typical buildings, all equipped with a working smoke detector.

4.3 Other Occupancies To Be Added

As new versions of the fire hazard assessment method are produced, examples for additional occupancies will be developed. These will probably follow as:

1. Other Residential (Apartment, Hotel/Motel)
2. Health Care
3. Assembly and Educational
4. Business and Mercantile

In each case, one or more representative building descriptions will be developed by the Building Configuration Panel. These will probably include the minimum number necessary to represent major types of configurations seen in practice. For example, in the Hotel/Motel area, we might expect to see a traditional hotel with guest rooms on a double loaded corridor, an atrium design, and an exterior balcony arrangement.

4.4 Additional Fire Scenarios

As the Building Configuration Panel develops additional building descriptions, the Fire Services Panel will provide associated fire scenarios. While the exact scenarios that develop cannot be predicted, the procedure followed in the first exercise indicates that they will probably focus on the types of fires where most of the losses have occurred. In the Hotel/Motel area for example, these may include the smoking related guest room fire and a fast developing fire originating in corridors or common spaces which impacts the exit access. They may also choose to include a scenario which represents a low frequency of occurrence, but has severe consequences in terms of hazard to occupants or firefighters, or which presents unusual suppression difficulties. This is the main reason for using an expert panel approach rather than simply relying on statistical data.

4.5 Applicability of the Examples

While the examples are intended to be representative cases for the given occupancy, they should not be considered a universal set of all conditions which define the hazard of products in that occupancy. That is, the fact that a product does not represent an unacceptable hazard in these cases does not mean that a hazardous condition cannot exist. It is important that each product application be analyzed for the scenarios of concern as they relate to the context of use of that product. The examples may be useful directly, only where the scenarios of concern match. Otherwise, the specific, identified scenarios must be analyzed using the procedure provided.

4.6 Impact on Occupants

The eight fire scenarios were analyzed by the HAZARD I software to establish the impact of fire on the occupants. The model provided the time to flashover as well as the time to reach maximum temperature. The smoke density and interface position predictions provided by the FAST model were used with EXITT to establish the time needed for the occupants to evacuate. The tenability program, TENAB used the data from FAST and EXITT with its default tenability limits (temperature, heat flux and toxicity) for each occupant in the eight scenarios.

Of the eight fire scenarios, five experienced ventilation controlled burning conditions (Scenarios 1, 2, 6, 7 and 8). In scenarios 2 and 8, some of the required data were not directly available in the data base, so estimated values were used. For scenario 2, data for the kitchen cabinets were estimated from data from the wardrobe cabinet, and in scenario 8 the data from a TV cabinet was used to estimate the burning rate of the desk; in each case adjusting for estimated total mass. Two scenarios (3 and 4) were ventilation controlled because the door to the fire room was closed. One scenario (5) contained insufficient fuel to reach ventilation control for the specified room and door opening.

Tables 4-6 through 4-13 summarize the predicted impact on the occupants in the eight fire scenarios. Almost all occupants safely exited the buildings. This can be attributed to the fact that all scenarios were specified with working smoke detectors which provided timely warning before conditions reached dangerous levels. This, coupled with the fact that all of the occupants were physically capable of escaping led to the results obtained.

As an example of how the impact of variations in assumed conditions can affect the predicted results, three different cases of conditions affecting occupant response to the eight example fire scenarios were formulated as follows:

- working smoke detectors were present,
- no smoke detectors were present, and
- an immobile occupant was positioned in each room.

Table 4-14 compares the predicted response of occupants in the cases with smoke detectors (column 1) and without smoke detectors (column 2), it can be seen that the major effect of smoke detectors is predicted to be earlier evacuation based on an earlier warning of the occupants to the presence of the fire. The absence of smoke detectors is predicted to result in two *more* fatalities in one of the scenarios (the Christmas tree fire in the townhouse). In this scenario, the two occupants who die in the case with smoke detectors become trapped inside the building while attempting escape. Without smoke detectors, the occupants become aware of the fire at a much later time and are trapped on the second floor.

It should be noted that, while HAZARD I can be used for many such "what if" comparisons, the user must take into account the limitations of the methodology. For example, the current version of the software does not predict structural failure of building components. Thus, occupants that were protected by closed doors and judged to survive, might actually be killed by leakage around or burn through of the door. In general, predicted effects may be artifacts of the assumptions or limitations inherent in the analysis, and should be examined by sensitivity analysis or by comparison to test data or the results of actual fires.

As an indicator of the sensitivity of the results to physiological and behavioral assumptions, an immobile occupant is assumed to be in each of the rooms in the houses, column 3 of table 4-14. Deaths are predicted in all cases, with some of the deaths occurring in as little as 2 minutes from the start of the fire. In almost all cases, this includes the person located in the room of fire origin. For example, the fatality indicated in example 4 could be a child playing with matches in the closet with the door closed. Obviously the assumed rate of fire growth is very important. In some scenarios, occupants remain safe in their room for the duration of the fire. This may be the result of the fire itself never growing large (e.g., the trash fire in the townhouse), or because occupants are protected by closed doors (e.g., scenarios in the two-story house).

The user is strongly urged to run these example cases and examine their sensitivities and key assumptions. Only then will enough experience be gained to recognize their appropriate application and use. Clearly, the example results, summarized in table 4-14, have no established relevance beyond the situations simulated and must not be assumed to apply generally.

Table 4-1. Building configuration panel

Mr. Glenn A. Erickson (Chairman)*
1917 Ridge Lane
Hasting, MN 55033

Mr. J. Vicars*
American Institute of Architects
1735 New York Avenue NW.
Washington, DC 20004

Mr. Richard M. O'Kawa*
International Conference of Building Officials
5360 South Workman Mill Road
Whittier, CA 90601

Mr. C. McGarity, Jr (AIA/NFPA)*
Box 2685
173 N. Converse Street
Spartanburg, SC 129304

Mr. Jim Dowling
National Association of Home Builders
15 & M Street, NW.
Washington, DC 20705

Mr. Paul K. Heilstedt
BOCA
17926 Heilstedt Road
Homewood, IL 60430

Mr. Richard Vognelt
SBCCI
900 Montclair Road
Birmingham, AL 35213

Mr. Frank Drake
International Conference of Building Officials
5360 South Workman Mill Road
Whittier, CA 90601

* indicates attendees at first meeting

Table 4-2. Fire services panel

Mr. Howard Boyd, (Chairman)*
4018 Lealand Lane
Nashville, TN 37204

Mr. Bob McCarthy (USFA/FEMA)*
Emmitsburg, MD

Chief Ken Henry (ISFSI)*
315 East Windhorst Road
Brandon, FL 33511

Mr. R.B. "Skip" Smith (FMANA)*
National Fire Protection Association
1110 Vermont Avenue NW. Suite 1210
Washington, DC 20005

Mr. Clyde Mariotti (IFSTA)*
Tristate Fire Protection District
419 Plainfield Road
Darien, IL 60559

Chief Bill Roberts*
Austin Fire Department
1621 Festive Beach
Austin, TX 78702

Mr. Dave McCormack (IAFF)*
Fire Safety Systems Inc.
2100 M Street NW. Suite 305
Washington, DC 20037

Mr. Richard Duffy*
IAFF
1750 New York Avenue
Washington, DC

Roger Lanahan (USFA/FEMA)*
Emmitsburg, MD

* indicates attendees at first meeting

Table 4-3. Consensus on ranch house furnishing

Living Room:	1 club chair 3 seat sofa - foam synthetic untreated cover ottoman - foam synthetic - untreated cover 19-inch TV stereo (wood) with 4 speakers coffee table (glass)
Master Bedroom:	double bed - foam synthetic dresser - formica top chest of drawers - formica top wooden chair - upholstered (neoprene) pad
Bedroom #2:	bunk beds - wood (maple) - 2 cotton mattresses chair & desk dresser - wood
Bedroom #3:	double bed on wood frame with polyurethane/innerspring mattress and vinyl sheet for bedwetting 2 wood end tables small desk (laminate formica) & wood chair dresser (laminate formica)
Dining Area:	wooden dining table with laminated top (formica) 6 wooden chairs with cushions sideboard - wood
Kitchen:	laminated table & 2 wood chairs cabinets (not wood) 1 pot grease (teflon coated pot) aluminum pot
Bathroom:	fiberglass sink plastic waste pipe fiberglass tub cotton towels vinyl shower curtains
Closets:	mixed natural & synthetics

Smoke detector in hallway - 85 decibels in hallway - run model with and without

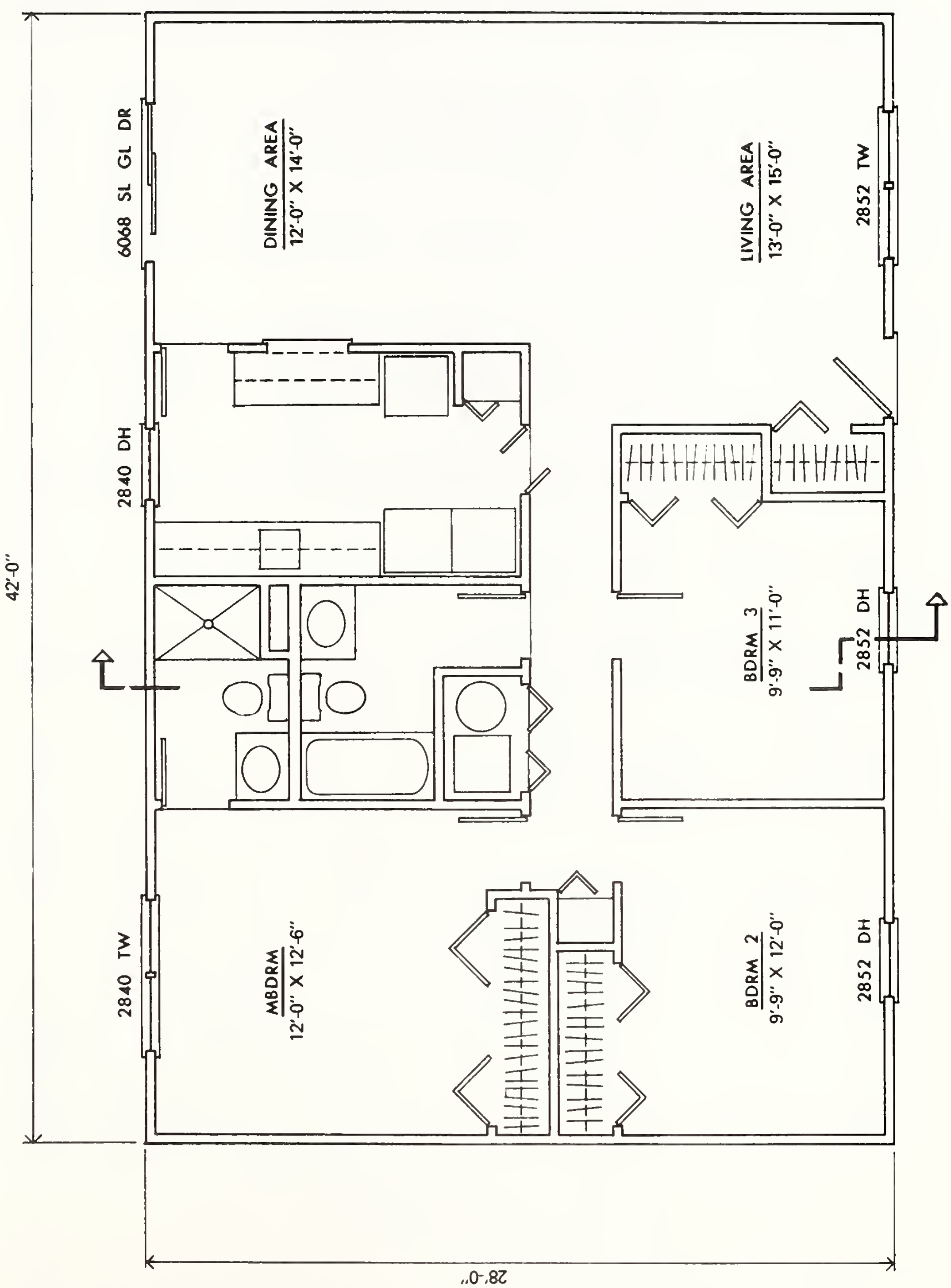


Figure 4-1. Layout of a typical ranch house.

Table 4-4. Consensus on townhouse furnishings

Living Room:	sofa chairs - 2 coffee table - wood stereo - large and 21" TV end table - wood buffet - wood large bookcase with books - wood large bean bag chair	
Family Area:	dinette table - chrome and vinyl chairs - 4 - chrome and vinyl high chair - chrome and vinyl side board - wood	
Kitchen:	laminated pressed board cabinets formica counter tops	
Master Bedroom:	queen waterbed dresser chest of drawers chairs 13" TV	
Bedroom #2:	single bed chest of drawers toy box - wood	
Bedroom #3:	crib - wood changing table chest of drawers - wood	
Smoke detectors:	non-interconnected photoelectric (85 decibels)	
	downstairs	middle of hall between door to toilet and door to laundry
	upstairs	between top of stairs and door to bathroom
Closet under stairs:	hot water heater household cleaning materials - broom plastic bucket, paper, rags, etc.	

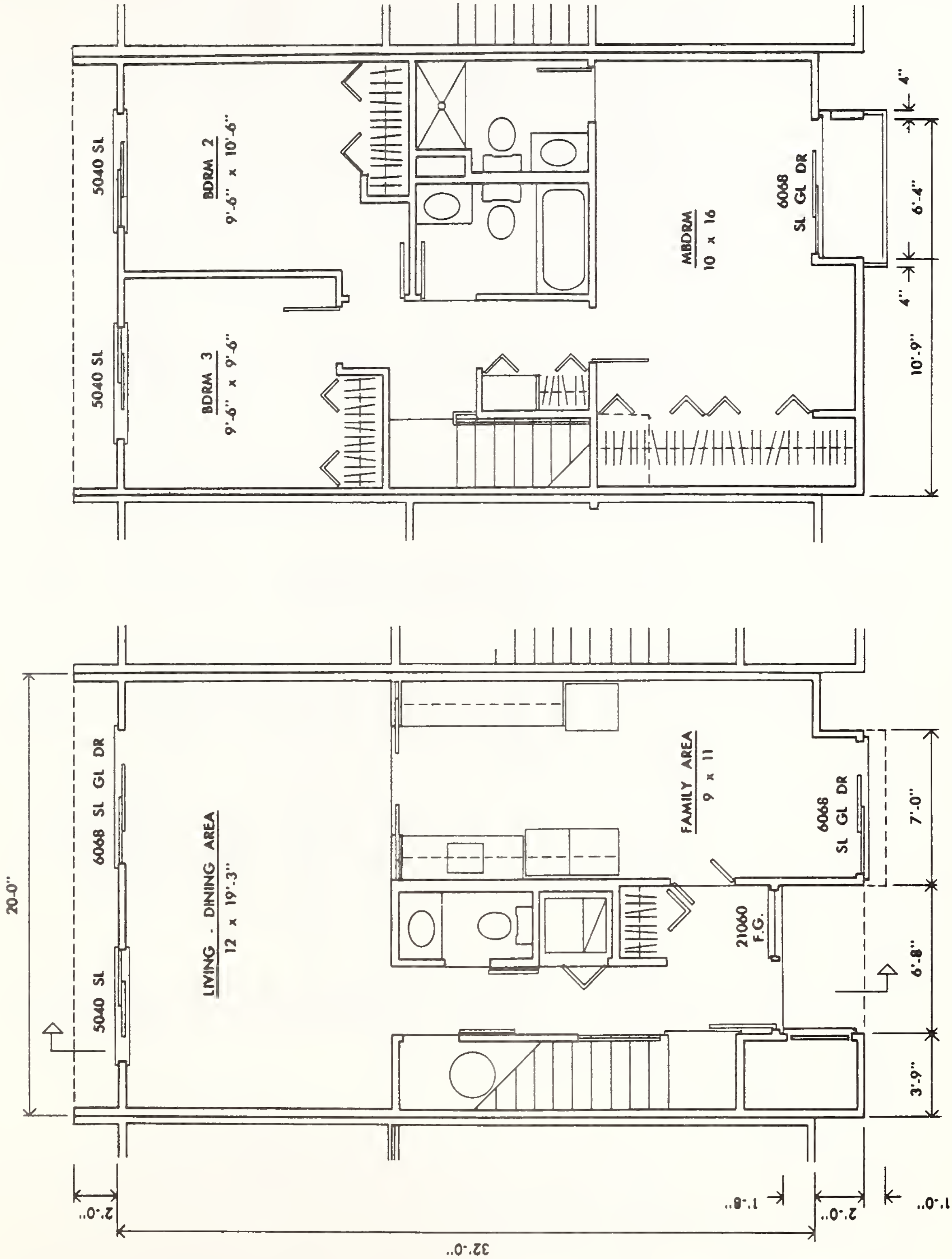


Figure 4-2. Layout of a typical townhouse.

Table 4-5. Consensus on two-story house furnishing

Family Room:	1/8 in luan wood panel over drywall; couch (90 in, velour cover, urethane interior); coffee table (24 lbs wood, 29 lbs books and magazines on lower shelf, 2 5 lb glass inserts in top); end table (49 lbs including books and magazines); lamp on end table; recliner (85 lbs, corduroy); entertainment center (188 lbs); 19" TV (51 lbs); VCR (16 lbs); tape deck (7 lbs); records (30 lbs); tapes (10 lbs); speakers (2, 22 lbs); bookcases (2, wood, 190 lbs, filled with 180 lbs books); liquor cabinet (11 750 ml bottles);
Living Room:	couch (180 lbs, fabric with urethane interior); end tables (2, wood, 124 lbs); chair (fabric with urethane interior, 38 lbs); chair (fabric with Kapok interior); curio cabinet; TV and TV stand (chrome)
Dining Room:	table (wood, 104 lbs); chairs (15 lbs each); buffet; breakfront
Breakfast Room:	wicker table (20 lbs plus glass top); wicker chairs (14 lbs each)
Kitchen:	cabinets (ash); liquor (24 750 ml bottles and 5 1750 ml bottles); usual appliances; formica counter tops
Utility Room:	washer and dryer
Master Bedroom:	king size bed (wood headboard); nightstands (2); table (antique wood); chair (30 lbs); dresser; highboy; TV (13 in); closet (contains 267 lbs clothes)
Bedroom #2:	trundle bed with bedspread; dresser; bureau; desk; end table; stereo receiver (12 lbs); speakers (12 lbs total); bookcase; books (108 lbs); chair (10 lbs); records (30 lbs); clothes in closet (136 lbs)
Bedroom #3:	double bed; wicker basket; cedar chest; dresser
Bedroom #4:	office; desk (wood); chair (40 lbs, executive type); typewriter table; typewriter; bookcases (3 five shelf units, 258 lbs); stereo receiver (small); TV (13 in portable)
Did not furnish basement	
Smoke Detectors:	non-interconnected ionization (85 decibels) opposite front door, left of door to passageway middle of hall, near door to bedroom #4

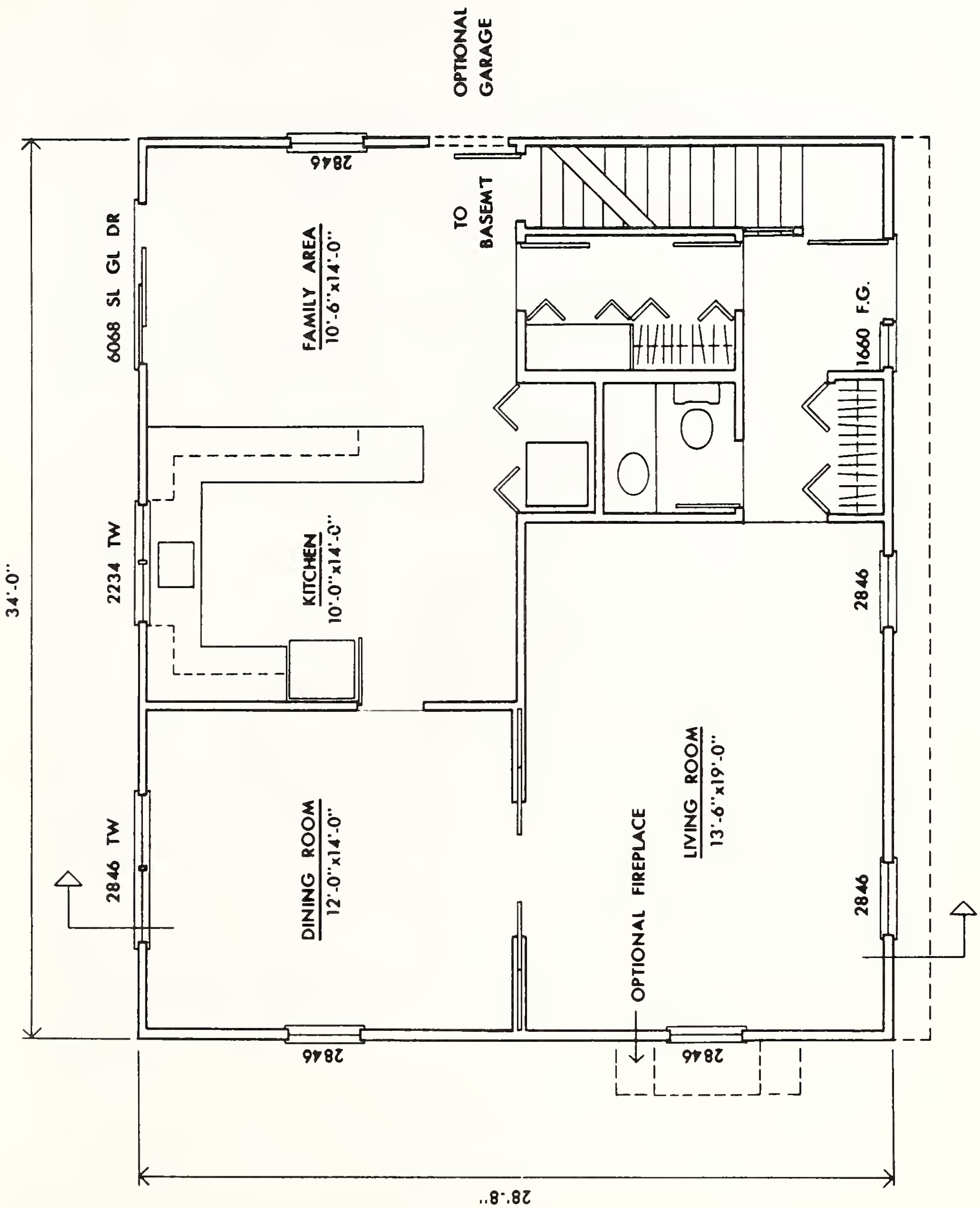


Figure 4-3. Layout of the lower floor of a typical 2-story house.

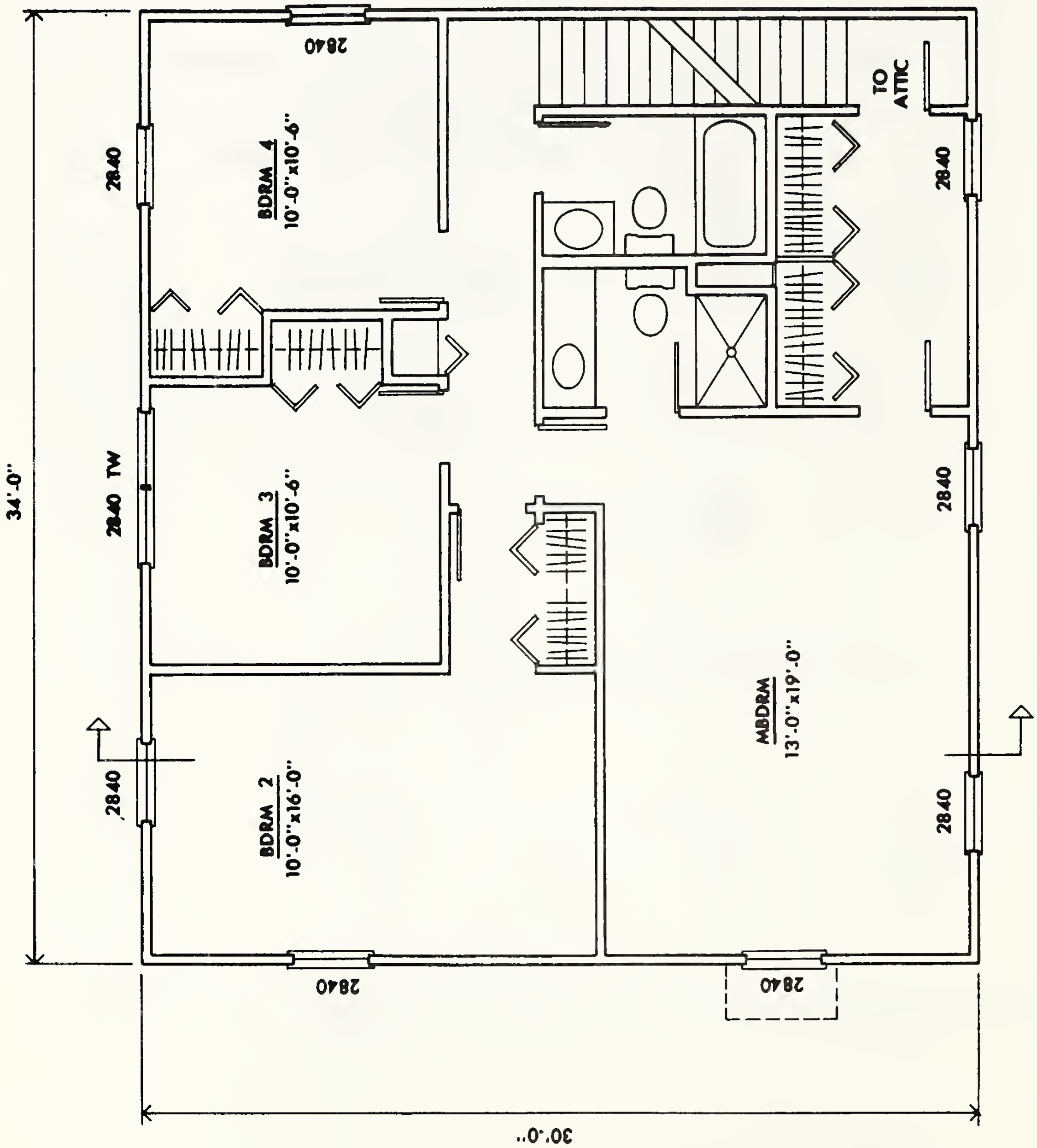


Figure 4-4. Layout of the upper floor of a typical 2-story house.

Table 4-6. Impact on occupants for fire scenario 1

Scenario 1 - Smoldering sofa in living room of the ranch house

FAST input file: SCEN-1.DAT
EXITT input file: SCEN-1.BLD

Assumed properties of product: Material code UPS001 (sofa)

Flashover time: did not flashover

Evacuation

Occupant	Time
1	Escape via window - 20 min

Table 4-7. Impact on occupants for fire scenario 2

Scenario 2 - Grease fire in kitchen of the ranch house

FAST input file: SCEN-2.DAT
EXITT input file: SCEN-2.BLD

Assumed properties of product: Material code CKG001 (cooking oil) and CLT001 (wardrobe) used for cabinets

Flashover time: 3 min

Evacuation

Occupant	Evacuation Time
1	1 min
2	1 min
3	1 min
4	1 min
5	1 min

Table 4-8. Impact on occupants for fire scenario 3

Scenario 3 - Mattress and bed linen in bedroom 2 of the ranch house

FAST input file: SCEN-3.DAT
EXITT input file: SCEN-3.BLD

Assumed properties of product: Material code BED002

Flashover time: did not flashover

Evacuation

Occupant	Evacuation Time
1	1 min
2	1 min
3	1 min
4	1 min
5	1 min

Table 4-9. Impact on occupants for fire scenario 4

Scenario 4 - Trash and cleaning materials in a closet in the townhouse

FAST input file: SCEN-4.DAT
EXITT input file: SCEN-4.BLD

Assumed properties of product: Material code TRB001 (bag of paper trash)

Flashover time: did not flashover

Evacuation

Occupant	Evacuation Time
1	1 min
2	1 min
3	1 min

Table 4-10. Impact on occupants for fire scenario 5

Scenario 5 - Christmas tree and bean bag chair in the living room of the townhouse

FAST input file: SCEN-5.DAT
EXITT input file: SCEN-5.BLD

Assumed properties of product: Material code CTR001 (xmas tree) and CHR001 (beanbag chair)

Flashover time: did not flashover

Evacuation

Occupant	Evacuation Time
1	Escape via doorway - 6 min
2	Incapacitated - 13 min Dead - 15 min
3	Incapacitated - 13 min Dead - 15 min
4	Escape via doorway - 6 min

Table 4-11. Impact on occupants for fire scenario 6

Scenario 6 - Couch and paneling in the family room of the two-story

FAST input file: SCEN-6.DAT
EXITT input file: SCEN-6.BLD

Assumed properties of product: Material code UPS001 (sofa)

Flashover time: 4 min

Evacuation

Occupant	Time
1	3 min
2	2 min
3	3 min
4	2 min

Table 4-12. Impact on occupants for fire scenario 7

Scenario 7 - Repeat of scenario 6 with different room doors closed

FAST input file: SCEN-7.DAT
EXITT input file: SCEN-7.BLD

Assumed properties of product: Material code UPS001 (sofa)

Flashover time: 4 min

Evacuation

Occupant	Time
1	3 min
2	3 min
3	3 min
4	3 min

Table 4-13. Impact on occupants for fire scenario 8

Scenario 8 - Trash, drapes and desk in the upstairs office/bedroom of the two-story

FAST input file: SCEN-8.DAT
EXITT input file: SCEN-8.BLD

Assumed properties of product: Material code WPB001 (wastebasket), CTN001 (drapes), and TLV001 (TV set)

Flashover time: 14 min

Evacuation

Occupant	Time
1	6 min
2	6 min
3	6 min
4	6 min

Table 4-14. HAZARD I example case variations

		(1) With Smoke Detectors		(2) Without Smoke Detectors	
Fire Scenarios[1]	Flashover	Escape Time[2]	Number of Fatalities[3]	Escape Time[2]	Number of Fatalities[3]
RANCH HOUSE					
1. Smoldering Sofa in L.R.	No	20 min	0/1	21 min	0/1
2. Grease Fire in Kitchen	3 min	1 min	0/5	1-2 min	0/5
3. Bed Fire in MBR	No	1 min	0/5	2->15 min	0/5
TOWNHOUSE					
4. Trash, etc. in Closet	No	1 min	0/3	6 min	0/3
5. Christmas Tree & Chair in L.R.	No	6 min	2/4	--[6]	4/4
TWO-STORY "COLONIAL"					
6 Couch & Paneling in L.R., B.R. Doors Closed	4 min	3 min	0/4	15 min	0/4
7. Couch with L.R. and B.R. Doors Closed	4 min	3 min	0/4	25 min	0/4
8. Trash, Drapes, Desk in Office/B.R.	14 min	6 min	0/4	7 min	0/4

	(3) Immobile Occupant in each room	
Fire Scenarios[1]	Time to Fatalities[4]	Number of Fatalities[3]
RANCH HOUSE		
1. Smoldering Sofa in L.R.	44-49 min	6/6
2. Grease Fire in Kitchen	2-8 min	6/6
3. Bed Fire in MBR	2->15 min[5]	5/6
TOWNHOUSE		
4. Trash, etc. in Closet	2->15 min	1/6
5. Christmas Tree & Chair in L.R.	7->40 min	5/6
TWO-STORY "COLONIAL"		
6 Couch & Paneling in L.R., B.R. Doors Closed	4->25 min	5/6
7. Couch with L.R. and B.R. Doors Closed	4->25 min	5/6
8. Trash, Drapes, Desk in Office/B.R.	7->33 min	4/6

1 For examples with and without smoke detectors, all occupants are assumed capable of escape and make no "mistakes."
2 Time needed for all escaping occupants to get out of building. Occupants who arrive at windows are considered to have escaped the building.
3 Number of fatalities / number of occupants in building.
4 Times over which fatalities occur.
5 The greater than sign (>) indicates times which are at least greater than the total time of the simulation.
6 All occupants are trapped inside the building and die within 37 minutes.

CHAPTER 5. FIRE INCIDENT DATA

5.1 Using Data for Scenario Selection

The fire hazard modeling system described in the step-by-step procedure is deterministic. This means that results obtained are uniquely related to the specific set of conditions provided as input to the analysis. Figure 3-2 provides the information needed to initiate a hazard analysis. This information can be based in part upon a fire scenario. Each scenario provides a description of the chain of events leading from the time, place and environment of the ignition through to the consequences (loss of life, injury or property damage) [1]. The scenario description also includes the influence of the ignition source, the characteristics of the product or products, the agents contributing to (or inhibiting) fire growth, the actions of human occupants and automatic protective devices. Selecting the relevant or important conditions which prevail most frequently in fires, particularly fatal fires, can be aided by analysis of the fire loss statistics. Often analysis of the statistics may indicate that there are a few predominant scenarios which occur more frequently than all the others.

5.2 United States Fire Statistics

To provide a perspective on the overall fire problem and the residential fire problem in particular, selected information follows, taken from several significant studies which have made use of fire statistics collected over the past several years. If more in-depth information or a fuller understanding is required the user is encouraged to refer to the original works. There are two main sources of fire statistics, the National Fire Protection Association (NFPA) and the United States Fire Administration (USFA). NFPA's fire loss statistics have been developed using a stratified weighting by community size through fire departments responding to an annual survey conducted by the National Fire Protection Association. These statistics provide a measure of the size of the problem but lack the detail needed to relate cause. Table 5-1 shows the distribution of fires, civilian deaths and injuries by occupancy for 1984 [2]. As table 5-1 indicates, residential fires in 1984 only represented about 25% of the total fires but contributed to over 80% of the civilian deaths. One- and two-family dwelling fires alone accounted for over 60% of the total. This proportion has remained fairly constant over the past several years [3].

Table 5-1. Estimates of reported fires, civilian deaths and injuries by occupancy, 1984

	Fires		Civilian Deaths		Civilian Injuries	
Occupancy	Estimate	Percent of All Fires	Estimate	Percent All Civilian Deaths	Estimate	Percent All Civilian Injuries
Residential (total):	623,000	26.6	4,240	80.9	19,275	68.5
One- and two-family dwellings	506,000	21.6	3,290	62.7	15,100	68.5
Apartments	99,500	4.2	785	15.0	3,650	13.0
Hotels and motels	9,000	0.4	120	2.3	300	1.0
Other residential	8,500	0.4	45	0.9	225	0.8
Nonresidential structures	225,000	9.6	285	5.5	3,750	13.3
Highway vehicles	437,000	18.7	530	10.1	3,250	11.6
Other vehicles	17,500	0.1	100	1.9	350	1.3
All others*	1,040,500	44.4	85	1.6	1,500	5.3
TOTAL	2,343,000		5,240		28,125	

* Includes fires outside of structures with value involved and fires in brush and rubbish with no loss involved.

Source: NFPA Survey of Fire Departments [2].

The U.S. Fire Administration has initiated the National Fire Incident Reporting System (NFIRS) for collecting causal information. Fire statistics providing information on individual fires which have led to loss of life, injury and property damage have been collected and provided to USFA by responding fire departments over a period of several years. This information has been tabulated from reports using the Uniform Coding for Fire Protection format (NFPA 901) and computer tapes are available for statistical analysis. In addition to losses, data collected include: building occupancy, age and condition of victims, area of origin, first material ignited, ignition source, time of day, etc.

Table 5-2 relates the causes for fires and losses in one- and two-family dwellings. Obviously, some fires result in worse consequences than others. Smoking, while only involved in 4.6% of the fires, causes 18.9% of the deaths; whereas heating which has contributed to over one-third of the total fires has a proportionately lower death rate, but still is attributed with a very significant 15% of the deaths in one- and two-family dwellings.

Table 5-2. Cause analysis, one- and two-family dwellings (mobile homes not included)

	Fatalities	Injuries	Property Damage	Fires
Smoking	18.9%	12.8%	4.7%	4.6%
Heating	15.0	16.0	18.1	34.4
Incendiary / Suspicious	10.2	7.0	16.1	8.5
Electrical Distribution	6.2	6.0	10.5	7.2
Children Playing	5.2	8.2	3.4	3.9
Cooking	5.2	20.1	6.4	13.6
Other Equipment	4.1	6.2	5.9	5.7
Open Flame	3.3	5.2	3.7	4.7
Appliances, Air Conditioning	2.4	5.6	5.0	1.0
Other Heat	1.4	1.6	1.3	1.0
Exposure	0.3	0.8	2.5	2.2
Natural	0.0	0.7	2.1	1.5
Unknown	27.8	9.8	20.4	7.1

Source: 1983 NFIRS.

Table 5-3. Cause and fatality rate by age in residences (1978-1982 average)

Cause	All Age Groups	2 and Under	3 to 5	6 to 9	10 to 19	20 to 29	30 to 49	50 to 64	65 to 74	75 and Over
Incendiary suspicious	12.7	10.5	8.3	11.7	17.1	19.1	16.1	12.8	9.5	4.7
Heating	16.9	17.8	18.9	20.1	26.8	12.9	16.1	12.4	15.5	18.0
Cooking	7.6	4.5	6.7	4.4	5.7	7.3	8.1	6.4	1.9	15.1
Electrical	7.2	7.4	6.7	11.3	8.1	8.4	4.0	5.1	6.6	9.6
Smoking	30.8	5.1	14.6	15.3	25.2	33.1	40.9	47.9	46.5	29.2
Children Playing	8.0	37.3	28.4	9.1	2.4	2.8	1.3	0.9	0.9	1.4
Other	16.9	17.4	16.5	33.6	14.6	16.3	13.4	14.5	12.7	22.1
Deaths per million population										
All Causes	23.7	51.2	55.6	27.4	12.3	17.8	14.9	23.4	31.6	65.7
Percentage of Civilian Fire Deaths	100.0	9.5	9.8	6.9	9.0	13.5	15.1	14.8	9.2	12.2
Percentage of Population	100.0	4.4	4.2	6.0	17.4	18.0	24.0	14.7	6.9	4.4

Clearly the fire risk is not equally divided among all persons. An analysis of the NFIRS data from 1978-1982, shown in table 5-3, indicates the very young (5 and under) and the elderly (75 and over) have death rates of about three and four times, respectively, greater than thc rate experienced by young and middle aged adults. Children under the age of 10 and adults 65 and over account for 47% of all fire deaths in residences but represent only 26% of the nation's population [3]. From the standpoint of the fire victim, table 5-3 presents by age group the cause of fire, the location at ignition and the condition before injury [4]. Figures 5-1 and 5-2 differentiate the location at ignition and the physical conditions expected for victims of different age groups. Such information is of direct use in locating the occupants relative to the fire and establishing their capabilities for escape and rescue.

A study which analyzed the leading causes for fire fatalities among the young and elderly summarized the important ignition factors based upon the 1982 NFIRS [3]. For children under 10 in fatal fires, the leading forms of heat of ignition are:

- Electrical (malfunctions, overload, etc.) 24%
- Open Flame (match, lighter, candle, etc.) 25%
- Heating/Cooking 30%

For adults 65 and over, the leading forms of heat of ignition are:

- Smoking 37%
- Heating/Cooking 20%
- Electrical (malfunctions, overload, etc.) 14%

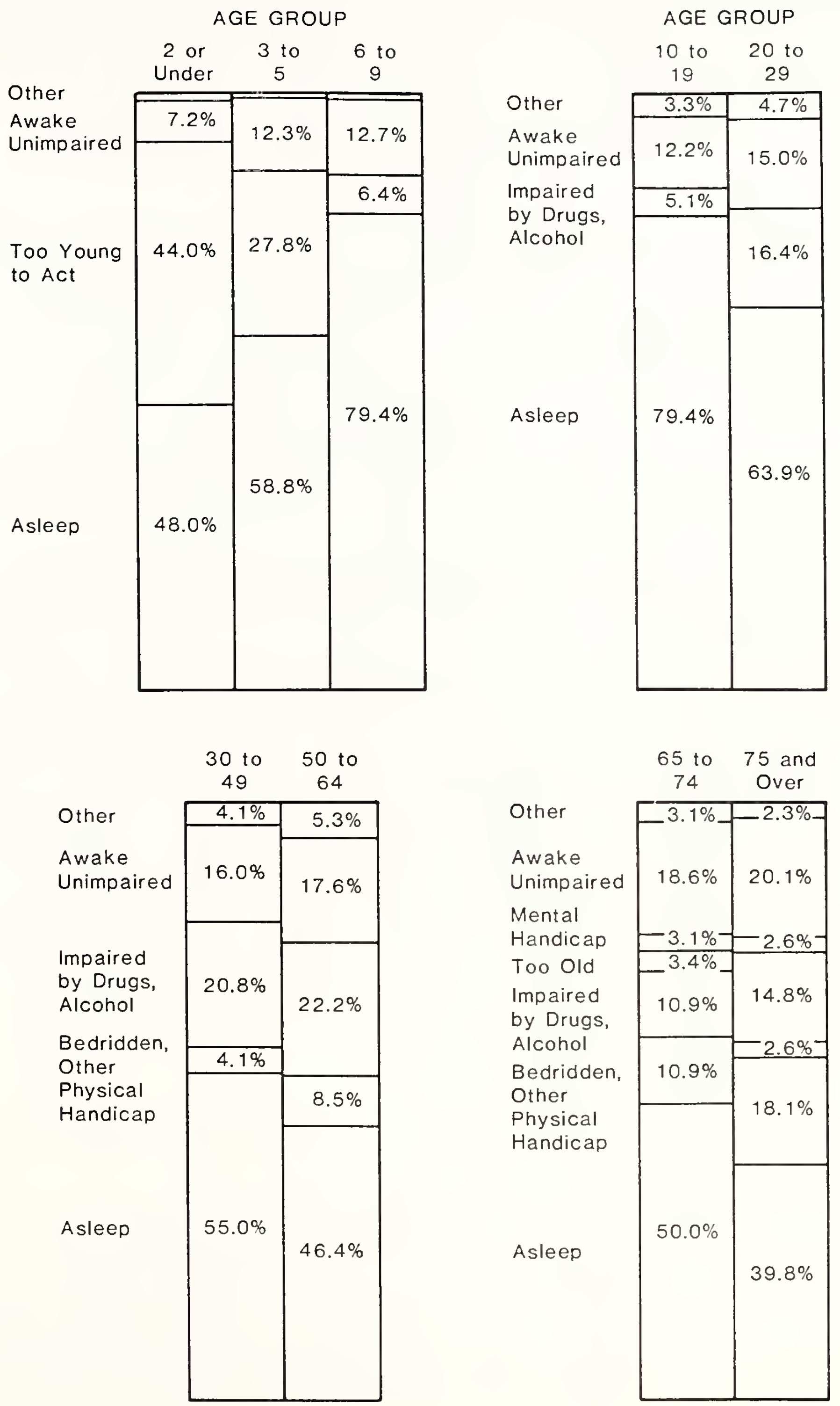


Figure 5-1. Civilian fire deaths in residences by condition before injury and age of victim, 1978-1982, Source: NFIRS [4].

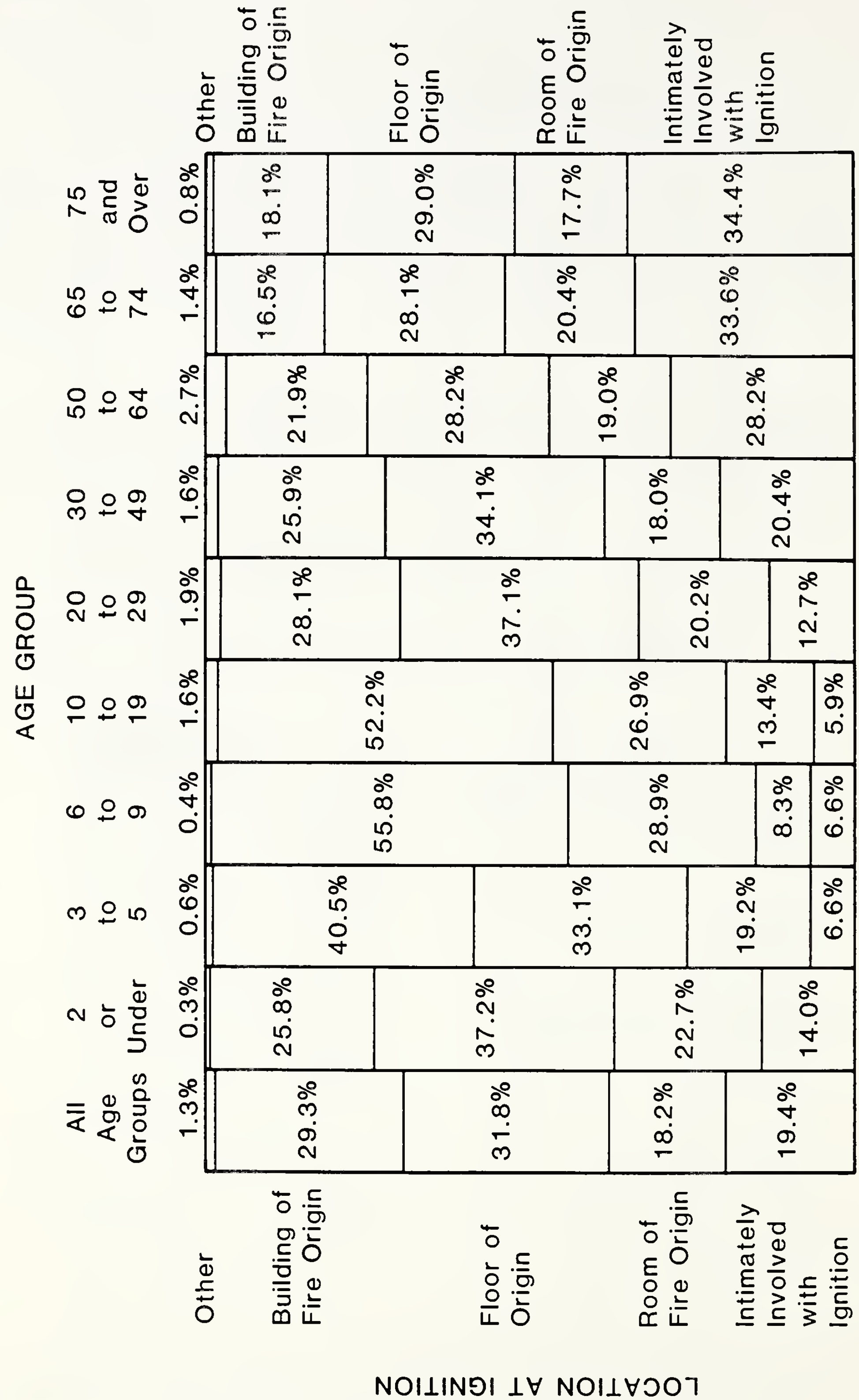


Figure 5-2. Civilian fire deaths in residences by location and age of victim 1978-1982, Source: NFIRS [4]

An analysis of the condition of the young and elderly victims prior to fatal injury showed:

Condition at Ignition	Percent Under 10	Percent 65 and over
Asleep when fire started	62.8	45.1
Unable to act because of age or bed ridden	22.7	23.8
Awake, but unable to escape	13.2	20.2

Additional studies on fatalities have been published which provide contrasts between the causes in rural, high fatality areas and nonrural areas including the influence of sex, race, and age [5,6].

An analysis of civilian injuries indicates that unlike fatalities, adults aged 20-39 have the highest risk of injury from fire in residences. The fifth edition of *Fire in the United States* provides information about the nature and cause of injury, which prevented the victim from escaping, and activity at the time of injury [3].

Table 5-4. Distribution of deaths in fatal fires; one- and two-family dwellings, 1981

Deaths Per Fire	Percent of Total Fires	Percent of Total Deaths
1	81	64
2	13	20
3	4	9
4	2	7
10*	-	-
	100	100

* A single fire was reported involving 10 deaths in 1981.

The distribution of fatalities for one- and two-family dwellings (table 5-4) indicates that the majority of fatal fires involve one or two deaths. While the occurrence of multiple death fires (defined as 3 or more) in residences represents a small fraction of the total; 87.3% of the multiple death fires reported in 1985 occurred in residential properties resulting in 79.7% of the total multiple deaths [7].

Table 5-5. Fires and loss per fire by detector status for one- and two-family dwellings (mobile homes not included)

Detector Status	Fires	Fatalities per 100 fires	Injuries per 100 fires	Dollar loss fire
With detectors	78,190	0.43	2.95	4009
Without detectors	279,765	0.85	3.00	4342
Detector status unknown	160,760	0.50	1.84	5551

Source: Average of 1981, 1982, and 1983 NFIRS

One of the major fire safety devices introduced into residences in the past 10 years has been the smoke detector. It has been estimated, based upon a 1985 Louis Harris poll, that three-fourths of U.S. households now have detectors. Unfortunately, evidence also suggests that the households that do not have detectors are those which have the highest risk of having a fire [8]. As table 5-5 shows, of the fires reported to NFIRS in 1981, 1982, and 1983 where detector status was known, over 75% of the fires occurred in one- and two-family dwellings without detectors.

5.3 Relation of Flame and Smoke Spread to Other Data Elements Useful in Scenario Development

Information relating the extent of flame and smoke damage at extinguishment to level of loss, cause of fire, influence of detectors, condition of victim (awake, age, asleep, handicapped), time of day, victim activity (escaping, rescue or fire control, sleeping, irrational or unable to act), and material ignited assist in developing the hazard model inputs and the dominant scenarios. Tables 5-6 through 5-9 provide an analysis of the 1982 NFIRS data [9]. Flame and smoke spread relate directly to the physics of fire development in buildings which are directly usable in the fire models.

Table 5-6. Extent of flame and smoke damage at extinguishment

Extent of Damage	Flame Damage Fires (%)	Flame Damage Deaths (%)	Smoke Damage Fires (%)	Smoke Damage Deaths (%)
Confined to object or area	59	10	28	3
Confined to room	15	7	14	2
Confined to compartment or floor	5	14	10	7
Extended beyond floor	21	69	48	88

Source: 1982 NFIRS [9].

Table 5-7. Extent of flame versus detector status

Extent of Flame	Percentage of Fires With Detectors	Percentage of Fires No Detectors	Deaths per 100 Fires With Detectors	Deaths per 100 Fires No Detectors
Confined to object or area	71	62	0.1	0.2
Confined to room	13	9	0.3	0.9
Confined to compartment or floor	4	5	1.6	2.7
Extended beyond floor	12	23	2.2	3.2
All fires with known extent	100	100	0.5	1.1

Source: 1982 NFIRS [9].

Table 5-8. Percentage of deaths for extent of flame versus victim condition and activity

Extent of Flame	All Cases	Awake	Asleep	Handicapped	Escaping	Rescue or Fire Control	Sleeping Irrational or Unable to Act
Confined to object or area	10	18	6	14	3	14	9
Confined to room	7	9	6	12	6	9	7
Confined to compartment or floor	14	14	12	19	13	12	14
Extended beyond floor	69	59	76	55	78	65	70

Source: 1982 NFIRS [9].

Table 5-9. Extent of flame versus time of day

Extent of Flame	Day (7 a.m. to 5 p.m.) Percent of Fires	Day (7 a.m. to 5 p.m.) Deaths per 100 Fires	Evening (5 p.m. to 1 a.m.) Percent of Fires	Evening (5 p.m. to 1 a.m.) Deaths per 100 Fires	Night (1 a.m. to 7 a.m.) Percent of Fires	Night (1 a.m. to 7 a.m.) Deaths per 100 Fires
Confined to object or area	61	0.1	64	0.1	40	0.3
Confined to room	16	0.3	15	0.4	14	1.2
Confined to compartment or floor	5	2.1	4	2.0	7	4.4
Extended beyond floor	18	2.2	16	2.1	39	5.7

Source: 1982 NFIRS [9].

5.4 Scenario Development

A study in 1976 by Clarke and Ottoson looked at fire death scenarios defined by occupancy, ignition agent and ignition source [10]. Their analysis indicated that about two-thirds of the fatalities could be accounted for by 14 general scenarios. Fire involving residential furnishings accounted for 36% of the deaths for all scenarios.

A study, based upon the 1982 NFIRS data, used this same approach to examine the leading ignition scenarios in residential structure fires [3]. Because of the potential influence of climatic and construction differences an analysis was performed for the northeast, north central, southern and western regions of the United States (see tables 5-10 to 5-13). Smoking materials dominated all four regions as the leading ignition source for civilian fire deaths (23.2 to 40.5%) for a small portion of the fires (3.6 to 5.1%). In the colder regions (Northeast and North central) the use of auxiliary heating devices (fireplaces and woodstoves) caused chimney fires to be the most common cause of fire. In the south and west, cooking fires using gas or electric stoves constituted the most common scenario.

Table 5-10. Leading accidental ignition scenarios in residential structure fires in the Northeast, 1982

Form of Heat of Ignition	Form of Material Ignited	Area of Origin	Incidents (%)	Civilian Deaths (%)
Solid Fuelcd Equipment	Residue, Soot	Chimney	16.8	0.9
Properly Operating Electrical Equipment	Cooking Material	Kitchen	3.6	0
Gas Fueled Equipment	Cooking Material	Kitchen	3.0	0
Solid Fueled Equipment	Special Form	Chimney	2.9	0
Smoking Material	Bedding	Bedroom	2.2	6.3
Solid Fueled Equipment	Structural Component,Finish	Wall Assembly	1.9	0
Solid Fueled Equipment	Other	Chimney	1.9	0
Solid Fueled Equipment	Trash, Waste	Chimney	1.8	0
Solid Fueled Equipment	Structural COmponent,Finish	Chimney	1.6	0
Smoking Material	Upholstered Furniture	Living Room	1.4	16.9

Source: NFIRS data from four states (Connecticut, New Jersey, New York, and Rhode Island) with 17,949 accidental residential structure fires and 117 civilian deaths in accidental residential fires with form of heat of ignition, form of material ignited, and area of origin reported [3].

Table 5-11. Leading accidental ignition scenarios in residential structure fires in the North central, 1982

Form of Heat of Ignition	Form of Material Ignited	Area of Origin	Incidents (%)	Civilian Deaths (%)
Solid Fuelcd Equipment	Trash, Waste	Chimney	10.7	0
Properly Operating Electrical Equipment	Cooking Material	Kitchen	6.3	1.1
Gas Fueled Equipment	Cooking Material	Kitchen	4.5	1.1
Solid Fueled Equipment	Other	Chimney	3.8	0
Smoking Material	Bedding	Bedroom	3.1	10.3
Smoking Material	Upholstered Furniture	Living Room	2.2	20.9
Solid Fueled Equipment	Structural Component,Finish	Living Room	1.6	1.5
Electrical Equipment Arcing, Overloaded	Cable Insulation	Kitchen	1.5	0.4
Solid Fueled Equipment	Structural Component,Finish	Chimney	1.3	1.5

Source: NFIRS data from eight states (Iowa, Illinois, Kansas, Michigan, Minnesota, Ohio, South Dakota, and Wisconsin) with 47,677 accidental residential structure fires and 283 civilian deaths in accidental residential fires with form of heat of ignition, form of material ignited, and area of origin reported [3].

Table 5-12. Leading accidental ignition scenarios in residential structure fires in the south, 1982

Form of Heat of Ignition	Form of Material Ignited	Area of Origin	Incidents (%)	Civilian Deaths (%)
Properly Operating Electrical Equipment	Cooking Material	Kitchen	10.2	0
Gas Fueled Equipment	Cooking Material	Kitchen	4.0	0
Solid Fueled Equipment	Trash, Waste	Chimney	3.5	0
Smoking Material	Bedding	Bedroom	3.2	11.5
Electrical Equipment Arcing, Overloaded	Cable Insulation	Kitchen	2.0	0.6
Smoking Material	Upholstered Furniture	Living Room	1.9	15.9
Match / Lighter	Bedding	Bedroom	1.7	1.3
Electrical Equipment Arcing, Overloaded	Cable Insulation	Bedroom	1.2	1.3
Solid Fueled Equipment	Structural Component,Finish	Living Room	1.1	0.6

Source: NFIRS data from eight states (Arkansas, Florida, Louisiana, Maryland, Tennessee, Texas, Virginia, and West Virginia) and Washington, DC with 22,561 accidental residential structure fires and 162 civilian deaths in accidental residential fires with form of heat of ignition, form of material ignited, and area of origin reported [3].

Table 5-13. Leading accidental ignition scenarios in residential structure fires in the west, 1982

Form of Heat of Ignition	Form of Material Ignited	Area of Origin	Incidents (%)	Civilian Deaths (%)
Properly Operating Electrical Equipment	Cooking Material	Kitchen	8.6	1.2
Solid Fueled Equipment	Trash, Waste	Chimney	6.2	0
Solid Fueled Equipment	Fuel	Chimney	4.9	0
Gas Fueled Equipment	Cooking Material	Kitchen	4.1	0.9
Smoking Material	Bedding	Bedroom	2.8	14.2
Smoking Material	Upholstered Furniture	Living Room	2.2	26.3
Electrical Equipment Arcing, Overloaded	Cable Insulation	Kitchen	1.1	2.6
Solid Fueled Equipment	Structural Component,Finish	Living Room	1.0	3.0

Source: NFIRS data from 10 states (Alaska, Arizona, California, Hawaii, Idaho, Montana, Oregon, Utah, Washington, and Wyoming) with 45,472 accidental residential structure fires and 242 civilian deaths in accidental residential fires with form of heat of ignition, form of material ignited, and area of origin reported [3].

5.5 Product-Specific Scenario Data

The same source of data (NFIRS) which provided the causal factors for residential fires and fatalities can also be queried from the viewpoint of a particular product. This is, however, significantly limited to the cases where the product is either the first material ignited or the product is equipment involved in ignition. Therefore, for fires where a product's main contribution is as an additional fuel source, the best source of data for hazard analysis is the list of general residential scenarios shown in tables 5-10 to 5-13.

Tables 5-14 through 5-17 contain analyses of fires involving contents and furnishings which were performed by the NFPA Fire Analysis Division for use by one of the NFPA Committees [11]. The 1980, 1981 and 1982 NFIRS data were used in the process of selecting the major contributors (upholstered furniture; mattresses and pillows; bedding, blankets, sheets and comforters; and curtains, blinds, draperies and tapestries). The information contained in tables 5-14 to 5-17 can be used as a resource in generating the product specific scenarios needed to perform relevant hazard analysis in one- and two-family dwellings. Three data elements are presented for each category of contents and furnishings. These elements were form of heat of ignition, equipment involved in ignition, and area of fire origin.

Table 5-14. Upholstered furniture fires in one- and two-family dwellings with unknowns distributed

	Incidents		Deaths		Injuries		Loss	
Form of Heat of Ignition								
Smoking Materials	60%		82%		66%		65%	
(Cigarettes)		(55)		(70)		(57)		(60)
Open Flame	20		10		20		14	
(Matches and Lighters)		(14)		(7)		(16)		(9)
Electrical Equipment Arcing	7		2		6		8	
Hot Objects	7		4		6		6	
Fuel-Fires Objects	5		2		3		5	
Other Known	2		1		0		2	
Equipment Involved								
None	83		94		87		83	
Heating Systems	7		2		6		8	
Electrical Distribution Equipment	6		1		5		7	
Other Known	4		2		2		3	
Area of Origin								
Living Room	71		90		85		83	
Bedroom	9		4		5		5	
Structural Areas	6		1		2		3	
Storage Areas	3		0		1		1	
Other Known	10		5		7		8	

Numbers in () are percent of the total for a subclass. For example, cigarettes contributed to 55% of the upholstered furniture fires. Totals may not add to 100% due to rounding errors.

Source: 1980, 1981, and 1982 NFIRS [11].

Table 5-15. Mattress and pillow fires in one- and two-family dwellings with unknowns distributed

	Incidents		Deaths		Injuries		Loss	
Form of Heat of Ignition								
Smoking Materials	43%		65%		53%		43%	
(Cigarettes)		(40)		(61)		(51)		(38)
Open Flame	34		21		28		32	
(Matches and Lighters)		(30)		(18)		(24)		(27)
Hot Object	10		7		7		9	
(Properly operating electrical equipment)		(3)		(2)		(2)		(4)
Electrical Equipment Arcing	8		4		7		9	
Fuel-Fired Objects	3		4		3		4	
Other Known	2		0		2		3	
Equipment Involved								
None	78		89		83		78	
Electrical Distribution Equipment	8		3		5		7	
Heating Systems	5		7		7		8	
(Stationary local unit)		(3)		(3)		(2)		(3)
(Portable local unit)		(1)		(3)		(4)		(3)
Appliances	5		1		4		5	
Other Known	4		2		2		3	
Area of Origin								
Bedroom	82		80		89		79	
Living Room	5		15		5		7	
Structural Areas	4		2		2		4	
Storage Areas	4		0		1		4	
Other Known	5		3		3		5	

Numbers in () are percent of the total for a subclass. For example, cigarettes contributed to 40% of the mattress and pillow fires. Totals may not add to 100% due to rounding errors.

Source: 1980, 1981, and 1982 NFIRS [11].

Table 5-16. Bedding fires in one- and two-family dwellings with unknowns distributed

	Incidents		Deaths		Injuries		Loss	
Form of Heat of Ignition								
Open Flame	33%		21%		33%		32%	
(Matches and Lighters)		(27)		(16)		(28)		(25)
(Candle)		(2)		(1)		(3)		(3)
Smoking Materials	26		61		31		25	
(Cigarettes)		(24)		(54)		(29)		(23)
Electrical Equipment Arcing	19		3		16		20	
Hot Object	18		12		14		19	
(Properly operating electrical equipment)		(9)		(8)		(9)		(10)
(Electric lamp)		(4)		(1)		(2)		(3)
Fuel-Fired Objects	3		1		3		2	
Other Known	2		0		3		2	
Equipment Involved								
None	57		84		65		60	
Appliances	21		2		15		20	
(Electric Blanket)		(16)		(2)		(12)		(18)
Electrical Distribution Equipment	11		2		7		10	
Heating Systems	9		9		11		9	
(Fixed local heating unit)		(4)		(2)		(4)		(4)
(Portable local heating unit)		(4)		(8)		(6)		(4)
Other Known	2		2		2		1	
Area of Origin								
Bedroom	85		88		90		86	
Living Room	4		10		6		3	
Storage Areas	3		0		1		3	
Other Known	8		2		3		6	

Numbers in () are percent of the total for a subclass. For example, cigarettes contributed to 24% of the bedding fires. Totals may not add to 100% due to rounding errors.

Source: 1980, 1981, and 1982 NFIRS [11].

Table 5-17. Curtain and drapery fires in one- and two-family dwellings with unknowns distributed

	Incidents		Deaths		Injuries		Loss	
Form of Heat of Ignition								
Open Flame	39%		41%		50%		28%	
(Matches and Lighters)		(24)		(5)		(25)		(17)
(Candle)		(10)		(23)		(17)		(8)
Electrical Equipment Arcing	24		32		21		34	
Hot Object	17		9		15		15	
(Properly operating electrical equipment)		(8)		(9)		(9)		(8)
(Electric lamp)		(3)		(0)		(3)		(3)
Fuel-Fired Objects	9		9		9		13	
(Gas-fueled equipment)		(4)		(9)		(6)		(5)
Smoking Materials	6		9		4		5	
(Cigarettes)		(4)		(9)		(2)		(4)
Other Known	7		0		2		4	
Equipment Involved								
None	50		50		50		39	
Electrical Distribution Equipment	17		8		17		22	
Cooking Equipment	13		14		14		7	
(Stove)		(7)		(14)		(10)		(4)
(Portable cooking unit)		(3)		(0)		(2)		(1)
Heating Systems	9		14		7		16	
(Portable local unit)		(3)		(8)		(5)		(4)
(Stationary local unit)		(3)		(8)		(2)		(5)
Appliances	8		14		9		12	
Other Known	3		0		2		5	
Area of Origin								
Bedroom	33		24		30		31	
Living Room	26		48		38		40	
Kitchen	20		15		21		11	
Bathroom	5		0		3		5	
Dining Room	4		5		1		3	
Structural Areas	3		0		1		3	
Other Known	8		2		3		6	

Numbers in () are percent of the total for a subclass. For example, matches and lighters contributed to 24% of the curtain and drapery fires. Totals may not add to 100% due to rounding errors.

Source: 1980, 1981, and 1982 NFIRS [11].

5.6 References

[1] Gross, D. The use of fire statistics in assessing the fire risk of products in Interflame 1985 Conference Workbook; 1985 March 26-28. 11-18.

[2] Karter, M. J., Jr. Fire loss in the United States during 1984. Fire Journal 79(3): 67-70, 73, 75-76; 1985 September.

[3] Anon. Fire in the United States 5th Edition, Executive Summary. U.S. Fire Admin.; 1985. 61p.

[4] Karter, M. J., Jr. Patterns of fire deaths among the elderly and children in the home. Fire Journal 80(2): 19-22; 1986 March.

[5] Gomberg, A.; Clark, L. P. Rural and non-rural civilian residential fire fatalities in twelve states. Natl. Bur. Stand. (U.S.) NBSIR 82-2519; 1982 June. 52p.

[6] Hall, J. R., Jr.; Helzer, S. G. civilian residential fire fatality rates: Six high-rate states versus six low-rate states. Natl. Bur. Stand. (U.S.) NBSIR 83-2754; 1983 August. 35p.

[7] Curtis, M. H.; LeBlanc, P. R. Analysis of multiple-death fires in the United States during 1985. Fire Journal 80(4): 18-30; 1986 July.

[8] Hall, J. R., Jr. A decade of detectors: Measuring the effect. Fire Journal 79(5): 37-40, 42-43, 78; 1985 September.

[9] Unpublished National Fire Protection Association Analysis of 1982 NFIRS Incidents. 1984 August.

[10] Clarke, F. B., III; Ottoson, J. fire death scenarios and firesafety planning. Fire Journal 70(3): 20; 1976 May.

[11] Fahy, R.; Hall, J. R., Jr. Memorandum from Fire Analysis Division, NFPA to Staff Liason Ad Hoc Committee on Contents and Furnishings ASTM Committee. 1985 January 16.

CHAPTER 6. CALCULATIONAL PROCEDURES

6.1 Determining the Rate of Heat Release

6.1.1 Introduction

The rate of heat release of the burning objects in a room is the primary driving force which governs the intensity of the fire. Thus, its determination is essential to any of the ensuing hazard computations. Until a few years ago, it was not possible to adequately determine the full-scale heat release rates of most articles. In a few cases, room fire tests had been performed and mass loss rate data were available [e.g., 1,2]. Since the actual heat of combustion is generally not known, these mass loss measurements are not readily translated into heat release rate values. When oxygen consumption calorimetry came into use [3], however, it became possible to design a new generation of full-scale calorimeters for measuring the heat release rate accurately. An apparatus, termed the Furniture Calorimeter [4] was developed at NIST, and a device on similar principles for industrial commodities was constructed at the Factory Mutual Research Corporation [5]. Several other units have recently been installed at laboratories in the United States and in Europe.

6.1.2 Data Obtained by Full-Scale Measurements

A compilation was recently made of data reported by various sources on full-scale measurements of rate of heat release [6]. Published data can be used by the designer if it can be determined that the articles being considered for the potential fire are similar to the items on which data have been reported. The data tabulated in [6] include the following categories:

- pools, liquid or plastic
- cribs (regular arrays of sticks)
- wood pallets
- upholstered furniture
- mattresses
- pillows
- wardrobes
- television sets
- Christmas trees

- curtains
- electric cable trays
- trash bags and containers
- industrial rack-stored commodities

Some examples of full-scale data relevant to the residential fire problem are tabulated in the database provided with the HAZARD I software. An earlier compilation by Gross [7] is also available. The tabulated test data can be very useful as generic representatives of items constructed of these materials, and with this general geometry. Where the analysis is intended to evaluate a specific product, that product should be tested in a suitable calorimeter and the data then used in the analysis. If the generic items of concern are not similar to the test articles in the furniture calorimeter database, it will be necessary to estimate the full-scale heat release rates from bench-scale test data or from other measurements of material properties.

6.1.3 Methods for Estimating Full-Scale Rates of Heat Release

In a few cases, detailed studies are available giving an engineering method for the estimation of full-scale rates of heat release from bench-scale data. Such methods have been published for:

- upholstered furniture
- mattresses
- wall lining materials
- electric cable trays

The last category is probably not useful for residential application; a summary is given in [6], and more details have been published by Lee [8]. Note that the methods and procedures given below are examples and do not represent the only methods (nor necessarily the most accurate) available, but rather that they are compatible with the input requirements of the HAZARD I software.

6.1.3.1 Estimating Method for Upholstered Furniture

The method for determining the full-scale heat release rates of upholstered furniture is an example [9,10]. The method was based on experimental studies in the Furniture Calorimeter of a large number of commercial upholstered furniture items, and also of full-scale mockups. The studies showed that most of the furniture had rate of heat release curves which could be approximated as triangles (fig. 6-1). Two methods were then developed for estimating this full-scale rate of heat release: (a) a method based on actual bench-scale measurements on fabric/padding composites, tested in the Cone Calorimeter, and (b) a more approximate method, based solely on the identification of the specimen

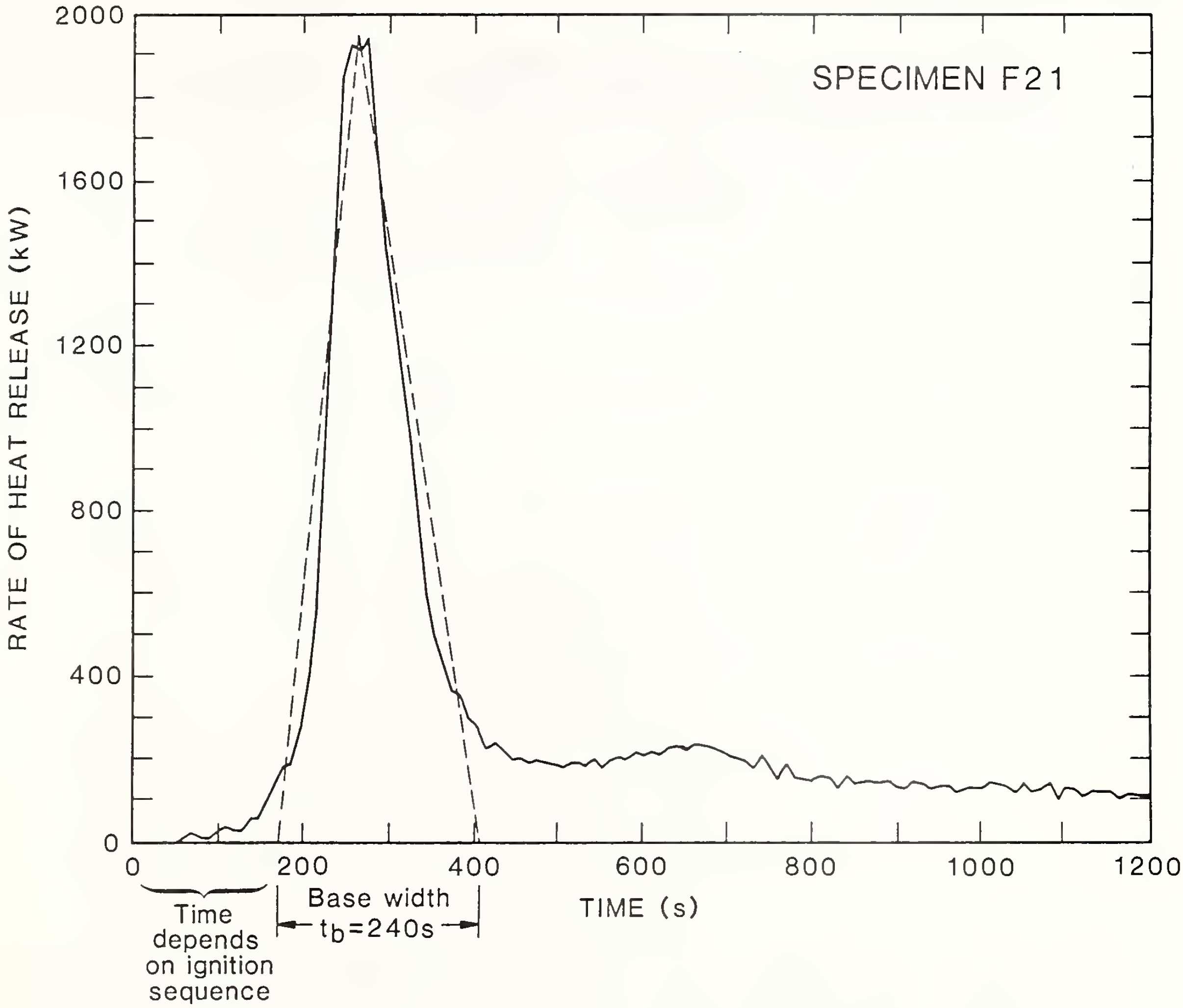


Figure 6-1. Approximation of the rate of heat release for an upholstered chair by a triangular shape.

weight and composition. The Cone Calorimeter is an apparatus for making a number of bench-scale measurements on a specimen, including heat release rate (also based on oxygen consumption), ignitability, smoke and soot production, and gas species production [11,12].

To determine the triangular shape of the heat release rate curve, it is necessary to find the peak height, which is the maximum heat release rate, and the triangle base width, which may be considered an effective burning time. In principle, it would also be necessary to determine the offset time, from ignition to start of triangle base. Unlike the triangular shape of the heat release rate curve itself, however, this offset time is not a valid property of the specimen, and is rather, primarily, a function of the ignition source and sequence. Thus, in the absence of detailed ignition source studies, it is conservative to set the offset time to zero. The procedures, then are as follows:

Peak heights based on bench-scale measurements. Whenever possible, bench-scale measurements should be made on the specific fabric/padding used. The estimate for the peak height $\dot{q}_{fs}$ (kW) is:

$$\dot{q}_{fs} = 0.63 \left[\dot{q}''_{bs} \right] \left[\begin{matrix} \text{mass} \\ \text{factor} \end{matrix} \right] \left[\begin{matrix} \text{frame} \\ \text{factor} \end{matrix} \right] \left[\begin{matrix} \text{style} \\ \text{factor} \end{matrix} \right] \tag{1}$$

where

$\left[\dot{q}''_{bs} \right]$ = rate of heat release (kW/m²) in the bench-scale test,

$\left[\begin{matrix} \text{mass} \\ \text{factor} \end{matrix} \right]$ = combustible mass, in kg

$$\left[\begin{matrix} \text{frame} \\ \text{factor} \end{matrix} \right] = \begin{cases} 1.66 \text{ for non-combustible} \\ 0.58 \text{ for melting plastic} \\ 0.30 \text{ for wood} \\ 0.18 \text{ for charring plastic} \end{cases}$$

$$\left[\begin{matrix} \text{style} \\ \text{factor} \end{matrix} \right] = \begin{cases} 1.0 \text{ for plain, primarily rectilinear construction} \\ 1.5 \text{ for ornate, convolute shapes} \\ \text{and intermediate values for intermediate shapes} \end{cases}$$

The constant 0.63 has units m²/kg. The bench-scale data are obtained from the Cone Calorimeter with radiant heating at 25 kW/m² and a 180 s averaging period (as this gave the best correlation to full-scale data). Further details on test conditions have been given in [10].

Peak heights based on generic materials identification. For rough estimation based only on generic materials identification, the expression for the peak height is:

$$\dot{q}_{fs} = 210 \left[\begin{matrix} \text{fabric} \\ \text{factor} \end{matrix} \right] \left[\begin{matrix} \text{padding} \\ \text{factor} \end{matrix} \right] \left[\begin{matrix} \text{mass} \\ \text{factor} \end{matrix} \right] \left[\begin{matrix} \text{frame} \\ \text{factor} \end{matrix} \right] \left[\begin{matrix} \text{style} \\ \text{factor} \end{matrix} \right] \tag{2}$$

where

$$\left[\begin{matrix} \text{fabric} \\ \text{factor} \end{matrix} \right] = \begin{cases} 1.0 \text{ for thermoplastic fabrics (fabrics such as} \\ \quad \text{polyolefin, which melt prior to burning)} \\ 0.4 \text{ for cellulosic fabrics (cotton, rayon, etc.)} \\ 0.25 \text{ for PVC or polyurethane film type coverings} \end{cases}$$

$$\begin{Bmatrix}\text{padding}\\ \text{factor}\end{Bmatrix} = \begin{cases} 1.0 \text{ for polyurethane foam or latex foam} \\ 0.4 \text{ for cotton batting} \\ 1.0 \text{ for mixed materials (i.e., both polyurethane or latex foam and cotton batting)} \\ 0.4 \text{ for neoprene foam} \end{cases}$$

and the constant 210 has units kW/kg.

Triangle base width. The triangle base width (fire duration time), t_b, is determined as follows:

$$t_b = \frac{C_e\, m\, \Delta h_c}{\dot{q}_{fs}} \quad (s) \qquad (3)$$

where C_e = 1.3 for wood frames and 1.8 for metal frames and plastic frames
m = combustible mass of item (kg)
Δh_c = effective heat of combustion (kJ/kg)

and $\dot{q}_{fs}$ is as given from eq (1) or eq (2) above.

If more specific measurements are not available, average effective heats of combustion may be obtained from tables given in [10].

Limitations. Estimates for the peak heat release rate do not hold when both the fabric and the padding are highly fire resistive (e.g., wool and neoprene foam). In these cases full involvement of the furniture item does not take place. Estimates of the peak heat release rate using bench scale data should not be made for measured heat release rates below 75 kW/m^2. Estimates of peak heat release rate based on generic materials identification should not be made for those cases where the product of the [fabric factor] times the [padding factor] is less than 0.25. In such low-burning cases, it can be assumed that the burning rate hazard is much lower than in actively flaming fires, however, a specific method for estimating this low rate is not available at present.

Table 12 in reference [10] compares estimates of the total heat released made by the triangle method to the measured (full-scale) values for a series of upholstered chairs. The peak heat release rates estimated by the "triangular approximation" method averaged 91% (range 46% to 103%) of values measured for a group of 26 chairs with noncombustible frames, but only 63% (range 46% to 83%) of values measured for a group of 11 chairs with combustible frames.

Example 1. A wood-framed chair is to be evaluated. Its padding is a polyurethane foam and the fabric is a polyolefin. A foam/fabric combination specimen has been tested in the Cone Calorimeter, where it has been determined that under the specified conditions of horizontal orientation, spark ignition, and 25 kW/m^2 irradiance, the 180 s average rate of heat release was $\dot{q}''_{bs}$ = 200 kW/m^2. The chair mass is 20 kg, thus the mass factor = 20. Since the frame was wood, the frame factor = 0.30. The chair is of modern, rectilinear construction, therefore, the style factor = 1.0. The estimate of the peak full-scale heat release rate is then $\dot{q}_{fs}$ = 0.63 (200)(20)(0.30)(1.0) = 756 kW. The heat of combustion was measured to be 18.0 MJ/kg. Since eq (1) requires Δh_c in units of kJ/kg, this is expressed as 18,000 kJ/kg. For a wood frame, C_3 is 1.3. A computation of t_b can then be obtained as t_b = 1.3(20)(18,000)/756 = 619 s.

Example 2. A more fire resistive construction is considered, involving also a wood frame, but using neoprene foam and cotton upholstery fabric. The chair mass is 28 kg. Bench-scale test data are not available, and so the method based on generic materials identification is used. The fabric factor for cotton is 0.4. The padding factor of neoprene foam is 0.4. Multiplied together, this gives 0.16. The restriction above, however, tells us that if this product is less than 0.25, then sustained flaming fire propagation will probably not occur, and that the rate of heat release will be small.

6.1.3.2 Estimates for Mattresses

Some years ago several studies were done at NIST on institutional mattresses and residential mattresses, all of "twin-size" (approximately 0.9 m by 2.0 m) and without combustible boxsprings. The data for the peak heat release rate have recently been correlated [10] and are shown in figure 6-2. There are a number of limitations to this correlation. No data on other mattress sizes are available; it is not known why the correlation is a curve and not a straight line; the bench-scale measurements are from an older apparatus (although it is expected that measurements in the Cone Calorimeter would not be greatly different); and, a complete representation of the rate of heat release curve, as a function of time, is not available. Nevertheless, with these limitations in mind, it is still possible to make useful engineering estimates. As for upholstered furniture, bench-scale data can be obtained from the Cone Calorimeter at a 25 kW/m^2 irradiance, and averaged over a 180 s period. The peak heat release rate can then be predicted directly, since, unlike for upholstered furniture, no additional multiplying factors enter into the correlation. As a first estimate, assuming a triangular shape for the heat release rate is appropriate. The triangle base width (burning time) could then be estimated by using eq (3) developed for upholstered furniture, and setting C_3 = 1.8, since a wood frame is not involved in mattress construction.

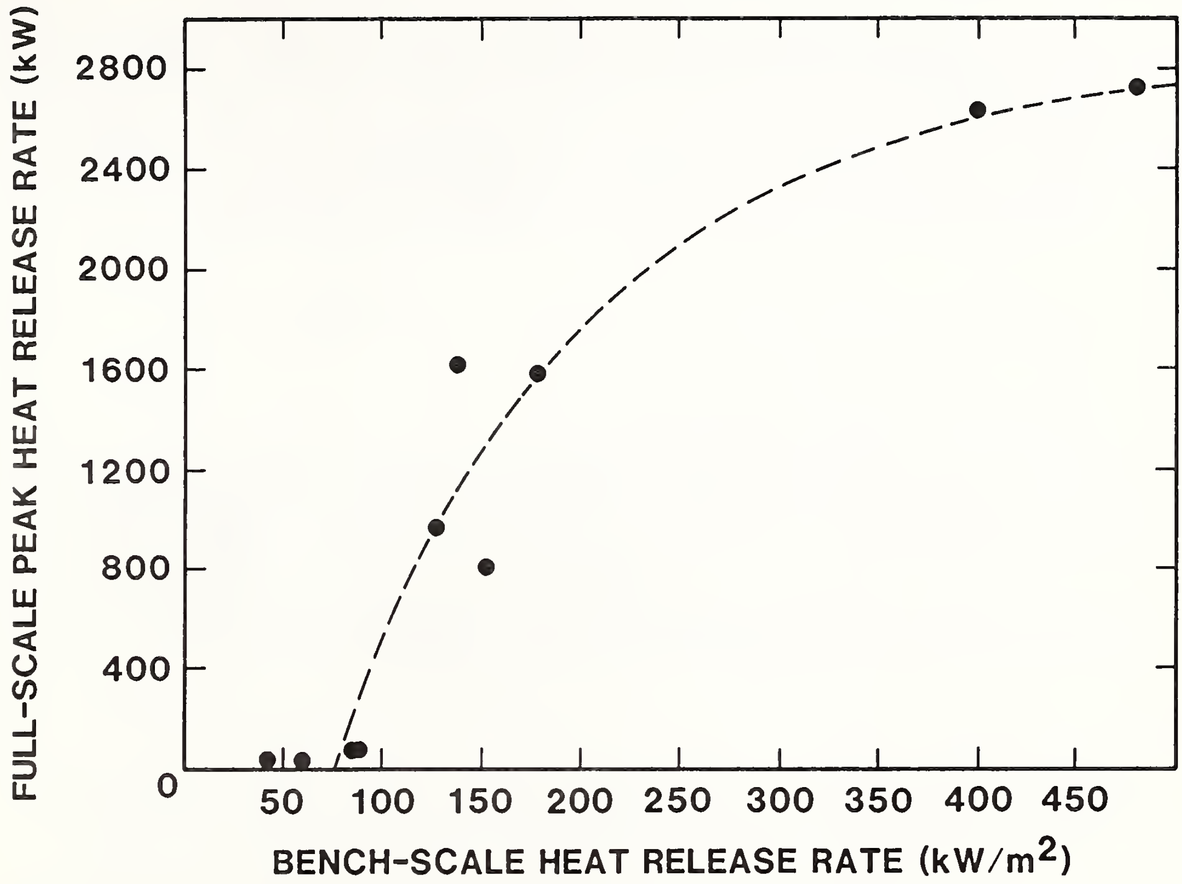


Figure 6-2. Correlation between bench-scale rate of heat release measurements for mattresses and peak full-scale rates of heat release.

6.1.3.3 Estimating Method for Wall Lining Materials

Combustible interior finish materials are substantially more difficult to treat than free-standing combustibles. They cannot be measured in a device such as the Furniture Calorimeter, and require any full-scale study to be a room fire. The materials cover a large area, but the area of active flame involvement is generally not predictable, except after flashover, when in many cases it can be assumed that all surfaces are involved. Recently, however, a series of wall materials was studied at NIST in full-scale room fires, and also in bench-scale, with the Cone Calorimeter [13]. These show the first promising correlation between bench scale and full scale for wall lining materials. For several materials in this test series, which included both cellulosics and plastics, it was found that the per-unit-area full scale heat release rates, $\dot{q}_{fs}$, could, after flashover, be related directly to values obtained from the Cone Calorimeter. The Cone Calorimeter data were the average values determined from the ignition time to a time 60 s later. The results showed that when the bench-scale data were taken under a 75 kW/m^2 irradiance, the bench-scale values $\dot{q}''_{bs}$ were directly comparable to the full-scale values $\dot{q}_{fs}$. Prior to flashover, the results were more uncertain, because of the difficulty of estimating the area involved, however, full-scale to bench-scale correlation could again be seen if the bench-scale data considered were ones obtained at a lower irradiance, taken as 25 kW/m^2.

Thus, it can be recommended that the rate of heat release for walls be approximated as

$$\dot{q}_{fs} = \dot{q}''_{bs} \bullet A_f \tag{4}$$

where $\dot{q}''_{bs}$ is the bench-scale rate of heat release (kW/m^2), averaged over a 60 s time period, starting with ignition, and A_f is the area of material burning (which must be estimated by the user). The pertinent test irradiance selected to be representative of full-scale conditions is 25 kW/m^2 prior to flashover, and 75 kW/m^2 after flashover. This simple prediction method assumes that the full-scale heat release rate value is constant, not varying with time. The heat release rate goes to zero when the fuel is exhausted, i.e., when

$$\int \dot{q}_{fs}\, dt = \Delta h_c \bullet M \tag{5}$$

where M is the total specimen mass (kg), and Δh_c is the heat of combustion (kJ/kg).

These findings are certainly exploratory and not conclusive. However, a preliminary method for determining the rates of heat release of wall materials is available. Magnusson and Sundström [14] have recently proposed a more detailed, but still largely empirical, model for describing the initial rising portion of the heat release rate curve; their method is pertinent primarily to cellulosic type wall materials. Further general improvements await the ability of models to track the area of flame involvement and of the heat fluxes being imposed on wall surfaces by other objects and other wall elements.

6.1.3.4 Estimating Method for General Combustibles

For most combustibles, neither estimating rules, such as developed above, nor detailed full-scale test results [6] are available. Since this is an area which represents one of the most serious limitations to the current modeling capabilities, it is hoped that significant progress will be made in future years. For the present, however, building design or evaluation efforts will require that some estimate be made, even if it is not highly refined.

In principle, the rate of heat release of full-scale combustibles can be directly evaluated from bench-scale data. To make this possible, it is necessary to know the rate of heat release per unit area, $\dot{q}''_{bs}$, as a function of time as measured in bench scale for various irradiances. If the model can treat the full-scale surfaces as a number of elemental areas, each of which can be subjected to its specific heat flux and ignited at its appropriate time, it can be possible to estimate the full-scale overall heat release rate, $\dot{q}_{fs}$, as:

$$\dot{q}_{fs}(t) = \sum_{i} \left[\dot{q}''_{bs}(t-t_{ig,i}) \right]_i \cdot A_i \tag{6}$$

where the summation is to be taken over all the area elements A_i. The time-dependence inherent in the heat release computation complicates analysis considerably, since the summation for each element has to be started from the time of its own ignition, $t_{ig,i}$, and not from the start of the fire. Such detailed capability may be available in the near future; for the moment, however, empirical correlations, such as those indicated for upholstered furniture above, take the place of that capability.

The reasonable success by Lee [13] in fitting full-scale, per-unit-area values, $\dot{q}''_{fs}$, by bench-scale $\dot{q}''_{bs}$ measurements suggest that for a rough analysis the problems introduced by time-dependence can be sidestepped. Data are also available from the studies of upholstered furniture burning on a per-unit-area basis [15]. The rules given above treat the rate of heat production by upholstered furniture on a per-unit-mass basis, since with practical residential furniture the determination of the actual surface area may be very difficult if the shape is complex; however, the per-unit-area analysis, done in the original study on simplified chair shapes, can help suggest an analysis for general combustibles. A special complication with upholstered furniture is the presence of a frame which, even if non-combustible, influences the burning behavior of the assembly. For simplest analysis, however, the experimental data [15] were seen to be correlated as

$$\dot{q}_{fs} = 1.13 \cdot \dot{q}''_{bs} \cdot A_e \tag{7}$$

where A_e is the exposed surface area of the item; in the case of chairs this was taken to exclude the reverse side of the back cushion and the underneath of the seat cushion. Since these two "shielded" surfaces represent nearly as large an area as the exposed one, a general-purpose rule, applicable to all not-otherwise-characterized combustibles could be:

$$\dot{q}_{fs} = C_4 \cdot \dot{q}''_{bs} \cdot A_t \tag{8}$$

where C_4 = 1.0 if all surfaces are exposed to fire or 0.5 if items are complex and only partly exposed to fire

and A_t = the total surface area of the specimen (m^2).

The bench-scale test conditions for determining $\dot{q}''_{bs}$ should be the following. An irradiance of 25 kW/m^2 is appropriate prior to room flashover. After flashover, 75 kW/m^2 can represent the post-flashover regime. The averaging period has also to be determined. The comparison for the wall data was to a bench-scale averaging of 60 s (after ignition). For upholstered chairs, the data best correlated when a 180 s period was used. Until more refined data are available, it should be adequate to select 120 s for other categories of combustibles.

The time-dependence of the behavior of $\dot{q}_{fs}$ also has to be specified. For upholstered furniture it was shown above that a triangular relationship best represents the data. For wall fires, a steady-state response was suitable. In the absence of more detailed studies for a class of combustibles, it is suggested that a steady-state response be used, with the end of heat release corresponding to the exhaustion of the fuel available. Suitable large-scale test data would be preferable.

6.2 Adjusting the Combustion Chemistry

The oxygen combustion chemistry scheme employed by FAST (for constrained - type 2 fires only) uses ratios for predicting CO, CO_2 (a ratio of CO to CO_2 is used), and soot (where a ratio of C to CO_2) and the more common yields (of mass of species produced per mass of sample burned) for other species. This approach allows for a carbon-hydrogen-oxygen balance to be maintained as the combustion efficiency varies due to changing ventilation conditions. Initial comparisons to experimental data show improved agreement with measured species concentrations.

Conceptually, the model uses the combustion of methane ($CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$) as the basic reaction with subsequent reduction of the CO_2 to CO and C (which becomes the smoke particulates). Since FIREDATA contains only yield data (i.e., grams of the species produced for every gram of fuel burned), the user needs to divide the CO and soot yield by the CO_2 yield to obtain the appropriate CO/CO_2 and C/CO_2 ratios for the *free burning* conditions represented by all of the data in FIREDATA.

As oxygen becomes limited, the combustion efficiency and these ratios need to be adjusted. Since there is currently no accepted theory of how this works, it has not been included within FAST. But rather it is left to the user to make a manual adjustment. The ratios obtained from free burn tests should be used up to the point that the oxygen concentration drops below the limit set by the user (6% by default). At this point the CO/CO_2 and C/CO_2 ratios should be *increased* by a factor of ten (10 times the free burn value) during the entire time that the fire is ventilation limited. If the fire is producing unburned fuel which then burns in the doorway (as indicated by examining the variable

VFIRE in FASTplot), this will tend to burn the excess CO back to CO_2. Experimental data indicates that the net production of CO beyond this combusting door plume is the same as if the free burn ratios had been used. Thus, if the door plume is releasing significant energy (about 0.5 mW or more) this adjustment need not be made. On the other hand if the oxygen concentration drops below about 1%, it may be necessary to increase these ratios by up to a factor of 20. References [16-18] can provide typical data and examples of these phenomena.

Yield of species i (f_i) is defined as the mass of species i produced per unit mass generation of gaseous fuel. By conservation of species i produced in the fire:

$$\frac{dm_i}{dt} + \sum_{\substack{j \\ \text{net,out}}} Y_{i,j}\dot{m}_j = f_i \dot{m}_{\text{fuel generated}}$$

$$\left[\begin{array}{l}\text{Rate of mass} \\ \text{of species i} \\ \text{changing in} \\ \text{a volume}\end{array}\right] + \left[\begin{array}{l}\text{Net rate of} \\ \text{flow of species i} \\ \text{out of the volume}\end{array}\right] = \left[\begin{array}{l}\text{Rate of} \\ \text{species i} \\ \text{produced in} \\ \text{a fire}\end{array}\right]$$

where: m_i is the mass of species i in the layer volume.
$\dot{m}_j$ is the net mass flow rate of gas through surface j (+out, -in).
$Y_{i,j}$ is the mass fraction of species i in the stream flowing in or out of surface j.

For oxygen, which is consumed in the fire, f_i is negative.

A knowledge of the f_i allows one to compute the concentrations in a fire Y_i mass fraction or X_i mole fractions. It is likely that f_i will be constant for a given fuel if sufficient air is available for combustion, but will change as the air is limited. If r_{ox} is the stoichiometric mass oxygen to fuel ratio for complete combustion of a hydrocarbon fuel to H_2O and CO_2, then we expect f_i for each species (production reactant) to depend on the equivalence ratio ϕ where

$$\phi \equiv \frac{\dot{m}_{\text{fuel generated}} \,/\, m_{\text{ox supplied}}}{(1 \,/\, r_{ox})}$$

or for a given fuel f_i depends on ϕ. f_{CO} is expected to increase sharply as ϕ approaches unity.

The data presented in the Cone and Furniture Calorimeters generally have $\phi < 1$, although a precise determination is impossible without knowing r_{ox} for the furniture array. For further information on yields as a function of equivalence ratio, see papers by Tewarson [19,20] and Beyler [21].

6.3 Ignition of the Second Item

The ignition of a second (or subsequent) item from a burning object in a room can occur from direct flame contact or by sufficient radiant energy reaching its surface to heat that surface to its ignition temperature. In the former case, the objects need to be spaced close enough together for such flame contact to occur (essentially touching). In the latter case, the radiation comes from the flame above the burning object, the hot upper layer in the room, and from the bounding surfaces of the room (ceiling and walls). Where data for piloted and nonpiloted ignition are available, always use the former as it is more conservative.

For the case of direct flame contact, the ignition time of the second item can be assumed to be the time at which contact occurs. (This assumption is conservative since time is required to pyrolyze fuel and heat the gases produced to their ignition temperature.) For radiant ignition, a crude assumption is that prior to flashover, the radiation from the upper layer and the room surfaces are negligible. Thus, the radiant energy transfer to the surface of the second item all comes from the flame above the first item. Based on this crude assumption, Babrauskas [22] has developed a procedure for estimating the ignition of the second item.

In this procedure, the radiant flux necessary to ignite an item is assumed to be 10 kW/m^2 for easily ignited items such as thin curtains or loose newsprint, 20 kW/m^2 for "normal" items such as upholstered furniture, or 40 kW/m^2 for difficult to ignite items such as wood of 1/2 inch or greater thickness. The mass loss rate of the burning item necessary to produce these ignition flux at various separation distances between the items is presented in figure 6-3. Thus, the time to ignition of the second item is the time at which the mass loss rate of the burning object first reaches the value necessary to produce the required flux at the distance between the objects.

To make a better estimate, using FAST and FASTplot, the flux from the upper layer and room surfaces can be included. That is, an initial run of FAST with only the first item burning will give the time-dependent flux to an object in the lower layer in the variable ON TARGET. This variable can be listed and/or plotted with FASTPLOT (see the instructions on running these programs in the **Software User's Guide**). When the

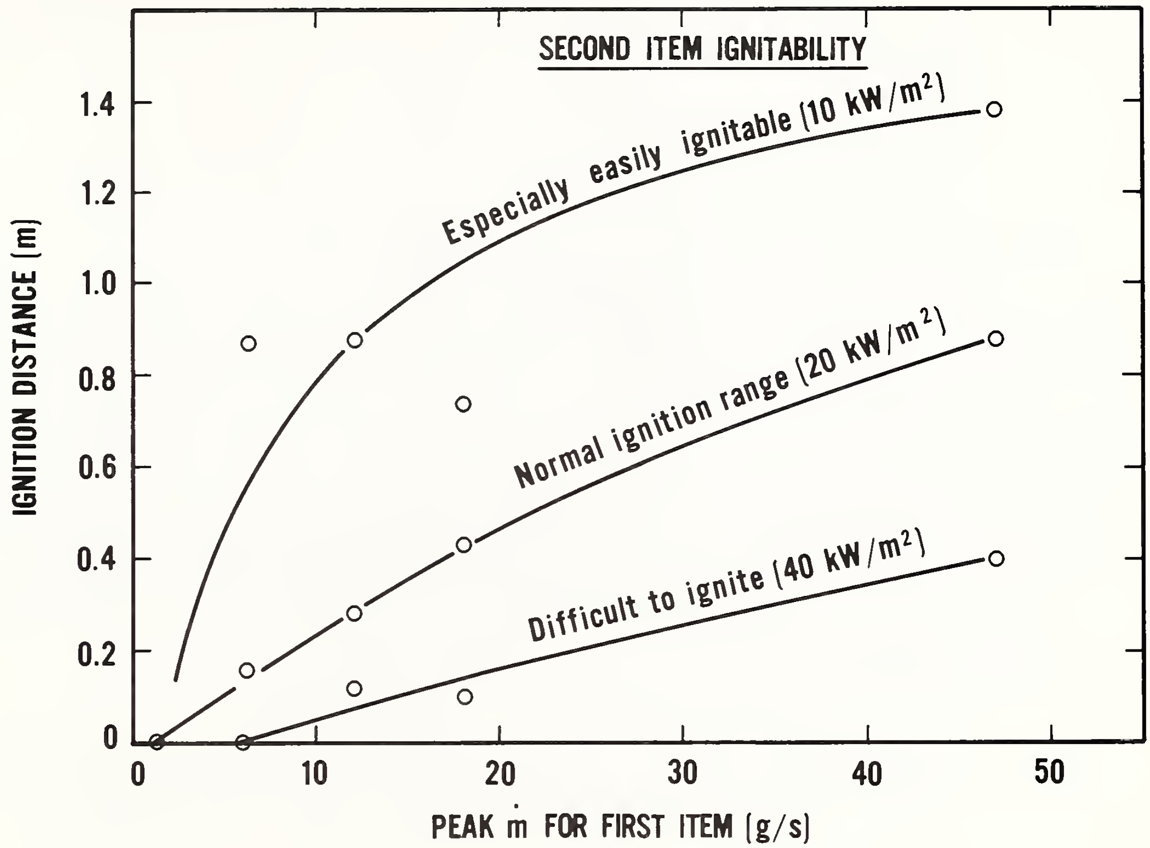


Figure 6-3. Relationship between peak mass loss rate and ignition distance for various ignitability levels.

predicted total flux (ON TARGET plus the flux from the flame estimated from figure 6-3) reaches the estimated ignition flux for the second item, ignition can be assumed. The second item is then added to the first as described in the section on MLTFUEL, and FAST is re-run with the new fire.

The method of estimating the flux from the flame presented in figure 6-3 is based on a correlation to experimental data for upholstered furniture. Thus, the range of materials on which this correlation is based is limited to those materials used in furniture. But the radiative output of a flame varies with the chemical composition of the burning material, limiting the applicability of this estimation technique. A more general (and more complex) method for estimating ignition time of a second item can be derived using data from the Lateral Ignition and Flamespread Test (LIFT) apparatus under development at CFR [23]. For materials tested in this apparatus, the parameters $\dot{q}''_{o,ig}$, t_m, and b are tabulated for use in the following relation:

$$\frac{\dot{q}''_{o,ig}}{\dot{q}''_{e}} = \begin{cases} b \ \ t^{1/2}, & t \leq t_m \\ 1, & t \geq t_m \end{cases} \qquad \begin{matrix}(1)\\(2)\end{matrix}$$

where: $\dot{q}''_{o,ig}$ is the minimum flux required for ignition
$\dot{q}''_{e}$ is the incident flux imposed on the sample
b is a constant derived from the test data appropriate to natural convection conditions
t is the time of ignition
t_m is a characteristic time for the sample to reach thermal equilibrium.

The total flux to the surface of an object ($\dot{q}''_e$) is the sum of the flux from the flame of the burning object ($\dot{q}''_{r,f}$) and the flux from the upper layer and room surfaces ($\dot{q}''_{l,w}$). As in the previous method, the flux from the upper layer and room surfaces ($\dot{q}''_{l,w}$) is obtained from a run of FAST with only the first item burning, from the variable ON TARGET (note that ON TARGET is in kW/m^2 and so the value must be divided by 10 to convert to W/cm^2).

Next, the flux from the flame above the burning item to the target item is computed. From Drysdale [24], the following equations for incident heat flux from a flame to a target ($\dot{q}''$r,f), flame power output (E), and flame length (ℓ) are obtained:

$$\dot{q}''_{r,f} = \varnothing E \ (\text{W/cm}^2) \qquad (3)$$

$$E = 1/2 \ (\xi) \ \dot{Q}/[\ell D] \ (\text{W/cm}^2) \qquad (4)$$

$$\ell = 0.23 \ \dot{Q}^{2/5} - 1.02 \ D \ (\text{cm}) \qquad (5)$$

where: $\dot{Q}$ is the rate of heat release of the burning item (W)
D is the flame diameter (cm)
$\varnothing$ is the configuration factor between the flame and target
ξ is the radiative fraction (assume 0.3 if a value is not available for the fuel involved).

Combining eqs (3) and (4), and substituting the configuration factor for a general case of a flame radiating to the horizontal surface of a target object located at the same elevation and d (cm) from the flame axis of the burning item, we obtain:

$$\dot{q}''_{r,f} = 0.3 \ \dot{Q} \ \ell d/[4\pi(d^2 + \ell^2/4)^2] \qquad (6)$$

Rearranging eq (1) (for $t \leq t_m$), we obtain an expression for the ignition time of the target item:

$$t = (\dot{q}''_{o,ig}/[b(\text{ON TARGET}/10 + \dot{q}''_{r,f}))^2] \tag{7}$$

And from eq (2), the target object will not ignite when:

$$\dot{q}''_{o,ig} < (\text{ON TARGET}/10) + \dot{q}''_{r,f} \tag{8}$$

Note that t_m as tabulated from the LIFT apparatus data is the time to reach thermal equilibrium for the sample (thickness) tested. This time will increase with thickness, so eq (7) should be used for thick objects. Also, both ON TARGET and $\dot{q}''_{r,f}$ vary over time. As a rough estimate, eqs (1) and (2) can be evaluated at each interval of fire growth specified until ignition of the second item occurs. More correctly, the second item's ignition temperature and thermal properties, also available from [23], should be used to compute the time of ignition for time-varying heating. At that point, the procedure described in the section in the **Software User's Guide** on MLTFUEL is used to obtain the combined rates of energy and mass release.

One of these methods is used to estimate the ignition of additional objects in the room up to the point of flashover. Once flashover occurs, all combustible items in the room can be considered to pyrolyze or ignite simultaneously.

6.4 References

[1] Babrauskas, V. Combustion of mattresses exposed to flaming ignition sources, part I. Full-scale tests and hazard analysis. Natl. Bur. Stand. (U.S.) NBSIR 77-1290; 1977 September. 145p.

[2] Quintiere, J. G.; McCaffrey, B. J. The burning of wood and plastic cribs in an enclosure, 2 vols. Natl. Bur. Stand. (U.S.) NBSIR 80-2054; 1980 November. 202p.

[3] Huggett, C. Estimation of rate of heat release by means of oxygen consumption measurements. Fire and Materials 4(2): 61-65; 1980 June.

[4] Babrauskas, V.; Lawson, J. R.; Walton, W. D.; and Twilley, W.H. Upholstered furniture heat release rates measured with a furniture calorimeter. Natl. Bur. Stand. (U.S.) NBSIR 82-2604; 1982 December. 73p.

[5] Heskestad, G. A fire products collector for calorimetry into the MW range. (FMRC J.I. OC2E1.RA), Factory Mutual Research Corp., Norwood, MA; 1981 June. 109p.

[6] Babrauskas, V. Free burning fires, Chapter 2 in The SFPE handbook of fire protection engineering. Society of Fire Protection Engineers, Boston (1988). 2-1 2-15.

[7] Gross, D. Data sources for parameters used in predictive modeling of fire growth and smoke spread. Natl. Bur. Stand. (U.S.) NBSIR 85-3223; 1985 September. 40p.

[8] Lee, B. T. Heat release rate characteristics of some combustible fuel sources in nuclear power plants. Natl. Bur. Stand. (U.S.) NBSIR 85-3195; 1985 July. 52p.

[9] Babrauskas, V.; Walton, W. D. A simplified characterization for upholstered furniture heat release rates. Fire Safety J., 11(3): 181-192; 1986 December.

[10] Babrauskas, V.; Krasny, J. F. Fire behavior of upholstered furniture. Natl. Bur. Stand. (U.S.) Monogr. 173; 1985 November. 101p.

[11] Babrauskas, V. Development of the cone calorimeter - a bench scale heat release rate apparatus based on oxygen consumption. Fire and Materials 8(2): 81-95; 1984 June.

[12] Proposed test method for heat and visible smoke release rates for materials and products using an oxygen consumption calorimeter. American Society for Testing and Materials; 1986. 1221-1237.

[13] Lee, B. T.; Steel, J. S. standard room fire test development at the National Institute of Standards and Technology. Natl. Inst. Stand. Tech. to be published.

[14] Magnusson, S. E.; Sundström, B. Combustible linings and room fire growth - A first analysis. T. Z. Harmathy, ed. Fire safety: science and engineering. American Society for Testing and Materials ASTM STP 882; 1985. 45-69.

[15] Babrauskas, V.; Krasny, J. F. Prediction of upholstered chair heat release rates from bench-scale measurements. T. Z. Harmathy, ed. Fire safety: science and engineering. American Society for Testing and Materials ASTM STP 882; 1985. 268-284.

[16] Babrauskas, V.; Harris, R. H.; Gann, R. G.; Levin, B. C.; Lee, B. T.; Peacock, R. D.; Paabo, M.; Twilley, W.; Yoklavich, M. F.; Clark, H. M. Fire hazard comparison of fire retarded and non-fire-retarded products. Natl. Bur. Stand. (U.S.) Spec. Publ. 749; 1988 July. 92p.

[17] Beyler, C. L. Major species production by solid fuels in a two layer compartment fire environment. C. Grant and P. Pagni, ed. Proceedings of the first international

symposium on fire safety science; 1985 October 7-11; New York, NY: Hemisphere Publications; 1986. 431-440.

[18] Tewarson, A. Fully developed enclosure fires of wood cribs. Twentieth symposium (international) on combustion. The Combustion Institute, Pittsburgh, PA; 1988. 1555-1564.

[19] Tewarson, A. Quantification of fire properties of fuels and interaction with fire environments. Natl. Bur. Stand. (U.S.) NBS GCR 82-395; 1982.

[20] Tewarson, A.; Steciak, J. Fire ventilation. Natl. Bur. Stand. (U.S.) NBS GCR 83-423; 1983.

[21] Beyler, C. L. Major species production by solid fuels in a two layer compartment fire environment. C. Grant and P. Pagni, ed. Proceedings of the First International Symposium on Fire Safety Science; 1985 October 7-11; New York, NY: Hemisphere Publications; 1986. 431-440.

[22] Babrauskas, V. Will the second item ignite? Fire Safety Journal 4(4): 281-292; 1981 December.

[23] Quintiere, J. G.; Harkleroad, M. T. New concepts for measuring flame spread properties. T. Z. Harmathy, ed. Fire safety: science and engineering. American Society for Testing and Materials ASTM STP 882; 1985. 239-267.

[24] Drysdale, D. An introduction to fire dynamics. New York, NY: John Wiley & Sons Publishers, First Edition, 67, 143-145; 1985.

CHAPTER 7. TENABILITY LIMITS

7.1 Introduction

The purpose of this section is to provide the background for the user to decide on the appropriate tenability criteria to use in the program TENAB. To assess the impact of fire on humans, it is essential to be able to assign appropriate limits to fire generated conditions. In the sections that follow, we provide an comprehensive review of research related to such limits which provides the background for the limits assumed in HAZARD I. An extensive bibliography of the research is included for those interested in further study. In all cases, only physical impacts are considered. Thus incapacitation refers to physical collapse and not to any diminution in mental capacity or judgment since such are difficult to evaluate in animal experiments.

7.2 Flashover

Flashover is a perceived event which can be denoted by any of a number of interrelated phenomena which can occur simultaneously during the course of a serious building fire. These include the reaching of temperatures of 500 °C to 700 °C in the upper portions of the room [2,3,4]; the reaching of a heat flux of 25 kW/m^2 at the floor level, with the near-simultaneous ignition of combustibles not previously ignited [5,6]; the filling of almost the entire room volume with flames [7]; and the dropping of oxygen levels to low values, typically 5% or less [8]. When flashover is reached in a room, habitability is completely precluded, due to high temperatures, high heat fluxes, low oxygen, and high concentration of combustion products. Flashover, as an event, is also an important marker since when it occurs the threat to the remaining spaces in a building usually becomes much greater.

7.3 Temperature

The effects of temperature as an exposure limit under fire conditions have not been well studied. Industrial hygiene literature primarily gives data for heat stress under conditions of prolonged, typically 8 hour, exposures. The older literature, as it relates to fire, has been reviewed by Simms and Hinkley [9], although, based on that review, they could not make any recommendations of tenability values.

Experimental data from studies with pigs have shown no injuries at 120 °C for 2 min, 100 °C for 5 min, and 90 °C for 10 min [10,11]. Some experimental data for humans have been reported which show that temperatures of 100 °C could be withstood by a clothed, inactive adult male for about 30 min before intolerable discomfort is reached; a 75 °C exposure could be withstood for about 60 min [12]. These experimental values seem high. To place them in context, Zapp [13] has stated that "...air temperatures as high as 100 °C can be tolerated only under very special conditions (i.e., still air) for more than a few min, and that some people are incapacitated by breathing air at 65 °C...". Crane [14] has recommended that for healthy, clothed, adult males, collapse due to elevated temperatures will occur when the exposure time, t, exceeds the following value:

$$t = 2.46 \times 10^{10} / T^{3.61} \tag{1}$$

where t is the time to collapse (s) and T is the air temperature (°C). This expression, however, does not take into account the relative humidity of the air.

Criteria for temperature are, in fact, especially difficult to set, since the temperature at which adverse effects are noted depends not only on the exposure time, but also on the relative humidity. Thus, for instance, in a study of acclimated adult males to a sauna exposure at 100 °C and 22% R.H. for 15 min, it was seen, despite physiological indications of stress, that no ill effects occurred [15]. Similar concurring studies are available for 85-90 °C exposures for 20 min [16]. In the room of fire origin, it can be expected that the air will be nearly, if not totally, saturated with water vapor. In this case, medical recommendations are that "Air at temperatures above about 50 °C produces severe discomfort in the oral, nasal, and esophageal passages if it is close to saturation with water vapor" [17].

The permeability and insulating value of the clothing worn can also have a significant effect on the ability to withstand elevated temperatures. For long exposures (greater than 30 min), extensive experimental data are available [e.g., 18]. Similar data have not been obtained for short exposures, such as may occur in building fires, however. In previous fire hazard evaluation recommendations, the tenability values for brief exposures at face level ranged from 65 °C [19] to 100 °C [20].

Purser [21] suggests an exponential relation for human tolerance (incapacitation) to convected heat. This relation produces a more realistic response prediction than simply a limiting temperature, since it allows for the time-dependant nature of the heat transfer to the subject. For longer exposure times, the asymptotic limit is similar to the limiting values discussed above. Thus for the present, the Purser equation for thermal tolerance will be employed within the HAZARD I software. As discussed in the section on TENAB, the output of the program provides a simple sensitivity analysis of this, and all tenability criteria selected.

7.4 Heat Flux

Elevated heat fluxes can produce direct pain sensation on hands and face, which can make escape untenable. Higher values of heat flux will produce blistering and burning of the skin.

From heat transfer studies, Henriques [22] developed an integrated injury index Ω, such that exposure can be tolerated without irreversible injury if $\Omega \leq 0.53$, and deep burn injury occurs if $\Omega \geq 1$.

$$\Omega = 3.1\times10^{98} \int_0^t e^{-75,000/T} \, dt \tag{2}$$

where T is the surface temperature of the skin (K), and t is time (s). This relation is sensibly in an Arrhenius form, however, it is not, by itself, predictive, since the surface rate of temperature rise has to be computed using external boundary conditions.

Hendler [23], meanwhile had made measurements of the thermal properties of human skin, and reported data on the spectral reflectance of human skin, both white and black, over the spectral range of 0.4 to 20 μm. He also obtained an experimental value for $k\rho C = 111 \pm 8 \times 10^{-5}$ cal^2/cm^4/C^2/s. Stoll [24], however, concluded that the $k\rho C$ of human skin varies according to irradiance, changing from 96 to 159 as the irradiance was quadrupled. She also determined that a more complex expression than Henriques' Ω value may be more realistic.

Stoll and coworkers [24,25,26] and Derksen and coworkers [27] have over the years collected a large amount of experimental data, some of which are summarized in table 8-1. Table 7-1 shows that literature agreement on the incident irradiance required for achieving a blister or a burn to blackened skin (which is the worst-case condition) is generally good. The work of Stoll and Chianta [26] also gives data for pain thresholds, and shows that both pain and blistering can be very well represented as power laws:

Pain $$t = 85 \, (\dot{q}'')^{-1.35} \tag{3}$$

Burn $$t = 223 \, (\dot{q}'')^{-1.35} \tag{4}$$

where t is the exposure time (s) and $\dot{q}''$ is the incident heat flux (kW/m^2).

Table 7-1. Time required to blister or burn blackened skin

Stoll/Greene [24]		Stoll/Chianta [26]			Derksen/Monahan/deLhery [27]		
Time (s)	Flux (kW/m^2)	Time (s)	Flux (kW/m^2)	Tot. heat (kJ/m^2)	Time (s)	Flux (kW/m^2)	Tot. Heat (kJ/m^2)
					0.5	75.2	37.6
					1.0	50.2	50.2
		1.08	50.2	54.2			
		1.41	41.8	59.0			
		1.95	33.5	65.3			
					2.0	29.3	58.6
		3.0	25.1	75.3			
					5.0	13.38	66.9
		5.6	16.7	93.7			
		7.8	12.55	97.9			
8.6	12.55						
					10.	9.2	92.0
		13.4	8.37	112.2			
					20.	6.06	121.3
		20.8	6.28	130.5			
24.4	6.28						
		33.8	4.18	141.4			
37.2	4.18						
					50.	3.10	154.8
					100.	2.13	213.4

The relationships are somewhat more clearly evident if they are expressed in terms of the time integral of the heat flux, H (kJ/m^2). It can then be seen that the total heat, H, required to cause pain or burn is not a constant, but it is a relatively slowly varying function of exposure time (or of flux level). The corresponding relations then become:

Pain $$H = 26.8\ t^{0.26} \qquad (5)$$

Burn $$H = 54.7\ t^{0.26} \qquad (6)$$

In assessing the capability to withstand pain, the experimental data and the derived equations above are all for relatively short times of exposure to constant flux levels. For longer exposures, some older experimental data indicate that heat flux values of 2.5 kW/m^2 can be tolerated for 3 min without reaching unbearable pain and that this value does not change appreciably for longer times [28-31]. By comparison, some 1943 Japanese data reported by Hasemi [32] showed that an asymptotic value is not quite reached even at 30 min. From 3 min to 30 min, however, the fluxes endured in the Japanese study changed only from 2.9 kW/m^2 to 2.1 kW/m^2, thus indicating general agreement to the 2.5 kW/m^2 limit derived from U.S. studies. This value has been used as a tenability criterion for some time

[5,20], and can be used for evaluation purposes. The appropriate height for evaluation will normally be at face level.

For evaluating burn injuries, in work on protective clothing, researchers [33] have employed a direct comparison of the time-integrated flux exposure of exposed skin to the relation in eq (6). The time at which the time-integrated flux exposure curve intersects the curve from eq (6) is assumed to define the occurrence of second degree burns, representing the point of irreversible cell damage requiring grafting.

In the hazard evaluation, this technique is used as a potential incapacitation criterion, but is not used as a lethality end point since death from skin burns depends on age, treatment, and the amount of skin exposed or the relative protection of clothing worn. Heat flux data to calculate the time-integrated flux exposure is taken from the FAST model prediction of the heat flux to the floor which is assumed to be the exposure that would be received by unprotected skin.

7.5 Smoke Obscuration

The setting of limiting values for smoke obscuration is very difficult. Unlike temperature, heat flux, or toxic gases, visibility obscuration is not, itself, lethal. A hazard results only if the reduction in visibility prevents required escape activity. This restriction of escape activity is crucial, however, and thus smoke production has, in fact, been regulated longer than any other product of combustion [34]. The most significant body of work in this area has been due to Jin [35,36], who found that there is an approximate reciprocal relationship between smoke and visibility distance (the distance at which a person can identify an exit sign), according to:

$$kV = 2 \tag{7}$$

where k = smoke extinction coefficient (m^{-1}), and V = visibility distance (m). While this relationship permits visibility to be estimated, further data are needed to set criteria values. Jin conducted experiments where the walking speed of individuals exiting buildings was measured as a function of smoke levels, and compared to the exiting speed for blindfolded subjects. For "non-irritating" smoke the walking speed of the subjects dropped to the blindfolded speed when a value of $k = 1.2\ m^{-1}$ was reached. For "irritating" smoke, the comparable figure was $k = 0.5\ m^{-1}$. Irritancy in Jin's experiments was not well-quantified; for the purposes of setting limit values, it may be appropriate to select $k = 1.2\ m^{-1}$ as the limit. This limit also corresponds to a visibility of 1.67 m by the relationship above, which appears to be a reasonable distance to see a room door in a residence, or the edge of a hallway. In some cases in the literature a much more stringent criterion, typically $k = 0.5\ m^{-1}$, has been selected [20,37].

Within the hazard evaluation system, smoke obscuration is accounted for only within the evacuation model. That is, the smoke density is used to adjust the walking speed of an occupant. (A little smoke makes the person walk faster, and a greater amount slows his progress. See Appendix B for a detailed discussion of the parameter values used in EXITT.) Smoke also represents a psychological barrier to an occupant entering a room. In the latter case, excessive smoke will cause the person to seek an alternate route and can result in the occupant being trapped in a room without a safe exit (door or window).

7.6 Toxic Gases

Studies on the causes of fire deaths have typically indicated that CO poisoning accounts for roughly one-half of total fatalities [38,39]. The remaining half is accounted for by direct burns, explosive pressures, and various other toxic gases. Although the analysis of blood cyanide (which would come from exposure to hydrogen cyanide) in fire victims is sometimes reported in autopsy data, blood carboxyhemoglobin saturation, resulting from exposure to CO is often the only data provided. This provides no information on the potential effect of other toxic gases on the lethality. Nonetheless, a significant emphasis on studying other toxic gases is placed by most research organizations in this field, due to the fact that high hazards may exist from additional combustion products whose presence is suggested by the decomposition chemistry, although not necessarily confirmed by medical evidence. Table 7-2 lists, in order of increasing estimated toxicity, those primary gases which have been suggested by various investigators as being potentially significant in fire situations. Human data are in most cases unavailable, and even primate data are rare. The tabulated values represent the estimated LC_{50}'s (in ppm), i.e., those concentrations which would be lethal to 50% of the exposed subjects for the specified time. Data on the combined effects are, as yet, rare, inconsistent, and insufficient for a general tabulation [40,46-56].

Oxygen deprivation is a special case of gas toxicity. Data on oxygen deprivation alone, without any other combined gas effects, suggest that incapacitation occurs when oxygen levels drop to approximately 10% [47]. Exposure to decreased oxygen levels alone is very unlikely in fire, however. More commonly expected is some diminution in oxygen levels together with the presence of CO, CO_2, and other toxic species. Such combinations have been explored, providing a few experimental points [49]. Currently, the potential effects of reduced oxygen are addressed in the FED parameter discussed below.

Toxicity from fire atmospheres can result not only from gases, but also from solid aerosols, or from material adsorbed onto soot particles. Data in this field are almost non-existent [57].

Table 7-2. Preliminary list of primary toxic gases

Gas		Assumed LC_{50} (for humans) 5 min (in ppm)	30 min	Ref. No.	Reference data (species, mins.) h=man r=rat m=mouse p=primate gpg=guinea pig
CO_2	carbon dioxide	>150,000	>150,000	[40]	r
C_2H_4O	acetaldehyde		20,000	[41]	LC(m,240)=1500 LC_0(r,240)=4000 LC(ham,240)=17,000
				[42]	LC(r,30)=20,000 LC(r,240)=16,000
$C_2H_4O_2$	acetic acid		11,000	[41]	LC(m,60)=5620
NH_3	ammonia	20,000	9,000	[43]	EC(m,5)=20,000 EC(m,30)=4400
				[44]	EC(r,5)=10,000 EC(r,30)=4000
HCℓ	hydrogen chloride	16,000	3,700	[45]	r,p
				[46]	LC(r,5)=40,989
CO	carbon monoxide		3,000	[40]	LC(r,30)=4600
				[47]	LC(h,30) 3000
HBr	hydrogen bromide		3,000	[41]	LC(m,60)=814 LC(r,60)=2858
NO	nitric oxide	10,000	2,500	[42]	1/5 as toxic as NO_2
					LC(h,1) 15,000
COS	carbonyl sulfide		2,000	[41]	LC_0(var.,35-90)=1000-1400
H_2S	hydrogen sulfide		2,000	[41]	LC(m,60)=673 LC_0(h,30)=600 LC_0(mam,5)=800
				[47]	LC(h,30) 2000
HF	hydrogen fluoride	10,000	2,000	[41]	LC(gpg,15)=4327 LC(p,60)=1774 LC_0(h,30)=50
					LC(m,60)=456 LC(r,60)=1276
				[46]	LC(r,5)=18,200
				[47]	LC(gpg,2)=300 LC(m,5)=6247 LC(r,5)=18,200
C_3H_4N	acrylonitrile		2,000	[41]	LC(gpg,240)=576 LC(r,240)=500
COF_2	carbonyl fluoride		750	[42]	LC(r,60)=360
NO_2	nitrogen dioxide	5000	500	[43]	EC(m,5)=2500 EC(m,30)=700
				[44]	EC(r,5)=5000 EC(r,30)=300
				[46]	LC(m,5)=831 LC(r,5)=1880
C_3H_5O	acrolein	750	300	[41]	LC(m,360)=66 LC_0(p,10)=153
				[48]	LC(p,5) 505 to 1025
CH_2O	formaldehyde		250	[41]	LC_0(r,240)=250
				[47]	LC(r,30)=250 LC(r,240)=830(??)
				[42]	LC(cat,480)=700 LC(m,120)=700
SO_2	sulfur dioxide	500		[41]	rodents poor; LC_0(m,300)=6000
				[47]	LC(var.,5) 600 to 800
HCN	hydrogen cyanide	280	135	[49]	LC(r,5)=570 LC(r,30)=110
				[46]	LC(r,5)=503 LC(m,5)=323
				[47]	LC(h,30)=135 LC(h,5) 280
$C_9H_6O_2N_2$	toluene diisocyanate		≈100	[41]	LC(gpg,240)=13 LC(rbt,180)=1500
					LC(r,360)=600 LC(m,240)=10
				[47]	LC(m,r,rbt,gpg,240)=9.7 to 13.9
COCℓ$_2$	phosgene	50	90	[41]	rec. 50 ppm short exp.
				[50]	LC(h,30) 90
C_4F_8	perfluoroisobutylene	28	6	[41]	LC(r,10)=17 LC(r,5)=28

Notes: EC - concentration for effect
LC_0 - concentration at which first lethal effects are observed

7.6.1 Fractional Effective Dose (FED)

Researchers at CFR [58], Huntingdon Research Centre (UK) [21], and at the Southwest Research Institute (SwRI) [59] have been exploring the hypothesis that the observed effect of the exposure of animals (and humans) to the products generated by burning materials can be explained by the impact of a small number of the gases actually released during combustion. That is that, while there are hundreds of compounds that can be identified, the effect is caused by only a few (N) key gases. By investigating the effect of exposure to these key gases, singly and in combination, a predictive model can be constructed. Thus, this model is referred to as the N-Gas model.

Once such a predictive model is produced, a material is tested in a Toxicity Screening Protocol, measuring the time-dependant concentrations of the gases included in the model. The model is used to predict the observed result, with a successful prediction indicative of the material's toxicity being only from those gases. If the prediction is unsuccessful, there are other gases of importance which would then be identified, studied in pure form, and included in the N-gas model. In this way, the model would be extended until the combustion toxicity of most important materials can be properly predicted for a range of combustion conditions.

The first version of such a model has been derived from the pure gas studies of Levin et al., and Hartzell et al. [58,59]. It includes the gases CO, CO_2, and HCN, along with reduced oxygen, combining their effect in a parameter called Fractional Effective Dose (FED) which is dimensionless and is defined as lethal at a value of one. The hypothesis of FED states that the total observed effect equals the sum of the effects of each of the component parts. That is, if one receives 50% of the lethal dose of CO and 50% of the lethal dose of HCN, death will occur. This has, in fact, been demonstrated by Levin et al., for these two gases [49]. Simply stated then, FED is the sum of the effects of each of the gases toward the total effect on the exposed person.

Since it is the major combustion product implicated in fire deaths, CO was the first gas studied in a long series of pure gas experiments. Rats were exposed to varying concentrations of pure CO for various times, and the concentrations necessary to produce deaths of 50% of the exposed animals (the LC_{50}) for each exposure time was determined. The plot of these data (fig. 7-1), shows that the curve has two asymptotes; an exposure time (about 1 min) below which no effect is seen for any concentration, and a concentration (about 1700 ppm) below which no effect is seen for any time. In the former case, this would represent such physiological effects as breath holding and the time required for the gas to be transferred to the blood and then to the tissues. In the latter case, this represents an exposure concentration for which the equilibrium concentration of COHb in the blood is below the level which causes a lethality [49].

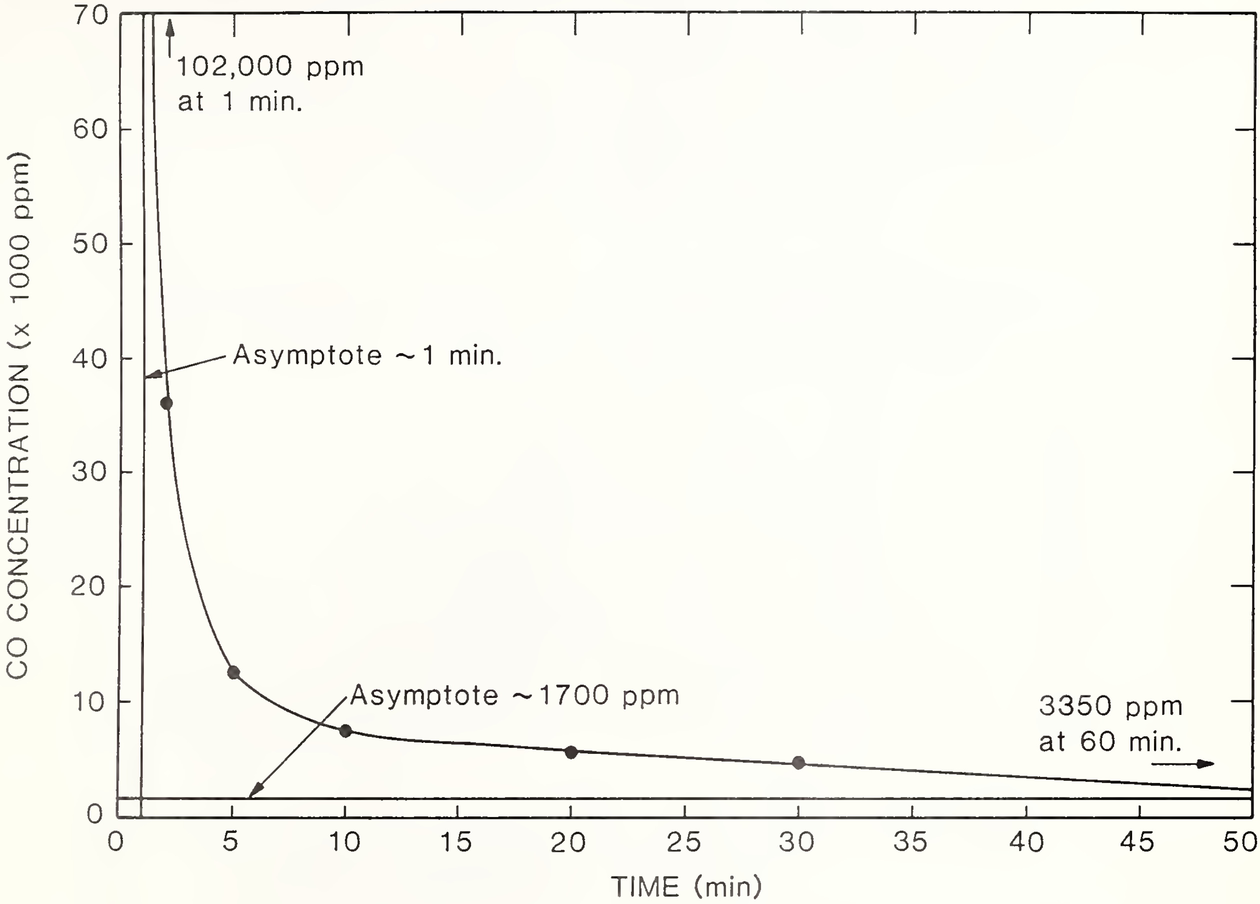


Figure 7-1. Carbon monoxide concentration versus time to lethality of 50% of exposed rats.

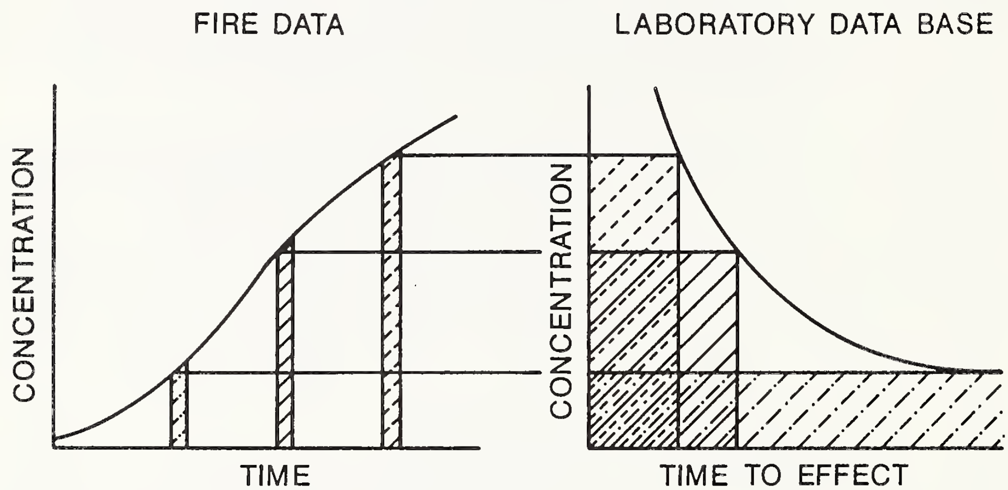
To account for these effects in the N-Gas model, a linear regression was performed on the curve of CO concentration versus 1/time. After adjusting the constants for a best fit to the data available and maintaining appropriate significant figures, this results in the following equation:

$$(C_{CO} - 1700)t = 80000 \tag{8}$$

where C_{co} is the CO concentration in ppm and t is the exposure time for lethality at that concentration. Note that the threshold concentration is included but that the minimum exposure time for effect is zero as a conservative assumption.

The FED concept states that the effect is the dose received (dose is the time integral of the concentration) divided by the critical dose to produce the effect. As shown in figure 7-1, the critical dose is not constant, but rather varies with concentration. Thus, eq 8 is used within the FED calculation to determine the critical dose at the particular incremental concentration (see fig. 7-2 [49]).

MODELING OF TOXICOLOGICAL EFFECTS OF FIRE GASES



$$\sum \frac{\bar{C} \times \Delta t}{(Ct)_c} = \text{FRACTIONAL DOSE TO PRODUCE EFFECT}$$

EFFECT OCCURS AT TIME t WHEN $\sum$ FRACTIONAL DOSES = 1

Figure 7-2. Fractional effective dose.

Following the work with CO, the effect of CO_2 on the observed CO toxicity was studied. The result of this work (shown in fig. 7-3 [40]) was the observation that the "effective toxicity" of CO increases linearly with increasing CO_2 concentration, doubling at a level of 5% (50000 ppm). The physiological effects of the CO_2 are to increase the respiration rate and reduce the blood pH, producing a metabolic acidosis.

These data were used to produce a CO_2 "correction" to the CO term in the calculation of FED whereby the denominator is multiplied by the following factor:

$$[100{,}000 - C_{CO_2} / 100{,}000] \qquad (9)$$

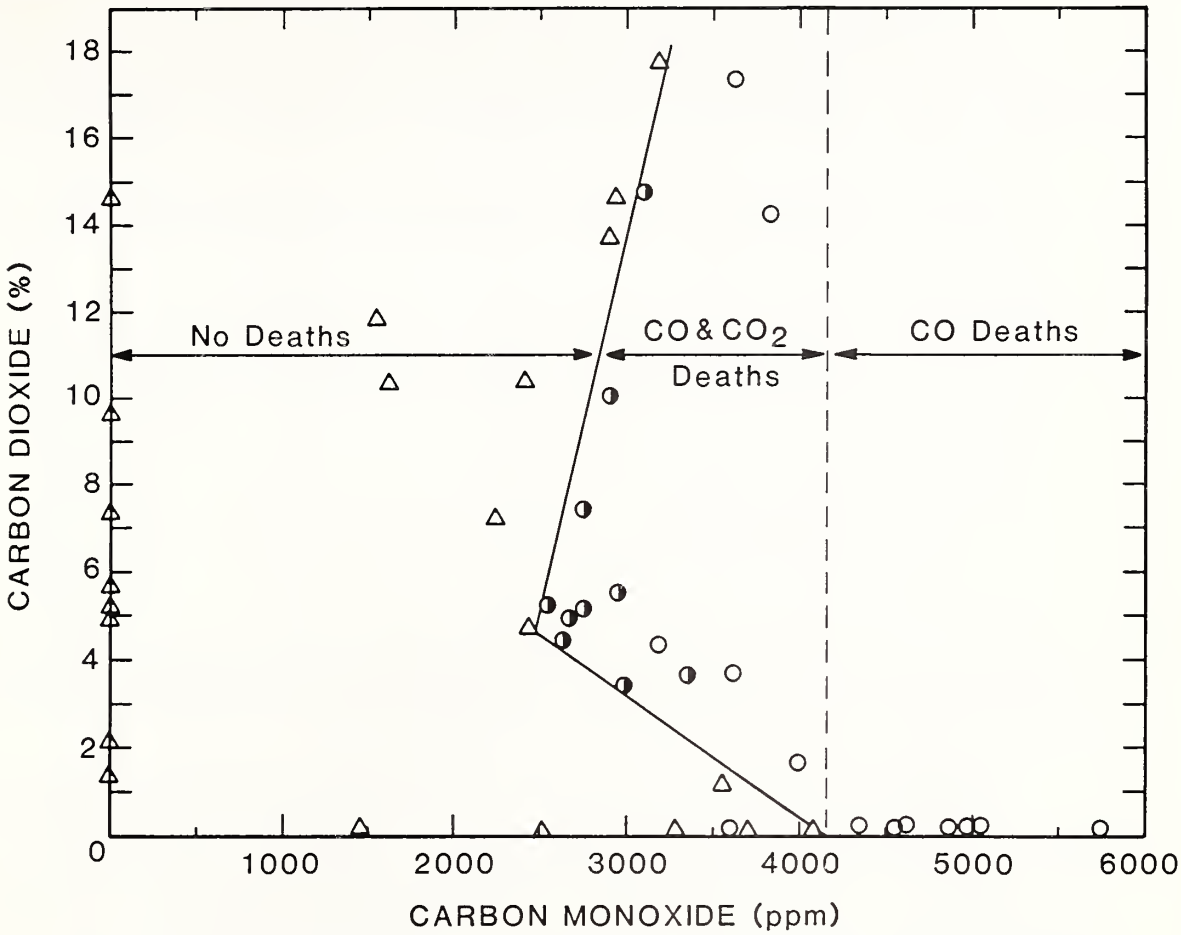


Figure 7-3. Combination of carbon monoxide and carbon dioxide which is lethal to 50% of exposed rats.

where the CO_2 concentration is in ppm. While the data show this effect diminishing above 5% CO_2, the model holds the correction constant at 5% and above as a conservative assumption. Also note that the data were only taken at 30-min exposure times. Preliminary data on shorter times indicates that CO_2 may have no effect, probably due to the fact that the acidosis takes long times to develop. Thus, in the absence of complete data, the conservative assumption is made that the effect holds for all times.

HCN and the combination of CO and HCN were similarly studied. The data on HCN [60] showed that the lethal dose (time-integral of concentration) was relatively constant at a value of 3100 ppm-min for exposure times from 2 to 30 min. Thus, this value is used in the HCN term of the FED calculation. The data on CO and HCN combinations showed that the effects are directly additive [49] (again for 30-min exposures). This is not surprising since they both act to reduce the transfer of oxygen to the tissues; CO by tying up the hemoglobin so that it cannot carry the oxygen, and HCN by preventing the utilization of the oxygen by the tissues.

Finally, the other combinations of gases were studied in the presence of diminished levels of oxygen. These were also found to be additive to the effects of CO and HCN in producing anoxia.

The resulting equation for FED, which represents the current N-Gas model (N=4) is as follows:

$$\mathrm{FED} = \sum \left\{ \frac{\bar{C}_{CO}\ \Delta t}{\bar{C}_{CO}\{80{,}000/(\bar{C}_{CO} - 1700)\}\ \{(100{,}000 - \bar{C}_{CO_2})/100{,}000\}} + \frac{\bar{C}_{HCN}\ \Delta t}{3100} \right\} + \frac{(9.2 - \bar{C}_{O_2})\ (\Delta t)}{15.2} \qquad (10)$$

where $\overline{C}_{co}$, $\overline{C}_{co2}$, $\overline{C}_{o2}$ and $\overline{C}_{HCN}$ are the average concentrations over the time interval and Δt is the length of the time interval (min). In TENAB, eq (10) is implemented such that negative values of any term do not result in a negative dose.

The predictive capability of eq (10) was tested against the material toxicity data included in the NBS Toxicity Screening Protocol report [61]. It should be noted that the oxygen term was not tested since the test protocol is designed to maintain the oxygen at its ambient value. First, the average gas concentration data provided in the report was used, assuming a constant value throughout the 30-min exposure period (i.e. a square-wave exposure). The equation successfully predicted the observed results of 14 materials, with two more within 10%. Levin proposed an equation for predicting the interactions of these same gases for 30-min, square-wave exposures only [49], which successfully predicts the results of the same 16 materials plus flaming red oak. The reason for eq (10) falling 30% short on red oak is currently unclear.

Next, the exposure time-independent nature of eq (10) was tested against the data reported by Hartzell et al., for two ramped exposures to CO only [62]. The equation predicted the results of the slower ramp within the standard deviation stated and predicted a somewhat shorter time to death for the faster ramp.

Table 7-3. Predictions for average gas concentrations

Material	Mode	Observed Deaths	Predicted FED at 30 min. Levin	Predicted FED at 30 min. Bukowski	Predicted Results Levin	Predicted Results Bukowski
ABS	F	W	1.21	1.3	Y	Y
	NF	P	1.62	1.3	Y	Y
DFIR	F	W	1.19	1.0	Y	Y
	NF	W,P	0.67	0.4	N	N
FPU	F	W	0.53	--**	N	N
	NF	P	0.29	--	N	N
FPU/FR	F	W,P	0.95,1.17*	0.9	N/Y	N
	NF	None	0.1	--	Y	Y
MOD	F	W,P	1.22,1.73	1.4	Y	Y
	NF	W	1.67	2.1	Y	Y
PPS	F	W,P	1.04	0.9	Y	N
	NF	W	1.10	1.1	Y	Y
PSTY	F	W	0.37	--	N	N
	NF	None	0.02	--	Y	Y
PVC	F	P	0.28	--	N	N
	NF	P	0.15	--	N	N
PVCZ	F	W,P	1.26,1.57	1.4	Y	Y
	NF	P	1.66	1.4	Y	Y
Redo	F	W	1.03	0.7	Y	N
	NF	P	0.61	0.3	N	N
RPV	F	W	1.27	1.4	Y	Y
	NF	None	0.72,0.84	0.6	Y	Y
Wool	F	W,P	1.03,1.04	1.0	Y	Y
	NF	W,P	1.73,2.42	2.1	Y	Y

*Left value is for within-exposure deaths only and right value includes post-exposure deaths.

**Cannot be predicted since the avg CO concentration does not exceed the threshold values in eq (10).

Table 7-4. Prediction of ramped CO exposure

Linear RAMP	Observed Lethality Time (min)	Predicted Lethality Time (Min)
to 9500 ppm in 10 min	22.8 ± 3.5	16.5
to 7500 ppm in 30 min	43.9 ± 13.9	33.3

Table 7-5. Prediction from time-varying gas concentrations

Material	Mode	Observed Deaths	Predicted FED at 30 min	Time to FED=1 (min)
ABS	F	W	1.0	30
	NF	P	1.7	21
DFIR	F	W	1.0	30
MOD	F	W,P	1.7	17
	NF	W	2.3	14
WOOL	NF	W,P	3.3	10

Since the gas data reported in the NBS report were averages over the 30 min while, in fact, they increased exponentially over some finite time in the experiment, the actual gas analyzer data from the tests of four materials were obtained and input into the equation. The results showed that, for materials which produced only within-exposure fatalities (except MOD,NF), the predicted FED reached unity (lethal) at 30 min. For materials which produced some or all post-exposure fatalities, the predicted FED reached unity earlier, in some cases, as early as 10 min. This would indicate that this is the time at which a lethal dose was received, even though the death occurred later. The details of these comparisons are provided in tables 7-3 to 7-5.

7.6.2 Species Ct

A second, independent indicator of toxicity is provided as species Ct, computed in the FAST model. This parameter represents the time-integrated exposure to the mass concentration of all of the mass of fuel lost within the structure and is thus a concentration-time product (hence the name Ct). The units are gram-minutes per cubic meter. The lethality of smoke from most common building materials is 900 g-min/m^3, so this can be used as a reference value. Where materials more or less toxic are considered, this reference value should be varied accordingly (e.g., by factors of 10).

Species Ct is calculated within the FAST transport model as a means of estimating the relative toxicity of the combustion products produced by the burning items without the need for extensive input data [63]. The concept of Ct evolved from the NBS Toxicity Screening Protocol [61] in the following way.

In the screening test, the animals are placed in an enclosure of known volume, which is connected to a furnace in which the material is burned. The mass of fuel lost during the experiment is divided by the chamber volume to obtain a mass concentration of "fuel vapors" to which the animals are exposed for a specified time. Multiplying the mass concentration by the time gives the "exposure dose" or a concentration-time product. Expressed mathematically:

$$Ct \equiv \int_0^t Y \rho \, dt \qquad (11)$$

where Y is the corresponding mass fraction of the layer and ρ is its density.

In a similar manner, Ct is calculated in the FAST model by taking the cumulative mass of fuel lost and distributing it into the upper layers in each of the rooms according to the calculated mass flows through the defined openings. The volumes of the layers are also calculated as a function of time, so a mass concentration of "fuel vapors" is obtained. This concentration is integrated over time to produce a concentration-time product, or Species Ct [64].

We suggest that a reference value for lethality of 900 g-min/m^3 be used for materials of "ordinary" toxicity. Several methods have been suggested for categorizing materials into classes which generally vary in LC_{50} by factors of 10 (fig. 7-4 [65]). Thus, we suggest that, when the material in question falls into a class above or below "ordinary," the reference value of Ct be adjusted by a factor of 10 (e.g., for a material one class more toxic, use a value of 90 for the lethal level).

7.6.3 Incapacitation

The work of Purser [21] employed nonhuman primates as subjects, and has used incapacitation as an end point. Using mathematical procedures similar to those discussed above, FED terms have been derived for the same gases and combinations. These relations, documented in the cited reference, have been incorporated as a measure of incapacitation of human subjects. The exact implementation is described in the section on TENAB.

Other than the work of Purser, most of the published toxicity data is for lethality since incapacitation is often subjective in terms of an indicator of its occurrence. Thus, it is sometimes suggested that values of 1/3 to 1/2 of the lethal values of FED and Ct be used as incapacitation indicators [66] in the absence of better data. This reference also includes a discussion of the various methods of determining the occurrence of incapacitation in animals. Also, it should be understood that the term incapacitation itself is subject to some interpretation, since it may be used to indicate the lack of physical ability to move (walk, crawl) or the mental ability to decide to move.

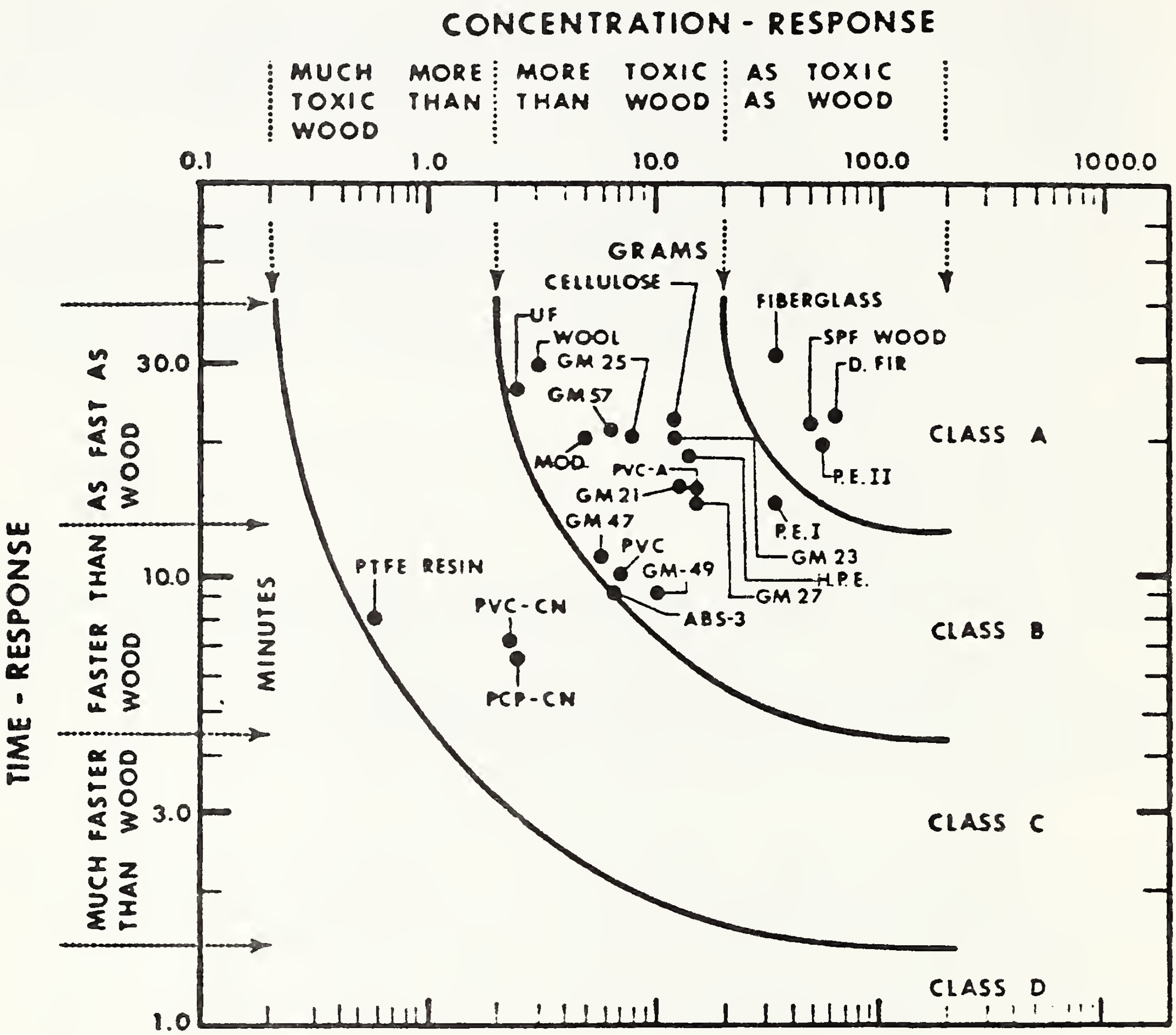


Figure 7-4. Example of a toxicity grading scheme by order of magnitude of observed effect.

7.7 References

[1] Malek, D. E.; Alarie, Y. Performance evaluation under intoxicating atmospheres. Fundemental and Applied Toxicology 8: 335-345; 1987.

[2] Hägglund, B.; Janssens, R.; Onnermark, B. Fire development in residential rooms after ignition from nuclear explosions Forsvarets Forskningsanstalt, Stockholm FOA C20016-D6(A3); 1974 November. 29p.

[3] Fang, J. B.; Breese, J. N. Fire development in residential basement rooms. Natl. Bur. Stand. (U.S.) NBSIR 80-2120; 1980 October. 97p.

[4] Martin, S. B.; Wiersma, S. J. An experimental study of flashover criteria for compartment fires. SRI International, Menlo Park, CA; Project PYC 6496, Report PRC No. P-77-3-1; prepared for the Products Research Committee; 1979 April. 88p.

[5] Babrauskas, V. Combustion of mattresses exposed to flaming ignition sources, part I. Full-scale tests and hazard analysis. Natl. Bur. Stand. (U.S.) NBS-IR 77-1290. 1977 September. 145p.

[6] Fang, J. B. Fire performance of selected residential floor constructions under room burnout conditions. Natl. Bur. Stand. (U.S.) NBSIR 80-2134; 1980 December. 79p.

[7] Babrauskas, V.; Williamson, R. B. Post-flashover compartment fires: basis of a theoretical model. Fire and Materials, 3(1): 1-7; 1979 March.

[8] Alpert, R. L., et al. Influence of enclosures on fire growth, volume 1: test data. Factory Mutual Research Corp., Norwood, MA FMRC Reports, Serial Nos. 0A0R2.BU-0 through 8; 1977 November.

[9] Simms, D. L.; Hinkley, P. L. Protective clothing against flames and heat. Joint Fire Research Organization, HMSO, London. Special Report No. 3; 1960 August. 40p.

[10] Moritz, A. R.; Henriques, F. C., Jr.; Dutra, F. R.; Weisiger, J.R. Studies of thermal injury. Archives of Pathology, 43: 466-488; 1947.

[11] Anon. Fire casualties of the German attacks, chapter 8 in Fire and the Air War. Bond, H., ed. National Fire Protection Association., Boston; 1946.

[12] Blockley, W. V.; Taylor, C. L. Human tolerance limits for extreme heat. Heating, Piping, and Air Conditioning 21: 111-116; May 1949.

[13] Zapp, J. A., Jr. Fires, toxicity and plastics. Proceedings of physiological and toxicological aspects of combustion products: international symposium; 1974 March 18-20; Washington, DC. National Academy of Sciences; 1974. 58-66.

[14] Crane, C. R. Human tolerance limit to elevated temperature: an empirical approach to the dynamics of acute thermal collapse. Federal Aviation Administration, Aviation Toxicology Laboratory, Oklahoma City Memorandum Report AAC-114-78-2; 1978.

[15] Leppäluoto, J., et al. Strong heat exposure and adenohypophyseal hormone secretion in man. Hormone and Metabolic Research 7: 439-440; 1975.

[16] Kosunen, K. J., et al. Plasma renin activity, angiotensin ii, and aldosterone during intense heat stress. J. Appl. Physiology 41: 323-327; 1976.

[17] Bell, C. R., Heat, hot work, in Encyclopedia of occupational health and safety, v.1. New York, NY: McGraw-Hill; 1972.

[18] Veghte, J. H.; Webb, P. Clothing and tolerance to heat. Wright Air Development Center, Wright-Patterson AFB; WADC technical report 57-759; 1957.

[19] Operation School Burning. National Fire Protection Association., Boston, MA 1959. 268.

[20] Budnick, E. K. Mobile home living room fire studies: the role of interior finish. Natl. Bur. Stand. (U.S.) NBSIR 78-1530; 1978 September. 163p.

[21] Purser, D. A. Toxicity assessment of combustion products, chapter 3 in The SFPE Handbook of Fire Protection Engineering. C. L. Beyler, ed. National Fire Protection Association, Quincy, MA 1988.

[22] Henriques, F. C., Jr. Studies of thermal injury, part V. Arch. Path. 43: 489-502; 1947.

[23] Hendler, E.; Crosbie, R.; Hardy, J. D. Measurement of the heating of the skin during exposure to infrared radiation. American Socity of Mechanical Engineers ASME Paper 57-SA-33; 1957.

[24] Stoll, A. M.; Greene, L. C. Relationship between pain and tissue damage due to thermal radiation, J. Appl. Physiol. 14: 373-382; 1959 May.

[25] Stoll, A. M. Heat transfer in biotechnology, Adv. Heat Transfer 4: 65-141; 1967.

[26] Stoll, A. M.; Chianta, M.A. Method and rating system for evaluation of thermal protection. Aerospace Medicine 40: 1232-1238; 1969 November.

[27] Derksen, W. L.; Monahan, T. I.; deLhery, G. P. The temperatures associated with radiant energy skin burns. Temperature - its measurement and control in science and industry, 3(3):171-175; 1963.

[28] Buettner, K. Effects of extreme heat and cold on human skin, ii. Surface temperature, pain and heat conductivity in experiments with radiant heat. J. of Appl. Physiology 3: 703-713; 1951.

[29] Hardy, J. D. Thresholds of pain and reflex contraction as related to noxious stimulation, J. of Appl. Physiology 5: 725-739; 1953.

[30] Parker, J. F., Jr.; West, V. R. Bioastronautics data book. NASA SP-3006, Scientific and Technical Information Office, NASA; 1973.

[31] Dinman, B. D. J. American Medical Association 235: 2874-2875; 1976.

[32] Hasemi, Y.; Shigekawa, K. Radiation tolerance of people in big fires. Bull. of Jap. Association of Fire Science and Engineering 31(1): 7-14; 1981.

[33] Braun, E.; Cobb, D.; Cobble, V. B.; Krasny, J. F.; Peacock, R. D. Measurement of the protective value of apparel fabrics in a fire environment. J. of Consumer Product Flammability, 7(1): 15-25; 1980 March.

[34] Steiner, A. J. Method of fire-hazard classification of building materials, ASTM Bulletin; 1943 March. 19-22.

[35] Jin, T. Visibility through fire smoke, Report of Fire Research Institute of Japan, 2(33): 31-48; 1971. 5(42): 12-18; 1975.

[36] Jin, T. Visibility through fire smoke, in Main reports on production, movement and control of smoke in buildings. Japanese Association of Fire Science and Engineering; 1974. 100-153.

[37] Malhotra, H. L. Movement of smoke on escape routes, part 1 - instrumentation and effect of smoke on visibility. Joint Fire Research Organization, Borehamwood Fire Res. Note 651; 1967 January. 21p.

[38] Berl, W. G.; Halpin, B. M. Fire-related fatalities: An analysis of their demography, physical origins, and medical causes. A. F. Robertson, ed. Fire standards and safety. American Society for Testing and Materials, Philadelphia ASTM STP 614; 1976. 26-54.

[39] Harland, W. A.; Woolley, W. D. Fire fatality study--University of Glasgow. Building Research Establishment, Borehamwood Information Paper IP 18/79; 1979 August. 3p.

[40] Levin, B. C.; Paabo, M.; Gurman, J. L.; Harris, S. E.; Braun, E. Toxicological interactions between carbon monoxide and carbon dioxide. Toxicology 47: 135-164; 1987.

[41] Sax, N. I., Dangerous Properties of Industrial Materials. New York: Van Nostrand Reinhold; 1984.

[42] American Conference of Governmental Industrial Hygienists, Inc. Documentation of the threshold limit values. ACGIH, Cincinnati; 1980.

[43] Sakurai, T. Toxic gas test by the several pure and the mixture gas, in Third Expert Meeting of the Canada-Japan-United States Trilateral Cooperative Study on Fire Gas Toxicity, Ottawa; 1984. Natl. Bur. Stand. (U.S.) NBS-IR 88-3753; 1988 October.

[44] Nishimaru, Y. Study on evaluation of toxicity of gas using pure gas. N. H. Jason; K. Davis, ed. Proceedings of the seventh Joint panel meeting of the U.J.N.R. panel on fire research and safety. Natl. Bur. Stand. (U.S.) NBSIR 85-3118; 1985 October. 613-628.

[45] Hartzell, G. E., et al. Intoxication of rats by carbon monoxide in the presence of an irritant; J. Fire Sciences 3(4): 263-279; 1985 July/August.

[46] Higgins, E. A.; Fiorica, V.; Thomas, A. A.; Davis, H.V. Acute toxicity of brief exposure to HF, $HC\ell$, NO_2, and HCN with and without CO, Fire Technology 8(3): 120-130; 1972 May.

[47] Kimmerle, G. Aspects and methodology for the evaluation of toxicological parameters during fire exposure. JFF/Combustion Toxicology 1: 4-51; 1974 February.

[48] Kaplan; et al. A research study of the assessment of escape impairment by irritant combustion gases in postcrash aircraft fires. Federal Aviation Administration, Atlantic City DOT/FAA/CT-84/16; 1984 September. 65p.

[49] Levin, B. C.; et al. Effects of exposure to single or multiple combinations of the predominant toxic gases and low oxygen atmospheres produced in fires. Fundamental and Applied Toxicology 9(2): 236-250; 1987 August.

[50] Clayton, G. D.; Clayton, F. E., ed. Patty's industrial hygiene and toxicology, vols. 2a-2c. New York: Wiley-Interscience; 1982.

[51] Gaume, J. G.; Bartek, P.; Rostami, H. J.; Experimental results on time of useful function (TUF) after exposure to mixtures of serious contaminants. Aerospace Medicine 42: 987-990; 1971 September.

[52] Pryor, A. J.; Johnson, D. E.; Jackson, N. N.; Hazards of smoke and toxic gases produced in urban fires. JFF/Combustion Toxicology 2: 64-112; 1975 February.

[53] Wohlslagel, J.; DiPasquale, L. C.; Vernot, E. H. Toxicity of solid rocket motor exhaust: effects of HCℓ, HF and alumina on rodents. J. Combustion Toxicology 3: 61-70; 1976 February.

[54] Saito, F. Evaluation of the toxicity of combustion products. J. Combustion Toxicology 4: 32-55; 1977 February.

[55] Sakurai, T. Toxic gas test by the several pure and the mixture gas, paper presented at the fifth expert meeting of the tripartite cooperative study group on the toxicity of combustion products; 1986 March 17-18; Washington, DC. Natl. Bur. Stand. (U.S.) NBS-IR-88-3753; 1987 March.

[56] Tsuchiya, Y. On the unproved synergism in inhalation toxicity of fire gas. J. Fire Sciences 4(5): 346-354; 1986 September/October.

[57] Stone, J. P.; Hazlett, R. N.; Johnson, J. E.; Carhart, H. W. The transport of hydrogen chloride by soot from burning polyvinyl chloride. J. Fire & Flamm. 4: 42-51; 1973 January.

[58] Babrauskas, V.; Levin B. C.; and Gann, R. G. A new approach to fire toxicity data for hazard evaluation. ASTM Standardization News 14(9): 28-33; 1986 September.

[59] Hartzell, G. E.; Priest, D. N.; Switzer, W. G. Mathematical modeling of toxicological effects of fire gases. C. Grant and P. Pagni, ed. Proceedings of the First International Symposium on Fire Safety Science; 1985 October 7-11; New York, NY: Hemisphere Publications; 1986. 1059-1068.

[60] Levin, B. C.; Gurman, J. L.; Paabo, M.; Baier, L.; Procell, L.; Newball, H. H. Acute inhalation toxicity of hydrogen cyanide, abstract only. The Toxicologist 6(1): 59; 1986 February.

[61] Levin, B. C.; Fowell, A. J.; Birky, M. M.; Paabo, M.; Stolte, A.; Malek, D. Further development of a test method for the assessment of the acute inhalation toxicity of combustion products. Natl. Bur. Stand. (U.S.) NBSIR 82-2532; 1982 June. 143p.

[62] Hartzell, G. E., et al. Mathematical modeling of intoxication of rats by carbon monoxide and hydrogen cyanide. J. Fire Sciences 3(5): 330-342; 1985 September/October.

[63] Jones, W. W. A multicompartment model for the spread of fire, smoke, and toxic gases. Fire Safety Journal 9(1): 55-79; 1985 May.

[64] Bukowski, R. W. Quantitative determination of smoke toxicity hazard- practical approach for current use. C. Grant and P. Pagni, ed. Proceedings of the First International Symposium on Fire Safety Science; 1985 October 7-11; New York, NY: Hemisphere Publications; 1986. 1089-1100.

[65] Alarie, Y.; Anderson, R. C. Toxicologic classification of thermal decomposition products of synthetic and natural polymers. Toxicology and Applied Pharmacology 57: 181-188; 1980 September 12.

[66] Kaplan, H. L.; Hartzell, G. E. Modeling of toxicological effects of fire gases: I. Incapacitating effects of narcotic fire gases. J. of Fire Sciences 2(4): 286-305; 1984 July/August.

CHAPTER 8. PROGRAM MODULES

This chapter will present the theory and assumptions inherent in the models and programs of the HAZARD I software. The instructions for using these models can be found in the **Software User's Guide.**

8.1 MLTFUEL

8.1.1 Purpose

The fire model FAST requires that the fire be input as a single heat of combustion, and a time series of mass loss rates and yields of species of interest. When there are multiple items burning simultaneously, this input requires that a composite of all of the items be used, where each separate burning item will generally have a different set of values for each of these parameters. The purpose of the program MLTFUEL is to convert these values for each burning item into the required composite fire.

8.1.2 Theory

The calculations performed by the program are based on conservation of energy and mass. That is the energy, or the mass of any specie, released by the composite fire at any time, equals the sum of the energies, or the species masses, released by each item at that time. Specifically, the values for the composite fire are obtained as follows:

1. The heat of combustion of the composite fire is the arithmetic average of the heats of combustion of the individual items.

2. Energy is a conserved quantity. Since the energy released is the heat of combustion times the mass loss rate, the mass loss rate of the composite fire at any time becomes the sum of the mass loss rates of each item, each multiplied by the ratio of its own heat of combustion to the average value.

3. Mass is also a conserved quantity. The mass of any species produced at any time is the mass lost by the fuel at that time times the yield of that species at that time. Thus, the effective yield of a given species for the composite fire at any time is obtained by multiplying

the mass loss rate of each item at any time by its yield at that time (which gives the mass of the specie), summing these masses over all items, and dividing by the mass loss rate of the composite fire for that time.

For additional data on species yields as a function of equivalence ratio, see papers by Tewarson [1-2] and by Beyler [3].

8.1.3 Limitations

The program assumes that the burning characteristics of multiple items burning together are the same as those measured for each item burning individually - that is, that there are no interactions. This is obviously not the case. Each item will be affected by the radiation and convection from the others, increasing the burning (mass loss) rates; thus making this assumption non-conservative. These interactions are, however, beyond the scope of the present model, but will be included in future versions. For the present, the user should keep this limitation in mind and may choose to make an arbitrary adjustment in mass loss rates as a safety factor.

Since the combined items are treated by the FAST model as a single fire source, the entrainment by the single plume may not be the same as would occur if the items remained separate. Thus, the total entrainment may be underpredicted resulting in an underprediction of the total mass flux to the upper layer (and an correspondingly low estimate of species concentrations).

8.2 DETACT

8.2.1 Purpose

DETACT is a program to predict the response of thermal detectors to fires of arbitrary heat release rate. In this context, a thermal detector can be a heat activated detector or a sprinkler head. It is an interactive program where the user answers questions to input the data, and the results are presented in tabular form. Any user familiar with the calculation procedure described in Appendix C of ANSI/NFPA 72E should have no problem with this program as the procedures are similar.

8.2.2 Theory

DETACT uses the plume equations of Alpert [4,5] for unconfined (no walls), smooth ceilings to predict the temperature and velocity in the ceiling jet at the detector location. The response of the thermal device itself is modeled using Response Time Index (RTI) [6]. Smoke detectors are modeled as a thermal device whose activation temperature is 13 °C above ambient. A detailed presentation of the equations employed in DETACT is included in the report by Evans [7] included as Appendix D of this **Technical Reference** volume.

8.2.3 Limitations

A significant (though conservative) limitation is the assumption of an unconfined ceiling. The lack of walls results in the absence of a ceiling layer and a slower rise in temperature at the detector. The models for heat and smoke detector response are correlations to experimental data and, as such, lack a theoretical foundation. Likewise, the treatment of smoke detectors as pseudo heat detectors does not account for the variation of physical properties of smoke among materials nor the physics of the two primary detection principles. Finally, DETACT is only applicable to flaming fires and should not used for smouldering. Other limitations are discussed in reference [7].

8.3 FAST

8.3.1 Purpose

FAST is a program to calculate the evolving distribution of smoke and fire gases and the temperature throughout a building during a fire. It is the heart of HAZARD and contains the most complex science of any of its modules. Many users find FAST to be the most difficult to "understand" in terms of establishing the necessary confidence in, or caution of, its results. The **Technical Reference Guide for FAST version 18** included as Appendix B is an in-depth presentation of the fundamental equations and the way in which they are implemented in the Code, values of internal constants and coefficients, and references to the literature sources from which these all come. The following is an overview of the assumptions and limitations of FAST. This provides perspective for the longer, more detailed text of Appendix B.

8.3.2 Theory

8.3.2.1 General

FAST is a member of a class of models referred to as zone or control volume models. This means that each space (room) is divided into a small number (normally two) of volumes (called layers), each of which is assumed to be internally uniform. That is, the temperature, smoke and gas concentrations within each layer are *assumed* to be exactly the same at every point. Since these layers represent the upper and lower parts of the room, this means that conditions within a room can only vary from floor to ceiling, and not horizontally. This assumption is based on experimental observations that in a fire, room conditions do stratify into two distinct layers. While we can measure variations in conditions within a layer, these are generally small compared to differences between the layers.

FAST is based on solving a set of equations that predict the change in the energy (and thus temperature) and mass (and thus the smoke and gas concentrations) over small increments of time. These equations are the conservation equations for energy, mass, and momentum, and the ideal gas law from chemistry. These conservation equations are always correct, everywhere. Thus any errors which might be made by the model cannot come from these equations, but rather come from simplifying assumptions or from processes left out because we don't know how to include them. Examples of each source of errors will be highlighted in the following discussion.

8.3.2.2 The Fire

The fire is a source of fuel, released at a rate specified by the user. This fuel is converted into energy (the conversion factor is the heat of combustion) and mass (the conversion factor is the yield of a particular species) as it burns. The burning will all take place within the fire plume for an unconstrained or free burning (type 1) fire, or for a constrained (type 2) fire if there is enough oxygen entrained into the plume to burn all of the mass released. For a constrained fire where insufficient oxygen is entrained into the fire plume (see discussion of plumes below), unburned fuel will successively move into and burn in, the upper layer of the fire room, the plume in the doorway to the next room, the plume in the doorway to the third room, and so forth until it gets to the outside or is consumed.

This version of FAST does not predict fire growth. Rather, the user must input a fire history. The similarity of that input to the real fire problem of interest will determine the accuracy of the resulting calculation.

8.3.2.3 Plumes

Above any burning object, a plume is formed which is not considered to be a part of either layer, but which acts as a pump for moving energy (temperature) and mass (smoke and gases) from the lower layer into the upper layer (upward only). For the fire plume FAST does not use a point source approximation, but rather uses an empirical correlation (fit to experimental data). The plume is *assumed* to be the only mechanism for moving energy and mass between the layers within the room. This is not entirely correct. While experiments show that there is very little mixing between the layers at their boundary (called the interface), sources of convection such as radiators or diffusers of heating and air conditioning systems, and the downward flows of gases caused by cooling at walls, will cause such mixing. These are examples of phenonema which are not included because the theories are still under development.

The other source of mixing between the layers which is included in FAST occurs at vents such as doors or windows. Here, there is mixing at the boundary of the opposing flows moving into and out of the room. The degree of mixing is based on an empirically-derived mixing relation. Both the outflow and inflow entrain air from the surrounding layers. The outflow at vents is also modeled as a plume (called the door plume or jet), and in fact uses the same equations as the fire plume, with two differences. First, a point source is calculated (to account for entrainment within the doorway) and second, the equations are modified to account for the rectangular geometry of vents compared to the round geometry of fire plumes. All plumes entrain air from their surroundings according to an empirically-derived entrainment relation. It is the entrainment of cool, oxygen containing air which adds oxygen to the plume to allow burning of the fuel, and which causes it to expand as it moves upward (in the shape of an inverted cone). The plumes are *assumed* not to be affected by other flows which may occur. That is, if the burning object is near the door the strong inflow of air will cause the plume axis to lean away from vertical. Such effects are not included in the model.

8.3.2.4 The Layers

As discussed above, each room is divided into two layers, the upper and lower. At the start of the simulation, the layers in each room are initialized at ambient conditions and each upper layer volume set to 0.001 of the room volume (an arbitrary, small value set to avoid the potential mathematical problems associated with dividing by zero). As energy and mass are pumped into the upper layer by the fire plume, the plume expands in volume causing the lower layer to decrease in volume and the interface to move downward. If the door to the next room has a soffit, there can be no flow through it from the upper layer until the interface reaches the bottom of that soffit. Thus in the early stages the expanding upper layer will act as a piston, pushing lower layer air into the next room through the door.

Once the interface reaches the soffit level, a door plume forms and flow from the fire room to the next room is initiated. This creates a corresponding flow from the second room into the fire room in the lower part of the door to make up for the air going out (You cannot draw a vacuum on the fire room.) All flows are driven by pressure differences and density differences that result from temperature differences and layer depths. Thus the key to getting the right flows is to distribute correctly the fire's mass and energy between the layers.

8.3.2.5 Heat Transfer

Heat transfer is the mechanism by which energy is distributed. Convective transfer occurs from the layers to the room surfaces. The energy thus transferred conducts through the wall, ceiling, or floor in the direction perpendicular to the surface only. FAST is more advanced than most models in this area since it allows different material properties to be used for ceiling, floor, and walls of each room (although all the walls of a room must be the same). Additionally, FAST uniquely allows up to three distinct layers (each with its own properties and thickness) for each surface, which are treated separately in the conduction calculation. This not only produces more accurate results, but allows the user to deal naturally with the actual building construction. Material thermophysical properties are *assumed* to be constant, although we know that they actually vary with temperature. This assumption is made because data over the required temperature range is scarce even for common materials, and because the variation is relatively small for most materials. However the user should recognize that some materials may change mechanical properties with temperature (melt or sag). These effects are not modeled.

Radiative transfer occurs between the fire and the gas layers, between the layers, and between the layers and room surfaces. This transfer is a function of the temperature differences and the emissivity. For the fire and typical surfaces, emissivity values only vary over a small range, so the values used cannot be far off. For the gas layers, however, the emissivity is a function of the concentration of species which are strong radiators: predominately smoke particulates, carbon dioxide, and water. Thus errors in the species concentrations cause errors in the distribution of energy among the layers, which results in errors in temperatures, resulting in errors in the flows. We now begin to see just how tightly coupled the predictions made by FAST can be.

8.3.2.6 Species Concentrations

When the layers are initialized at the start of the simulation, they are set to ambient conditions. These are the initial temperature specified by the user, and 23% by mass (21% by volume) oxygen, 77% by mass (79% by volume) nitrogen, a mass concentration of water specified by the user as a relative humidity, and a zero concentration of all other species. As fuel is burned, the various species are produced in direct relation to the mass of fuel burned (this relation is the species yield specified by the user for the fuel burning). Since oxygen is consumed rather than produced by the burning, the "yield" of oxygen is negative, and is set internally to correspond to the amount of oxygen needed to burn the fuel.

Each unit mass of a species produced is carried in the flow to the various rooms and accumulates in the layers. The model keeps track of the mass of each species in each layer, and knows the volume of each layer as a function of time. The mass divided by the volume is the mass concentration, which along with the molecular weight gives the concentration in volume percent or ppm as appropriate.

FAST version 18 uses a combustion chemistry scheme different from any other model. While others (and all prior versions of FAST) compute each species concentration with an independent yield fraction, FAST maintains a carbon-hydrogen-oxygen balance with a two-step process. That is, fuel carbon and hydrogen go to CO_2 and water (e.g., methane combustion) which then reduces to CO and C (soot) by user specified ratios. This means that the model cannot produce more CO without producing less CO_2 or C, and vice versa. This becomes especially important as the combustion efficiency changes under ventilation-limited combustion conditions. The input data on species yields is generally of limited accuracy. Thus, this is a clear area for sensitivity checks.

8.3.3 Limitations

While FAST has been subjected to comparative validation against several series of multi-room size experiments, and has shown reasonable ability to produce results closely approximating the test measurements, it is not currently possible to provide the user with a precise, analytical statement of the accuracy of the predictions produced by the model. Thus, it is recommended that this model, and the HAZARD I software package, be used for evaluating the relative change in predicted hazard rather than the absolute hazard from a single calculation. Such use will minimize the impact of systematic errors, as these will be present in all of the calculations to be compared. Some specific problems with regard to calculations with the FAST model that have been identified include:

1. When the case involves a room (which is not the room of fire origin), with a door which is closed except for a small gap at the bottom (i.e., an undercut), the model may predict a temperature in the lower layer of the closed room which exceeds the upper layer temperature. This is caused by the fact that the initial flow into the closed room (through the undercut) is by expansion of the lower layer gases in the adjacent room. The model has no way to transport these gases to the upper layer until the layer interface at the door drops to the level of the undercut. At this time, the temperatures should correct themselves. The situation may be corrected by including a vertical crack at the door, but sometimes

this also does not work. As long as the lower layer temperature is not a great deal higher than the upper layer, the results will not be too far in error. It should also be noted that cooler gases above warmer is a physically impossible condition, and as such should immediately raise a flag with the user.

2. FAST (like all zone models) assumes that all predicted parameters are horizontally uniform within any given compartment. This assumption ignores the transient jet produced as the fire gases flow across ceilings. In many situations this jet is thin and the zone assumption has little or no consequences.

3. This assumption of horizontal uniformity also results in the FAST model being insensitive to room shape. The model assumes that all rooms are rectangular. Nonrectangular rooms (e.g., L-shaped) must be entered as equivalent rectangles, although if the six room limit is not a factor, an L-shaped room can be entered as two rectangular rooms connected by a full height and width opening.

4. The accuracy of predictions of species concentrations produced by FAST depend on data on the yields of these species provided by the user. Users are cautioned that the yields obtained in free burn tests may be inappropriate for fully developed fires. This is expected to be most evident in the conditions that can develop in internal unvented corridors exposed to a room that is involved in a post-flashover condition.

8.4 EXITT

8.4.1 Purpose

The HAZARD I software package includes a computer model that simulates the decisions and actions, as well as the evacuation progress of the occupants of a residence during a fire. This model is used to determine the locations of the building occupants during the progress of the fire. The model is called EXITT (since the word exit is reserved in most computer operating systems).

8.4.2 Theory

The simulated occupant decisions and actions are based on the fire psychology literature and interviews of persons who have successfully escaped from fires in buildings of various sizes. In assigning decisions to an occupant, the computer considers such factors as: age of occupant; sex; whether occupant is asleep; smoke conditions; whether smoke detector is sounding; whether occupant needs help in moving; and location, condition and status of other occupants. The permitted actions include: investigate the fire; alert others; awake others; assist others in evacuating; and evacuate. Actions that are not incorporated in the current version include: telephoning fire department from within the building; fighting the fire; and re-entering the building to make a second rescue. The program prints tables detailing the occupants decisions as they are assigned by the computer, and creates a file of occupant locations over time which is used by other programs in the HAZARD I software.

The building is represented within the computer by nodes that represent rooms, exits and secondary locations within rooms; and links or distances between adjacent nodes. The smoke conditions in each room at the beginning of each time period are used in assigning occupant decisions. The occupants move from node to node at a speed that is a function of their assigned normal travel speed, the smoke conditions, and whether or not they are assisting another occupant. Occupants move within the building from node to node. The path assigned is largely based on a shortest path algorithm. The path is also based on smoke conditions and exit doors are preferred to windows.

All the decision rules programmed in the computer and based on the relevant research are designed to make the decisions as similar as possible to decisions that building occupants would make. These rules along with references to the literature from which they derive are detailed in Appendix C of this **Technical Reference Guide**.

8.4.3 Limitations

The model is sufficiently developed for use in estimating occupant locations when comparing two fire situations. If the model were either optimistic or pessimistic in predicting the progress of the occupants in evacuating, the bias would be similar for both situations being compared. The model will provide a set of occupant movements and locations through a formalized procedure.

Limitations of the current model include:

1. The model is deterministic. Many occupant actions are probabilistic (in a given circumstance, a person will do A,

X% of the time and B, Y% of the time). But adding probabilistic branching will result in pseudo-random results unless the model is run multiple times to give a distribution. Such is planned for the next version.

2. Only typical behavior is modeled: aberrant behavior is not permitted. In future versions, "wrong decisions" may be considered as a function of exposure to narcotic fire gases.

3. Calibration of the parameter values incorporated into the model algorithms is required to quantify their validity.

8.5 TENAB

8.5.1 Purpose

FAST predicts the conditions of the upper and lower layers of each room in a building as a fire, begun in a particular room, progresses. The FORTRAN program EXITT, determines for each occupant of a burning building, the optimal escape route according to knowledge about occupant behavior and building layout. The purpose of TENAB is to estimate the hazard for each occupant according to the room conditions encountered along the escape route. The hazard is assessed by determining the fractional effective doses due to CO_2, CO, HCN, O_2, CO_2, convective heat, temperature, flux, and the integrated concentration-time product. When any one of these hazards exceeds its critical value, the occupant is considered incapacitated or dead.

8.5.2 Theory

The judgment of whether a person is incapacitated or killed by exposure to the fire induced environment is based on the best state-of-the-art of combustion toxicology. The specific equations and the experimental and theoretical considerations used in their derivation are presented in detail in chapter 7. Beyond this, the logic employed to determine the specific exposure of each occupant is given below.

From EXITT, TENAB obtains for each time, the location of each occupant in the building. From FAST, TENAB obtains for each time step the gas concentrations, interface height, temperature, flux and integrated concentration-time product for each layer of each room in the building. At each time interval, (t_{i-1},t_i), TENAB determines for each occupant of the building the current room being occupied and the layer (upper or lower) to which the occupant is exposed. From this information, the average layer (upper or lower as appropriate) temperature of the room, the fractional effective doses, the flux and integrated concentration-time product are computed. If the FED, FEDP, FEDCO2, FEDTEMP, TEMPA, or CT for a particular occupant exceeds the "critical" incapacitation level (which can be supplied by the user), or if the FLUX at time t_i seconds exceeds the corresponding tenability limit then the occupant is considered incapacitated. If the FED, TEMP or CT for a particular occupant exceeds the "critical" lethality level (which can be supplied by the user), then the occupant is considered dead. When an occupant exits the building, reaches a window, becomes incapacitated or dies, the program records the time, the room, the occupant's condition (incapacitated, dead, or alive), the cause (if applicable) and the levels of FED, FEDP, FEDCO2, FEDTEMP, TEMPA, CT, and FLUX. In the case that an occupant reaches a window, he is treated as being at the node from which he came prior to reaching the window, so that the tenability measures will continue to be computed (*i.e.*, assumed not to exit). At the final time (the end of the simulation), the program records for each occupant, the final time, the room occupied at the final time, and the levels of the various tenability measures. The program then prints out the information on each person to a disk file, the screen, or the printer.

8.5.3 Computation of FED, FEDP, FEDCO2, FEDTEMP, TEMP, CT, and FLUX in TENAB

A discussion of the selection of the critical values used and the derivation of the formulation for the tenability measures are contained in Chapter 7 of this **Technical Reference Guide**.

Variable Definitions

$ACCUMCT_k(t_i)$	:	The total integrated-time concentration accumulated by person k by time t_i (g-min/m^3)
$ACCUMFLUX_k(t_i)$	:	The total accumulated flux to which person k has been exposed by time t_i (KW-min/m^2)
$CO(r(k,t_i),t_i,layer)$	:	The amount of carbon monoxide (ppm) in a particular layer of the room occupied by person k at time t_i
$CO2(r(k,t_i),t_i,layer)$	:	The amount of carbon dioxide (vol %) in a particular layer of the room occupied by person k at time t_i
$CT(r(k,t_i),t_i,layer)$	:	The integrated concentration-time product (g-min/m^3) at time t_i in a particular layer of the room occupied by person k at time t_i
Δt_i	:	The length of the time interval (t_{i-1},t_i) (seconds)

$FED_k(t_i)$	:	Total fractional effective dose due to CO_2, CO, HCN and O_2 by the time t_i for person k
$FEDCO2_k(t_i)$	:	Fractional effective dose due to carbon dioxide by time t_i for person k (Purser)
$FEDP_k(t_i)$	:	Total fractional effective dose due to CO_2, CO, HCN and O_2 by time t_i for person k (Purser)
$FEDTEMP_k(t_i)$	:	Total fractional effective dose of convective heat (calculated by a function of temperature) accumulated by person k by time t_i (in °C) (Purser)
$FLUX(r(k,t_i),t_i,layer)$	:	The flux (KW/m^2) in a particular layer of the room occupied by person k at time t_i
$HCN(r(k,t_i),t_i,layer)$	:	The amount of hydrogen cyanide (ppm) in a particular layer of the room occupied by person k at time t_i
$INTERFACE(r(k,t_i),t_i)$	:	The interface height (m) in the room occupied by person k at time t_i
$O_2(r(k,t_i),t_i,layer)$	:	The amount of oxygen (vol %) in a particular layer of the room occupied by person k at time t_i
$r(k,t_i)$	:	The room occupied by person k during the time interval (t_{i-1},t_i)
$TEMP(r(k,t_i),t_i,layer)$	:	The temperature (degrees Centigrade) at time t_i in a particular layer of the room occupied by person k at time t_i
$TEMPA_k(t_i)$	:	The average temperature to which person k is exposed during the time (t_{i-1},t_i).
t_i	:	The i-th time step (seconds)

The following computations are made for occupant k in room R during time (t_{i-1},t_i):

The room layer determination is as follows:

If	$INTERFACE(R,t_i) > 1.5$: person k is exposed to the lower layer
If	$1.0 <= INTERFACE(R,t_i) <= 1.5$ and $(TEMP(R,t_i) >= 50)$: person k is exposed to the lower layer
If	$1.0 <= INTERFACE(R,t_i) <= 1.5$ and $(TEMP(R,t_i) < 50)$: person k is exposed to the upper layer
If	$INTERFACE(R,t_i) < 1.0$: person k is exposed to the upper layer

The fractional effective dose due to gases for person k by time t_i, $FED_k(t_i)$, is determined by four components: carbon monoxide (CO), hydrogen cyanide (HCN), oxygen (O_2), and carbon dioxide (CO_2).

$$FED_k(t_i) = \Sigma_{j=1}^{i} \{FEDCO_k(t_j) + FEDHCN_k(t_j) + FEDO2_k(t_j)\}$$

The effect of CO and CO_2, $FEDCO_k(t_j)$, for person k during the time interval (t_{j-1},t_j) is determined as follows:

If (COAVG = 0): $FEDCO_k(t_j) = 0$
Otherwise:
If HCNAVG > 0: COTH = 1300
If HCNAVG = 0: COTH = 1700
If CO2AVG <= 50000:
DCO = COAVG (80000/(COAVG-COTH)) (1-.00001CO2AVG)
If CO2AVG > 50000:
DCO = COAVG (80000/(COAVG-COTH))(.5)
If DCO < 0 and $\Sigma_{n=1}^{j-1} FEDCO_k(t_n) <= 0$:
$FEDCO_k(t_j) = 0$
If DCO >= 0 or $\Sigma_{n=1}^{j-1} FEDCO_k(t_n) > 0$:
$FEDCO_k(t_j)$ = COAVG (Δt_j/60.)/DCO

where

COAVG = [CO(R, t_{j-1}, layer) + CO(R, t_j, layer)]/2
CO2AVG = [CO2(R, t_{j-1}, layer) + CO2(R, t_j, layer)]10000./2
HCNAVG = [HCN(R, t_{j-1}, layer) + HCN(R, t_j, layer)]/2
COTH = carbon monoxide threshold.

The effect of HCN, $FEDHCN_k(t_j)$, for person k during the time interval (t_{j-1},t_j) is determined as follows:

If HCNAVG = 0: $FEDHCN_k(t_j) = 0$
Otherwise:
$FEDHCN_k(t_j)$ = HCNAVG (Δt_j/60.)/3100.

The effect of O_2, $FEDO2_k(t_i)$, is determined as follows:

$$FEDO2_k(t_j) = \begin{cases} \{ (5.8 - O2AVG)\ (\Delta t_j/60.) \} \ / \ 9.2 & O2AVG < 5.8 \\ 0 & O2AVG \geq 5.8 \end{cases}$$

where

O2AVG = [O2(R, t_{j-1}, layer) + O2(R, t_j, layer)]/2

The fractional effective dose due to gases, $FEDP_k(t_i)$, for person k by time t_i is determined by four components: carbon monoxide (CO), hydrogen cyanide (HCN), oxygen (O_2) and carbon dioxide (CO_2).

$$FEDP_k(t_i) = \Sigma_{j=1}^{i} \{FEDCOP_k(t_j) + FEDHCNP_k(t_j)\} \ \ VCO2P_k(t_j) + FEDO2P_k(t_j).$$

The fractional effective doses due to CO, HCN, and O_2, $FEDCOP_k(t_j)$, $FEDHCNP_k(t_j)$, and $FEDO2_k(t_j)$, for person k during the time interval (t_{j-1},t_j) are determined as follows:

$$FEDCOP_k(t_j) = .00082925 \ COAVG^{1.036} \ (\Delta t_j/60.) \ / \ 30.$$

where

$$COAVG = [CO(R, t_{j-1}, layer) + CO(R, t_j, layer)]/2$$

$$FEDHCNP_k(t_j) = 4.4 \ (\Delta t_j/60.) \ / \ (185 - HCNAVG)$$

where

$$HCNAVG = [HCN(R, t_{j-1}, layer) + HCN(R, t_j, layer)]/2$$

and

$$FEDO2P_k(t_j) = (\Delta t_j/60.) \ exp(-7.98+.528(20.9-O2AVG))$$

where

$$O2AVG = [O2(R, t_{j-1}, layer) + O2(R, t_j, layer)]/2.$$

$VCO2P_k(t_j)$, the multiplication factor for CO_2 induced hyperventilation, for person k during the time interval (t_{j-1},t_j) is given by

$$VCO2P_k(t_j) = exp(.2496 \ CO2AVG + 1.9086)/6.8.$$

where

$$CO2AVG = [CO2(R, t_{j-1}, layer) + CO2(R, t_j, layer)]/2.$$

$FEDCO2P_k(t_i)$, the fractional effective dose due to CO_2 (Purser) for person k during the time interval (t_{i-1},t_i) is given by

$$FEDCO2P_k(t_i) = (\Delta t_i/60.) \ exp(-6.1623+.5189 \ CO2AVG)$$

where

$$CO2AVG = [CO2(R, t_{i-1}, layer) + CO2(R, t_i, layer)]/2.$$

The average temperature during (t_{i-1},t_i) to which person k is exposed, $TEMPA_k(t_i)$, is determined as follows:

$$TEMPA_k(t_i) = [TEMP(R,t_{i-1},layer) + TEMP(R,t_i,layer)]/2.$$

The fractional effective dose due to convective heat for person k by time ti, $FEDTEMP_k(t_i)$, is determined as follows:

$$FEDTEMP_k(t_i) = \Sigma_{j=1}^{i} (\Delta t_j/60.) \exp(-5.1849+.0273\ AVGTEMP_{kj})$$

where

$$AVGTEMP_{kj} = [TEMP(R,t_{j-1},layer) + TEMP(R,t_j,layer)]/2.$$

The accumulated integrated concentration-time for person k by time t_i, $ACCUMCT_k(t_i)$, is determined as follows:

$$ACCUMCT_k(t_i) = ACCUMCT_k(t_{i-1}) + CT(R,t_i,layer) - CT(R,t_{i-1},layer).$$

The accumulated flux for person k by time t_i, $ACCUMFLUX_k(t_i)$, is determined as follows:

$$ACCUMFLUX_k(t_i) = ACCUMFLUX_k(t_{i-1}) + [FLUX(R,t_{i-1},layer) + FLUX(R,t_i,layer)]/2.$$

A person k's state (alive, incapacitated, or dead) at time t_i is determined by comparing the values of $FED_k(t_i)$, $FEDP_k(t_i)$, $FEDCO2_k(t_i)$, $FEDTEMP_k(t_i)$, $TEMPA_k(t_i)$, $ACCUMCT_k(t_i)$ and $ACCUMFLUX_k(t_i)$ with corresponding incapacitation critical levels or $FED_k(t_i)$, $TEMPA_k(t_i)$, or $ACCUMCT_k(t_i)$ with corresponding critical lethality levels. The incapacitation and lethality critical levels and the Derksen curve are discussed in the tenability limits section of this **Technical Reference Guide.** When a person exceeds any critical level for the first time the program records all the pertinent information for that person at time t_i.

8.5.4 Limitations

To assess the impact of fire on humans, it is essential to be able to assign such tenability limits to fire generated conditions. It will be assumed here that tenability limits correspond to the best available human or animal data on complete, acute incapacitation of otherwise healthy victims. The lack of adequate data on sub-lethal incapacitation effects make such benchmarks into upper limits, instead of best-estimates. Ideally, these limits would specify precisely at what point of fire development escape is no longer considered feasible. In practice, the response of different individuals to various fire threats is diverse. Specifically, fire atmospheres survivable by the healthy individual can be lethal to the sick or impaired. Furthermore, the individual with, say, a cardiac or respiratory impairment can be overcome by a fire condition which is only very slightly different from ambient. Thus, if the target population to be protected were seriously impaired individuals, no fire at all could be tolerated. Such a design philosophy is rather specialized and will not be considered in this report.

For most hazard calculations, it can be assumed that the individual at risk is a "healthy" individual. Even this, of course, is an indistinct concept, since endurance limits for healthy individuals are not identical for various threats. In most cases, only animal data are available. Thus, the assumption is made that the response of the healthy individual can be represented by a well-chosen animal model. Also, there is almost no information on the sub-lethal response of humans, or, indeed, of animals, to fire situations. In many instances it would be more appropriate to ask not if the fire atmosphere is, by itself, lethal, but, rather, if it is sufficient to introduce confusion, narcosis, or such strong irritancy that the individual will no longer act to rescue himself. Currently, the University of Pittsburgh is considering studies of the sub-lethal effects of carbon monoxide (CO) [10]; but they have not yet resulted in conclusions on appropriate limits for such exposures.

8.6 References

[1] Tewarson, A. Quantification of fire properties of fuels and interaction with fire environments. Natl. Bur. Stand. (U.S.) NBS GCR 82-395; 1982 June. 37p.

[2] Tewarson, A.; Steciak, J. Fire ventilation. Natl. Bur. Stand. (U.S.) NBS GCR 83-423; 1983 February. 29p.

[3] Beyler, C. L. Major species production by solid fuels in a two-layer compartment fire environment. Pagni, P. J.; Grant, C. E., ed. Proc. of the First Intl. Symp. on Fire Safety Science. New York: Hemisphere Publishing Corp.; 1986. 431-440.

[4] Alpert, R. L. Calculation of response time of ceiling mounted fire detectors. Fire Technology, 8(3): 181-195; 1972 August.

[5] Alpert, R. L. Turbulent ceiling jet induced by large-scale fires. Combustion Science and Technology, 11: 197; 1975.

[6] Evans, D. D.; Madrzykowski, D. Characterizing the thermal response of fusible-link sprinklers. Natl. Bur. Stand. (U.S.) NBSIR 81-2329; 1981 August. 39p.

[7] Evans, D. D.; Stroup, D. W. Methods to calculate the response time of heat and smoke detectors installed below large unobstructed ceilings. Natl. Bur. Stand. (U.S.) NBSIR 85-3167; 1985 July. 49p.

[8] Klote, J. H. A computer model of smoke movement by air conditioning systems (SMACS). Natl. Bur. Stand. (U.S.) NBSIR 87-3657; 1987 November. 24p.

[9] Jones, W. W.; Peacock, R. D. Technical reference guide for FAST version 18. Natl. Inst. Stand. Technol. Tech. Note 1262; 1989 May. 126 p.

[10] Malek, D. E.; Alarie, Y. Performance evaluation under intoxicating atmospheres. Fundemental and Applied Toxicology 8: 335-345; 1987.

CHAPTER 9. CONCLUDING REMARKS

HAZARD I is a prototype of a general purpose fire hazard assessment method. The scope of this prototype, its data base and the example cases are focussed on single family residential occupancies. Based on the perceptions of and feedback from users of this product, and continued support for planned research, expanded and improved versions of this system will be released. Expansions and improvements will include increased applicability of the current procedure, improved usability, the ability to address additional building features, and more accurate treatment of the fire itself and the effects of the fire on people and their actions.

The scope of applicability of the system can be extended to additional occupancies through expansion of the database and example cases. The next occupancies to be considered will probably be hotel/motel and health care.

Improved usability will be guided by input from users, but will most likely include additions that would provide a CAD interface for entering and manipulating building components, and direct compatibility to AUTOCAD files. All database files would be accessed directly in a manner similar to that implemented for the thermal properties data. This would allow selecting contents items from a list, and having the burning rate properties read automatically.

Additional building features that need to be addressed to extend the method to larger buildings include vents in floors and ceilings and HVAC systems. In a fire, a building's HVAC system may distribute fire products to some parts of the building faster than the fire would alone. A model of the HVAC system will be developed and probably linked to or incorporated in the smoke transport model.

The accuracy of the current procedure is limited by the fire being uninfluenced by radiation from its surroundings, and by our inability to quantify accurately the effects of fire on people and their actions. Research is underway to better understand radiation enhanced burning under post flashover conditions, and predict fire growth and spread, fuel mass loss rate and combustion product generation rates under those conditions. More research is also needed to better understand the effects of fire on humans and their actions during the fire incident.

The ability to provide these and other improvements to the hazard assessment technology will depend on the reception and support given to this first effort. User feedback is crucial to the process of identifying the most needed changes and we encourage such from all interested parties. Through this process, research priorities can be established to address the needs of the community in the most efficient manner. In addition, we challenge the research community to review and comment on this effort. The gaps in knowledge identified herein can then help guide their work toward resolving these issues.

APPENDIX A. HAZARD I - RESULTS OF A USER EVALUATION OF THE PROTOTYPE SOFTWARE

HAZARD I - Results of a User Evaluation of the Prototype Software

Richard W. Bukowski, P.E., Head
Fire Hazard Analysis
Center for Fire Research

Abstract

After five years of development, the prototype of a personal computer based, fire hazard analysis method was distributed to 93 volunteers representing all aspects of the fire community. These persons agreed to evaluate the software and documentation, and attempt to apply it to a problem of their own choosing. Written comments were to be returned, which would be used to establish priorities for future changes, and where possible, be incorporated into the general release version of the product.

Written responses were received from 47 participants, most of which dealt with suggestions for improvements to the user interface (rather than any technical shortcomings). Based on the responses received, it has been concluded that: the software will be of substantial, broad benefit; with the identified improvements, the user interface is comparable to commercial software in ease of use; the data base is particularly useful, but needs to contain many more entries; and priority enhancements need to be made in the areas of combustion modeling and pictorial graphics.

Key Words: computer models; computer programs; evaluation; fire models; hazard models

1. Background

In July of 1983, the Center for Fire Research (CFR) made the commitment to produce a practical fire hazard assessment method within 3 to 5 years. In July of 1987, the first embodiment of this method, called HAZARD I, was approved for release to and evaluation by a limited group representing all facets of the eventual user community.

The organized evaluation by users of computer software is such a common practice that it has a name - beta testing. Specifically, the alpha test version of software is that evaluated within the developing organization, but by persons not directly involved in its creation. The beta test version is then made available (often sold at a price significantly below the introductory retail price) to users. Beta testers are encouraged to report problems and provide comments on the software so that the release version is both free of "bugs," and meets the expectations of the user audience. Often, beta testers are provided a copy of the final release version of the software at reduced price (or free).

The details of the beta test plan for HAZARD I were developed to provide information on the expectations of the fire community with respect to the design and implementation of such software in order to:

- assure that their experience with hazard analysis software is not so negative as to adversely impact people's willingness to use it,

- identify the degree to which the package meets the needs of the range of potential users,

- document the expectations of the fire community as to the level of "user friendliness" in the software and documentation, and

- identify the level of thoroughness required in the science for the applications of interest to our constituency.

Since the fire community is made up of a number of disciplines each of which might have different needs and requirements, the test program was designed to encourage a relatively balanced representation from each. Also, since CFR staff have little experience in most of these areas, surveys or other forced responses which might inhibit users from freely reacting to their experience were avoided. Thus the general philosophy was to treat each participant like the purchaser of a commercial software package and deal with their complaints and comments as they wish to make them.

2. Goals of the Beta Test

The beta test was intended to provide feedback on:

- Usefulness
- User friendliness
- Application-specific improvements/modifications
- Hardware compatibility
- Level of interest

As was discussed above, the process was intended to provide specific feedback on the HAZARD I package, and general guidance on the needs and expectations of the fire community for analytical software. Information on the computer skill level of the "typical" user, equipment available to them, appropriate technical level for the software and documentation, and the degree to which judgment can be assumed, all were to be explored.

From the comments and suggestions received, priorities for improvements have been assigned. In addition, several issues of concern with the package were identified by CFR staff during its development and review. There was a desire to determine if the points which bother us also cause concern to our "customers." With regard to these specific issues, if no specific responses were received, they could be explored by personal contact with one or more users who would be knowledgeable in that area. Likewise, comments or complaints that we did not expect or which show very strong feelings were followed up by telephone.

Another important topic to be addressed was that of hardware compatibility - not only with foreign hardware, but also with systems such as UNIX computers which run DOS as a task. We need to know if there are common system configurations which are incompatible with the way in which the package is installed (e.g., the use of external drives for system and user software).

A final aspect to the process is the need to assess the level of interest by the fire community in a hazard analysis method which can be used to assist them in their work. To give verbal support to such a concept is easy. To be willing to invest time in self-learning one demonstrates a real commitment to it. If there is insufficient commitment, the required investment may be considered too large and require a change to our research priorities. But if the commitment is high, we can expect that a viable method will be incorporated into the fabric of fire protection practice almost as fast as we can deliver it.

One issue which the beta test was not designed to address is accuracy assessment. While we certainly expected to hear about any cases where the models gave unusual results, the fact that they did or did not is not proof of accuracy or a lack thereof. Such assessments can only be made through a statistically-designed program of validation studies.

3. Selecting Participants

Participants were secured by invitations, sent initially to persons selected from various CFR mailing lists, and later from inquiries received in response to a press release or to recommendations from other participants. The package of material provided with the invitation letter included a description of the software capabilities, assumptions, and limitations; and the "Getting Started" booklet. This booklet is a verbatim copy of the use of the software on an example problem, intended to show clearly the amount of work involved in a case. In addition, the letter estimated the need for about 40 hours of self-study before the user is prepared to work a case of his or her own. The primary intent of all this was to make sure that all participants understood the extent of their commitment.

Respondents were asked to classify their interests into one or more of eight user categories which were used to insure a relatively even representation. In responding to unsolicited inquiries, the choice of sending only an information package or a package and invitation to participate was used to effect this control. One category (fire protection engineering) had to be closed to additional participation due to too many respondents. In general, there was a limit of one package per company or organization; although users were free to copy the software and documentation, and several did.

A total of 217 invitation packages were sent out, resulting in 93 registered beta test participants. The representation by application area is as presented below (each organization selected multiple application areas). Several of the participating organizations with multiple offices distributed copies to each office, but counted as only one participant. In addition, a few copies of the software were provided to organizations who were not official participants and from whom a response was not required.

Of the 93 registered participants, 72 were within the United States, and the remainder distributed as follows: Canada (1), England (2), Sweden (3), Australia (3), New Zealand (1), Norway (1), Germany (3), Spain (1), and Japan (6). In each category, the organizational sizes varied from one person businesses to large, multiple office operations.

The eight user categories along with their final distribution of participants were:

Fire investigation/reconstruction - 37
Fire Protection engineering (design or analysis) - 37
Architectural design - 15
Code administration/enforcement - 24
Product development/manufacture/marketing - 18
Fire services - 14
Fire research/testing - 37
Public fire safety education - 14

4. Requirements for Participation

Each recipient was required to respond in writing in order to participate in the program. This response was to include:

- the name, address, and telephone number of the person actually working with the software, so that we could maintain direct contact through a series of newsletters and by telephone;
- a detailed description of the computer hardware on which the software was installed, to document any hardware compatibility problems;

- the commitment to learn the system and then apply it to a problem of their choosing, which they hope the software would properly address; and

- respond in writing with observations, comments, and suggestions on their successes or failures.

In some cases, participants commented on the problems which they planned to tackle with the system. Examples of these excerpted from their acceptance letters include:

- A **producer** of a fire-resistant product is comparing the performance of his product to the traditional alternative to demonstrate the benefits of its additional cost, and another is developing specifications for new products.

- A **code official** is evaluating the impact of a proposed code change for use as supporting data in his presentation to the legislative body.

- A **fire investigator** is testing the ability to reconstruct a residential fire incident by predicting in advance the result of a test in which an abandoned house will be burned.

- One **fire department** is evaluating proposals for alternative means of compliance with the code, another for firefighter training, and a third for educating the public on the benefits of residential detectors and sprinklers.

- A **government agency** is evaluating emergency evacuation procedures for fires in underground mines.

- A **university** is using the package in conjunction with a course on fire dynamics and predictive methods.

- A **fire researcher** is evaluating fire safety on large ferry boats, and another on offshore oil platforms; both are in conjunction with projects which include small- and large-scale testing.

- Several **consultants** are conducting analyses for use in civil and criminal litigations. Topics include the relative contribution of one burning item to the overall outcome, the potential impact of a detector which was not present or not operating, and in supporting a finding of arson.

- A **testing laboratory** is reducing the number of tests of varying geometric arrangements by using the models to reproduce the tested configuration and then predict others.

5. Results

5.1 Participant Response

As of the date of this writing, 47 participants have provided written comments on their thoughts and experiences. This represents a response rate of 50%. These collected thoughts are summarized in the following sections.

5.2 Hardware Compatibility

In their original acceptance letter, each participant provided details of the computer on which the software was operated, allowing us to verify the compatibility of the software with a broad range of computers, and to assist in troubleshooting user problems. A number of the larger users identified multiple machines on which the software would be installed.

The user hardware represented the equipment of 27 manufacturers, including U.S., Japanese, and European origin. The distribution of processor types was: 54 (8088), 35 (80286), and 6 (80386) machines. All three of the supported graphics systems (CGA, EGA, and Hercules) were represented by a myriad of card and monitor suppliers.

Hardware incompatibilities were surprisingly few. Two users of AT&T machines obtained a peculiar run-time error message while the software was trying to write to the screen. The associated error code is described by the compiler producer as of unknown origin, and is obtained during input or output operations on some hardware (it was reported only by these two AT&T users). They go on to say that not only do they not know what causes it, but they have no intention of fixing it.

A problem with Japanese machines is related to their typical 5 1/4 in floppy drives being 650 kB density, so they cannot read our 360 kB disks. This drove most users in Japan to buy a U.S. made computer or at least install a U.S. drive. Late in the program, one U.S. user bought a PS/2 machine which had only a 3 1/2 in drive and found that he could not transfer the software to it. We supplied him with a copy on 3 1/2 in format which he installed with no problem.

5.3 Software Compatibility

There were two reported problems related to "bugs" in DOS 2.X. The first involved the batch file (HAZARD.BAT) which calls the programs from the main menu. The batch file branches to a labeled line in response to the keyboard input. The number of characters in the labels varied, which is allowed in DOS 2.X as long as the first eight characters are unique. In fact what DOS 2.X does is to truncate the label at eight characters, resulting in a mismatch and a "label not found" error for any label longer than eight characters. This "bug" does not appear in DOS 3.X, so it was not found earlier. The fix was simply to shorten the labels in the batch file to no more than eight characters. This could be done easily by the user, or we supplied a corrected file that could be downloaded from the CFR bulletin board (CFRBBS).

The second DOS 2.X "bug" was more subtle. Users would randomly get the error message "File Allocation Table Bad on Drive *", requiring a re-boot of the system. We do not know what causes it, but it has never appeared on a system running DOS 3.X. One user who was having this problem consistently solved it by upgrading his DOS version.

An incompatibility about which we warned users from the start is the fact that the graphics drivers that we supply are not compatible with ANSI.SYS - a utility supplied with DOS to allow custom configuration of your screen (to display information like time, date, directory, etc. at any location). There were a few problems associated with users initially not seeing the instruction to remove the call to ANSI.SYS from their CONFIG.SYS file before trying to use the HAZARD I graphics. A reminder in the first newsletter took care of most of these problems.

While we supplied printer drivers for the CGA and Hercules graphics, we did not supply one for the EGA since it operates in color, requiring significantly more coding to map the colors to patterns for output to a monochrome device. Instead, we recommended a commercial printer interface software package such as PIZZAZ, which is inexpensive and does this for you. When triggered, PIZZAZ pauses the task while it transfers the screen image to the printer. The problem is that after the copy is made, PIZZAZ fails to resume the task and the computer must be re-booted.

There was also a problem noted with the CGA printer driver. While the CGA graphics driver properly displays the graph in monochrome on the screen, the printer driver alternates the curves between the foreground and background colors. This results in the curves 2, 4, 6, and 8 disappearing on the printer output. While this might seem to be an easy fix, it was not; so we chose to address this and several other problems with a single change which will be discussed later.

A minor problem was encountered with BASIC. The batch file calls BASICA (the IBM version), but many clones use BASIC, GWBASIC, or even N88BASIC (on a NEC machine in Japan). This required a simple correction to the batch file. Once this change was made, only N88BASIC had problems running the three BASIC programs provided in HAZARD I.

There were no reports of conflicts with any resident programs, even though the graphics driver is resident - such conflicts usually involve two programs vying for the same computer resources. Since this is a fairly common problem with resident software, we were surprised that such did not occur.

5.4 User Compatibility

This addresses the degree to which the users were able to cope with the software and supporting documentation. This is where the majority of the problems were encountered.

If there is one thing we have learned from the beta test, it is that we must make the installation and set-up of the software as automatic as possible. There are a number of users who run applications software on their computer with "(little or) no working knowledge of DOS or the PC itself," as one respondent pointed out. This created problems such as when BASIC was not on the machine or the PATH was not defined such that it could be found. Likewise, several users had trouble with the question about what graphics board was present in their machine. Several participants wrote that they did not understand directories and default drives - even though these were handled automatically.

Based on these observations, the use of a carefully-written installation routine is crucial to the success of a software product for general use. With HAZARD I, we were assured that all of the software was installed in a uniform manner, making troubleshooting easier when people called with problems. All of the needed files were sure to be copied to the correct place, and properly named. The remaining problems generally involved the incorrect selection of the graphics system or errors in the path name to DBASE.

What was somewhat surprising was the large assortment of disk storage arrangements found to be in use. Many systems are shared among staff who have their own removable platter for an external drive. Common use software is then on an internal drive or second external platter (the latter being non-bootable). This means that the software needed to run the program can be scattered over multiple drives, leading to complex path statements. This also means that the install program must allow full freedom of drive and file path for the source and target drives, and system files.

To minimize these problems, the software should be made independent of files in other directories. This means that everything needs to be compiled. Compiling all BASIC modules will also correct problems associated with variations in BASIC interpreters and even the name of the interpreter (e.g., BASICA vs GWBASIC vs N88BASIC in Japan). By compiling the DBASE program files we can also eliminate the need to access the DBASE interpreter. The plan for HAZARD II is to create our own data base without a proprietary database software system.

Several users requested an "escape button" to stop a run at any time from any module, and return to DOS. We simply need to point out that such exists in DOS (Ctrl C). Others commented on the need for overall consistency in the way in which data is input. Two examples are (1) with all but some inputs in FIREDATA, a <RETURN> is required after any response and (2) the default entry for (Y or N?) responses vary. In the latter case, this was done intentionally so that the default is the normally-expected response to that question.

Also noted was that "bootleg" copies often did not work because they were COPY 'd rather than DISKCOPY 'd - which did not copy the LABEL used by INSTALL to verify the correct disk.

6. Specific Programs, Comments and Fixes

In the following sections, detailed user comments on each of the programs in HAZARD I will be discussed, along with a description of the changes which have been made to the general release version (referred to as HAZARD I v1.0) to address these problems. A block diagram of HAZARD I is presented in figure 1.

6.1 PRODUCT.ONE

The only complaint was that many users did not understand the purpose of this module. Most ignored it; it could be eliminated if desired.

6.2 FIREDATA

The main complaints were that the database should be connected to the input program so that data could be transferred automatically, and that it needs to contain much more data. The first will be done with thermophysical data in the new input program (FAST_IN) to be a part of HAZARD I v1.0. All database files will be directly integrated in HAZARD II, without the use of any proprietary software. Several positive comments were received on the advantages of having an organized fire database in which the user's data could be incorporated as well. One person (not a participant in the beta test) requested a copy of FIREDATA only as a way to store his own data.

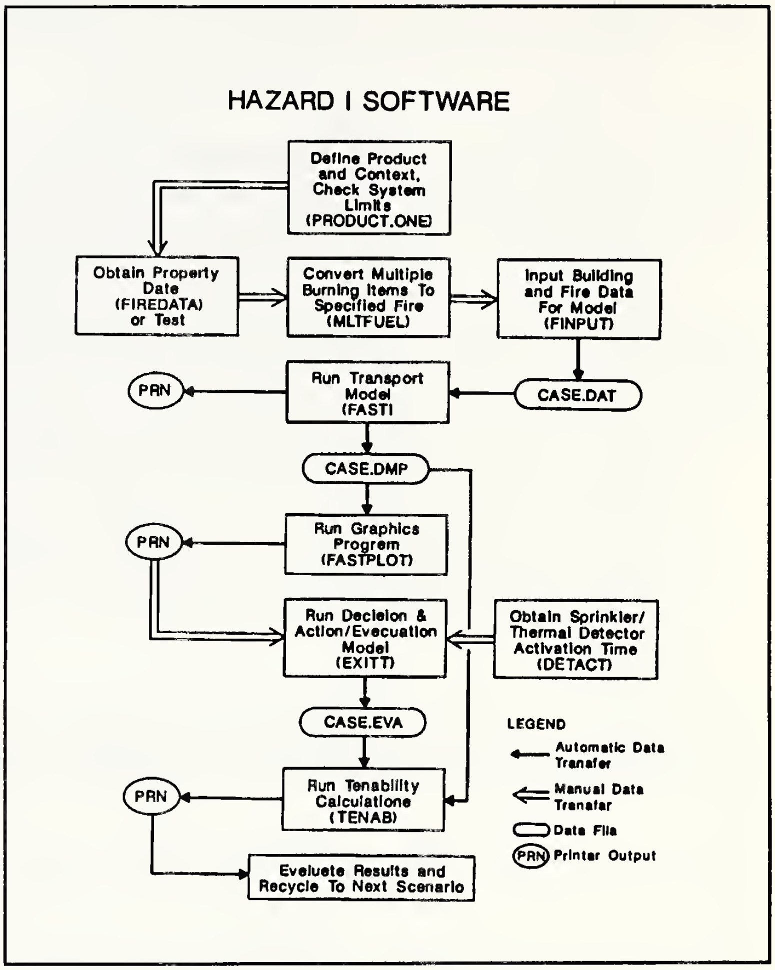


Figure 1.

6.3 MLTFUEL

The few comments received on this module centered on the suggestion that it incorporate spread from item to item and the establishment of the time line now done manually. It should then be integrated into the input program. Both will be done for HAZARD I v1.0.

6.4 FINPUT

A few "bugs" were identified and have already been fixed. Other comments received addressed the scrolling display and help text which sometimes caused confusion. The total replacement of FINPUT by FAST_in will resolve all of these comments and then some. File lists will be supported, and even the "quick analysis" mode should help address complaints on the slowness of FAST.

Positive comments were made concerning the error checking and units conversion features. These make the program much more "friendly", and avoid simple errors. The capability to change units sometimes results in the user forgetting what the current units are. FAST_in will always display the current units, avoiding this trap.

One comment was received on the prohibition of overwriting an existing file. This was done intentionally, to prevent an inadvertent loss of a file; but this user would like to replace a corrected file without going back to DOS for a delete and rename. We will go to a "replace existing file (Y/N) ?" message in FAST_in.

6.5 FAST

Since FAST is run in a batch mode, there is not much to say about the software interface. Comments were limited to: "too slow," "how do I know that it is still running?," and "how do I stop it?."

There is little that we can do about the execution speed. Frequent users can invest in faster hardware - a PS/2 Model 80 will run FAST 25 times faster than an XT. We have implemented a "quick analysis" mode within FAST_in which gives lower accuracy but much faster results for the impatient.

For those who want reassurance that FAST is running, and in fact how far it has progressed and when it may finish, HAZARD I v1.0 will support run-time graphics. This will allow the user to select a few, key variables and watch them evolve. This will also show when the desired results are not being obtained so that the user can choose to abort the run.

6.6 FASTPLOT

The primary problems reported were associated with it not producing plots at all (they loaded the wrong graphics driver in INSTALL) and difficulties in obtaining printer copies of the plots as was discussed in section 5.3. Both problems have been corrected in HAZARD I v1.0 by the change to a universal graphics and printer driver from a commercial vendor. This single driver supports CGA, EGA, Hercules, and VGA; is not memory-resident, and will not conflict with ANSI.SYS. Thus this one change solves a range of problems.

Other minor comments about the gap in the curves for their label always appearing in the most important part of the curve and the labels themselves (variable number rather than room/layer) have been corrected in HAZARD I v1.0. The gap has been removed and provision made for eight line patterns (that correspond with the eight colors in EGA) and a legend window that identifies room and layer.

Other improvements such as:

- autoscaling,
- X and Y offset by a constant,
- clearer variable naming,
- more appropriate units for species,
- the ability to input and display variables from multiple files, and
- provisions to allow plotting of tenability data

have been implemented to make the program much more useful. Requests to provide the ability to create ASCII files in a format compatible with other graphics programs (LOTUS, CHART, etc.) and support for HP plotters have also been implemented, the latter through an HPGL file format option.

It is interesting to note that several users commented on the low resolution of the plots in CGA mode. Of course, this is totally hardware-controlled and not within our ability to change; although the ASCII interface to LOTUS or CHART allows output to a pen-plotter.

6.7 DETACT

From the general lack of comment on this program we surmise that few people used it. In HAZARD II the plan is to integrate it within FAST.

6.8 EXITT

Comments included:

- too many questions in the beginning,
- use of numbers for both the nodes and for the people is confusing,
- the process to enter your own building is tedious,
- node location is arbitrary and will result in variations in escape times,
- manual entry of smoke data should be replaced by transfer from a file, and
- some behaviors did not make sense (e.g., if a family has more young children than adults, some get left in the house even though there is enough time to rescue).

To address these points, a number of changes have been made:

- Initial questions have been reduced,
- to avoid confusion letters are now used to represent people and numbers for nodes, and
- many inconsistent behaviors have been identified and corrected.

When EXITT is compiled, we will add the ability to transfer the required smoke data directly from the FAST dump file. Unfortunately, it is not feasible to make improvements on the method of entering a new building and establishing the node map, although these data will be read from a file. Full graphic input will have to await the Computer Aided Design (CAD) type interface planned for HAZARD II or III.

6.9 TENAB

There were no negative comments about TENAB. On the positive side, comments included: straightforward, easy to use, and good data presentation. For HAZARD I v1.0 we will include a second calculation of Fractional Effective Dose (FED) using a refined model for incapacitation. We will also update the original to include reduced oxygen effects.

To enhance the presentation of output, TENAB will be modified to produce an output file compatible with FASTPLOT. This will allow plots to be made of the tenability parameters against time, for each occupant.

7. User Needs

Based on the comments received and numerous discussions with participants, an opinion was formed of the needs and desires of the user community with respect to fire hazard analysis software in general. These identified issues will be used to help shape future versions of HAZARD and other software products under development.

7.1 Breadth (flexibility)

Clearly the greatest desire among users is for the ability to address a broad range of problems and situations. The most frequently heard comment started out "It's really great, but I wish it could ... ." Examples from the user wish list include:

- spreading the fire from item to item,
- spreading the fire from room to room,
- burn through of a partition,
- wall burning,
- transport and evaluation of the toxic effect of species related to the product in which they are interested e.g., $HC\ell$, HBr, TDI, etc,
- enhanced burning due to radiation feedback to the fuel surface,
- ventilation controlled burning,
- forced convection,
- additional occupancies (especially industrial),
- high-rise buildings,
- suppression by sprinkler systems,
- vertical openings,
- long corridors,
- more data in the database on ... (fill in your product),

It is not that every user wishes the method to address all of these items, but rather that each user has specific applications in which one of these are involved. It is also important to understand that the users are asking for the models to address these phenomena, without giving specific thought to the technical level at which they should be included. This is a factor which was explored further with the users and is discussed in section 7.4.

7.2 Ease of Use

The second most important factor for users is the ease with which the system can be used for their analyses. This refers to more than just the "user friendliness" of the software. It includes the usefulness of the documentation in answering their questions (and how easy it is to find something), consistency in the commands employed for a given purpose, compatibility with other software systems (e.g., CAD or spreadsheets), and the ability to display results in a presentation quality.

Some of these issues can be a two-edged sword. For example, documentation which is thorough enough for a fire researcher can be too voluminous for a user doing public fire safety education. Likewise, building in flexibility to interface with other software can result in too many choices among which the users must decide. Finally, there is a competition for resources between improvements in the science-related aspects and those which are purely computer programming. Each of these competing forces must be considered in the development of a package for use on a broad range of problems.

7.3 Execution Time

Many users expressed frustration in the amount of time needed to do an analysis. Part of this frustration comes from the large quantity of information needed to "feed" all of the programs. But these data needs are at least partly related to the large number of phenomena included, and will increase as the wish list in section 7.1 is implemented. One potential answer is the development of versions of HAZARD which are customized for specific applications. The first such package is currently under development in cooperation with the Consumer Product Safety Commission (CPSC).

The other part of the frustration comes from the long execution time required by FAST. The most efficient approach to shortening this time is for the user to buy a faster computer - the range in speed for current PC hardware is a factor of 25! We also feel that a part of the frustration is that the user must stare at a blinking cursor for many hours while FAST is running, wondering if it has crashed, or what may be happening. The run-time graphics with HAZARD I v1.0 will at least relieve this.

7.4 Technical Depth

One of the key findings of this evaluation is that the majority of users are relatively unconcerned with the technical depth of the models and calculational procedures included in HAZARD I. This is borne out by discussions with users and the fact that only two respondents raised issues related to the underlying science.

There are two explanations for this attitude among the user group. First, for most applications any answer that does not defy reason is an improvement to the status quo (expert judgment); and second, most trust that a scientific method produced by CFR will be at least technically credible, if not the best that can be done. The latter was probably more of a factor among the beta testers than might be expected from the universe of potential users since the participants are mostly persons with whom we have had prior professional interactions. But in general, users trying to answer a question would rather have an educated guess (so labeled) than to be told that it is beyond the scope of the method.

Another possible factor, although not expressed as such, is the tendency of people to accept computer output without question ("Garbage in; gospel out!"). This syndrome could have been exacerbated by the fact that most users did not find the time to exercise the software to the extent originally planned, so they probably did not have the time to examine the underlying science in detail.

8. Applications

In section 4, a list of applications proposed in, and excerpted from, letters of acceptance sent by beta test participants is presented. Unfortunately, as of the date of this writing, only one user application has been documented in writing to us. This is a reconstruction of a full-scale fire experiment conducted in 1982 in which an upholstered chair was burned in the living room of a residential house. The only available details of the building dimensions and construction, and of the materials used in the chair and other combustibles in the room were those included in the published report.

For the first model run, items (drapes and a chair) which appeared to be similar to those described in the experimental report were selected from FIREDATA and used to model the fire. The ignition of the drapes by the burning chair was modeled using the procedure provided in the HAZARD I documentation. Examination of the results as shown in figure 2 revealed that the agreement was of the same order of magnitude, but appeared to be shifted in time.

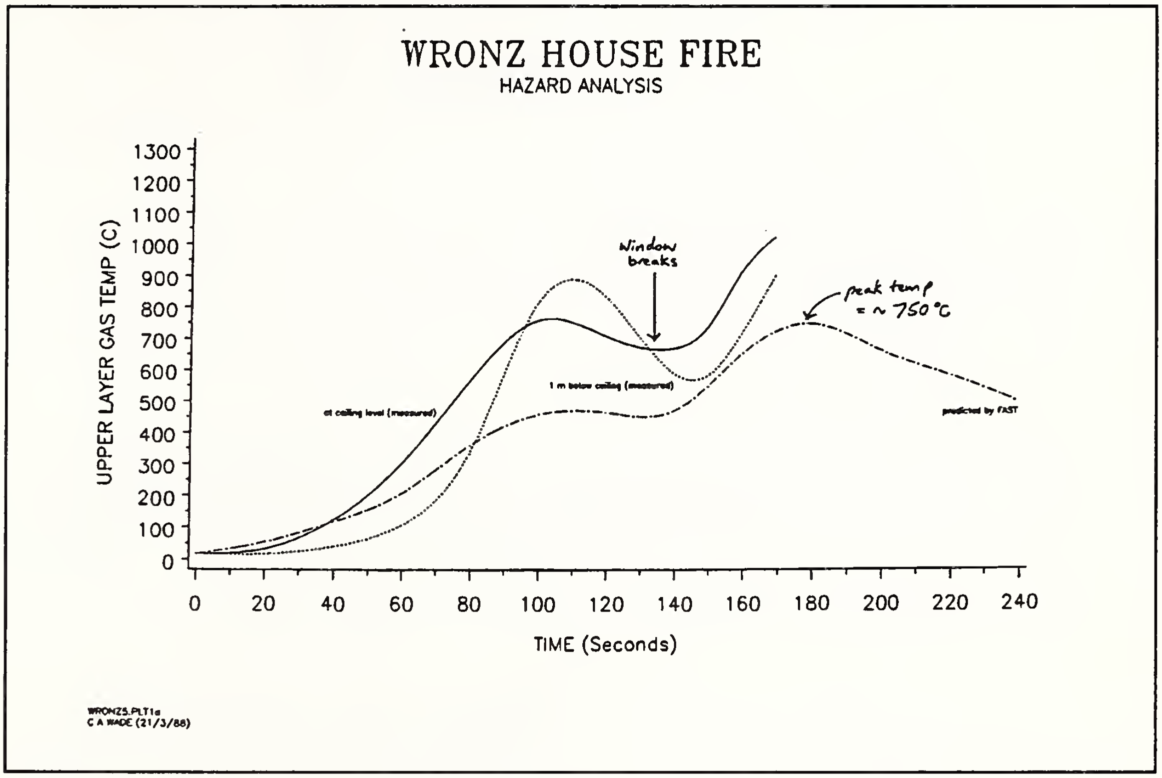


Figure 2.

A comparison (figure 3) was then made between the rate of heat release of the items obtained from the HAZARD I database, and that estimated from the observations published in the test report. This showed that the burning rate of the fuel in the experiment was faster than for the database items selected.

After an adjustment in the assumed burning rate based on the comparison in figure 3, a second FAST run was made. This resulted in an excellent match between the measured temperature near the ceiling and the upper layer temperature predicted by the model (as shown in fig. 4), up to the time at which a window broke in the experiment. (Modeling of a vent opening during the run is a feature which could not be addressed in the beta test version, but will be included in the HAZARD I v1.0 release.)

It should be stated that, although the results obtained by this user were excellent, such results may not be reflective of an inherent accuracy in the models or software but may be the result of errors which cancelled in this particular analysis. The quantitative accuracy of these methods are the subject of ongoing study, which will be published as the work progresses.

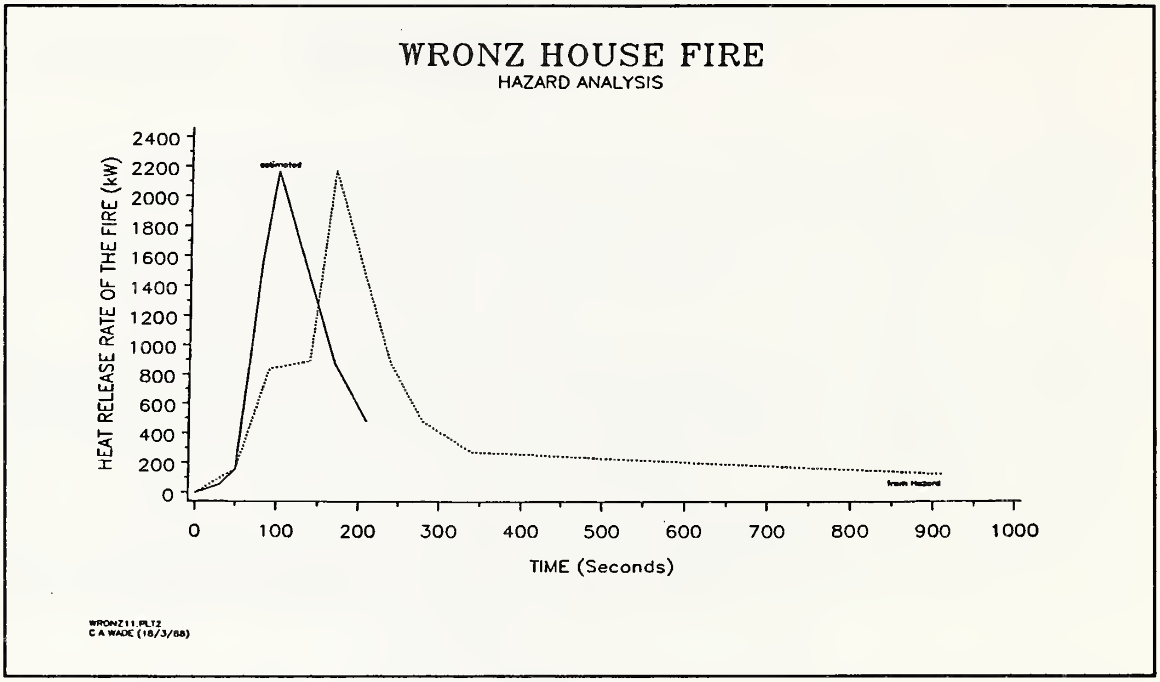


Figure 3.

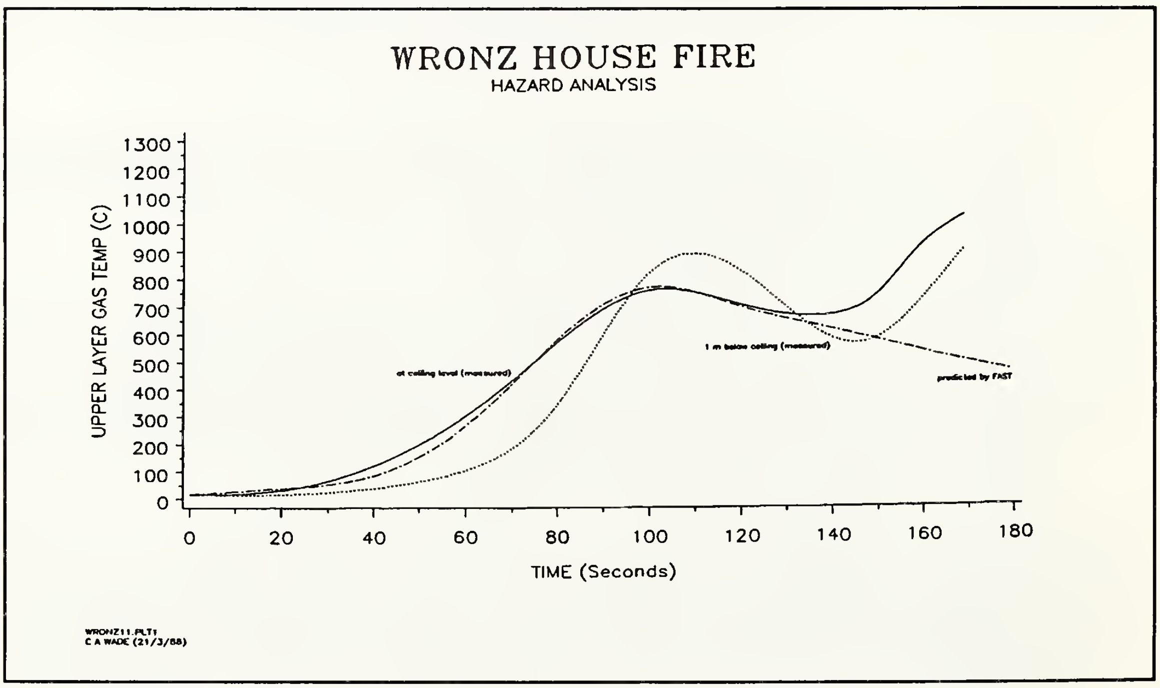


Figure 4.

9. Conclusions

The overall reaction of the program participants was highly positive. Most participants commented that the software would provide a valuable tool in their area(s) of interest. Most respondents made suggestions which they felt would improve the ability of the software to meet their needs; with most of these in the general category of user interface issues (rather than science issues).

There was a general consensus that the database was very useful. (One person outside of the beta test program requested a copy of the database by itself as a means of storing and retrieving his own data.) Most, however, expressed the need for a significant expansion of the list of burning items. One manufacturer's association is contracting with a testing laboratory to conduct Furniture Calorimeter tests on a range of products representative of those currently being marketed by their membership, to support their own use of HAZARD I.

Several of the respondents expressed a strong desire for the pictorial graphics capabilities which we have demonstrated in the past, but are not a part of the current implementation. This was particularly the case in applications where results are presented to persons outside of the fire community; such as for marketing presentations or for public fire safety education. We hope to be able to deliver this capability with HAZARD II.

Perhaps the biggest success of the evaluation program was the fact that we were able to address almost all of the participant comments with changes to the software. Thus, the time and effort invested by the users will be rewarded in the release version, along with some technical improvements that will greatly enhance the capabilities of the software package. These include the influence of reduced oxygen levels on the combustion and the ability to open and/or close interior or exterior openings at will.

The greatest disappointment of the program was the failure of the respondents to conduct and/or document the applications to which they committed. While their intentions were good, the press of business prevented most from completing this important task. To fill this remaining gap, we intend to conduct and publish a series of applications (as our funding permits) using the release version, and to encourage users of the release version to share their results (perhaps by holding a HAZARD I user's conference).

In summary, the beta test program has provided us with considerable insight into the needs and desires of the fire community for the software implementation of predictive tools. The lessons learned in this program will have a long lasting impact on the work of CFR and other organizations involved in the development of these tools, and on the degree to which they become integrated into the application of fire protection principles in the future.

APPENDIX A

SELECTED EXCERPTS FROM PARTICIPANT RESPONSES

Each indented paragraph is a direct quote from a participant response letter. The statement following is a comment on the change implemented in the release version of HAZARD I to respond to that point.

> **"I believe that the concept of bringing together past and current research done by your organization and others in this very useful way is a good one."**

We agree! A hazard assessment must integrate all facets of fire research into a single analytical tool. HAZARD I represents the first time that the complete package has been so assembled.

> **"Your recommendations suggest that the next release of HAZARD I will require DOS 3.0 or higher. I would suggest that you make this clear in the next release, as many users not only have no working knowledge of DOS or their PC, but will not know what version of DOS they are running."**

Several "bugs" in the beta test were traced to problems in DOS 2, and which were corrected by upgrading to (or never showed up with) DOS 3. Since DOS is less than $100, this should not be a hardship.

> **"HAZARD I appears to be an extremely good tool for assisting us in evaluating whether or not our analysis of a fire occurrence is correct, feasible and supportable."**

This points out that in fire reconstruction, the theories will likely be posited by the investigators, and then tested using HAZARD I. It is a way of obtaining a corroboration without having to hire a second expert.

"We are delighted with HAZARD I and feel that a hearty pat on the back and thanks should go to all involved in its conception and writing. You have created a landmark in the annals of fire safety!"

Thank you!

"It should always be clear to the user when a decimal point is required. Use 'Don't forget the decimal point' in appropriate places."

This refers to the fact that computers demand a decimal point for the entry of a "real number", even if it is a whole number. The input program (FINPUT) and the new user interface program (FAST_in) take care of this for you. Thus, you only use a decimal point when you enter a number with a decimal portion.

"Could not find the default units for thermal K ..."

The new user interface (FAST_in) displays the current units for all entries.

"The installation was completed without any problems and all communication with the programs was as expected."

This was the general observation. Where there were installation problems, they were normally associated with answering one of the INSTALL questions wrong. The release version has eliminated all of the INSTALL questions.

"The biggest problem I have found thus far is in finding a good source of data for the type of objects that I would like to simulate..."

This was a common problem. The need for appropriate data will be the largest impediment to the rapid adoption of these predictive methods. We are working on ways to address these needs on a national or international basis. But they all involve the willingness of the material and product producers to collect and share data on their products.

> "More data on product performance is needed. Possibly additional data disks made available as data becomes available. NBS could act as clearing house for data that is made available by outside labs, companies, etc."

Several distribution methods are being explored including a subscription update service and a dial-up master data base from which data can be downloaded.

> "Our ability to utilize it in our own product evaluation was quite limited as we did not have data available from your data base on products close to our own designs."

For applications to specific products, it is clear that the product producer will need to supply the data. It is already possible to have such data taken by testing laboratories such as Underwriters Laboratories or Factory Mutual.

> "The test example for the FAST program was executed without problems, but the run time felt rather long compared with the time of simulation."

The required execution time is typically beyond our control. As discussed in the report, for a given problem the run time varies by a factor of 25 from the older PC to the 386/25 machines. Within a year, the high end PC will run at 33 MHz, and a year after that at 50 MHz. As long as the computational complexity stays relatively constant, the run times will continue to decrease - as long as the user is willing to upgrade to new machines. Here, the cost of the equipment will be weighed against the benefits of the method.

> "Add a message to the software that indicates to the user that the software is running properly. I did not know if the software was running or hung up."

This has been addressed by the implementation of run-time graphics.

> "In terms of experience (for fire reconstruction), I have had moderate success with the program. One run was exceedingly good. There have been several intermediate runs that were of mixed success. The last one was a complete bomb. I am currently reviewing the input data to make sure I

have not entered erroneous data. It may also be that the fire scene is beyond the limits of the program."

Users will always need to ask themselves if the model results make sense. We are examining automatic ways to provide uncertainty estimates as the case is entered.

"It would be desirable to be able to input the fire description using rate of heat release information."

This change has been implemented in the release version.

"When water is defined as one of the species to be tracked by FAST, the water concentrations computed for the various compartments over time include only the water produced from the fire chemistry. Typically, the ambient humidity is of the same order of magnitude and should therefore be included if the true water concentration is desired."

This has also been implemented. The relative (ambient) humidity is set by the user, and is converted to a mass (of water vapor). Water produced by the combustion is added and the resulting total mass concentration is tracked.

"We have noticed one theoretical disadvantage - the program can not simulate ventilation controlled fires."

This feature has also been added with the incorporation of a vitiated combustion algorithm.

"Output data expressing heat flux at floor level would be useful information in judging the effects of fire on a compartment."

This too has been added. The incident heat flux at the floor is available in FASTPLOT as the variable "ON TARGET".

"The ability to open a vent during the simulation period either at a specified time or a predicted time (or both?) [is suggested]."

Once again, this feature has been implemented in the release version. With the parameter CVENT, interior or exterior vents can be opened or closed at any time (or multiple times) during the simulation.

"Less critical but still important problem [is] the assumption of a constant heat of combustion (our data often contradict this assumption)."

With the addition of the ability to enter rate of heat release, the heat of combustion is no longer necessarily a constant. By specifying the heat release rate and the mass loss rate, heat of combustion can be varied at will.

"A comparative plotting capability, i.e., plotting the same variable found in different [files is suggested]."

The ability to make comparative plots from different files has been implemented in FASTPLOT. Moreover, it is simplified in that once you select the desired variables from the first file, you simply select a new file and use the command "AGAIN" to duplicate the variable list from the new file(s).

"It is very time consuming to get hard copies of the graphs from FASTPLOT. Using PIZZAZ, the program hangs up after each graph, thus requiring a reboot and another dump file search for the next variable(s) to be plotted."

This problem has been solved with entirely new graphics and printer drivers that are universal (works with all displays from CGA to VGA automatically) and are not resident, so do not conflict with ANSI.SYS. By also adding dash/dot line patterns to FASTPLOT, color is not required to differentiate the curves. Thus, you can see it in color on the monitor and then send it to the printer in monochrome.

"Would like results output to ASCII files."

We have added an option to FASTPLOT to save variables in ASCII files as columns of data, which should be compatible with most commercial spreadsheet and graphics software.

"EXITT: The inclusion of an allegedly deterministic model of human behavior implies the same confidence level in its algorithm as say the model in FAST. This is, of course, not the case. The concept of such a behavioral model is fundamentally flawed. Its inclusion in HAZARD I cheapens the entire package. In addition, the implementation is poor and the sources for the decision algorithm undefined. I strongly recommend that you reconsider releasing EXITT as part of HAZARD I."

One person was quite opposed to EXITT on the basis that behavior is a largely stoichastic process. However, we feel that occupant hazard cannot be assessed without a measure of the time needed. In family settings (and certain other situations such as health care), there is a strong altruistic component to evacuation which can actually dominate this process. Thus, until something better comes along, EXITT will remain a part of the package.

"EXITT is also an excellent program with excellent graphics. I quite enjoy its game-like aura. Providing that the assumptions are sound, the program should be quite good for exit problems. Somehow, I think the assumptions need to be refined. One example is where 4 residents are in the ranch house. The father got out of the house first, leaving the mother to take care of the infant and the 5 year-old to escape by himself. One must wonder if the father had nothing to do for two minutes, or the program was written by a biased, prejudiced, and sexist programmer."

Yet another user recognizes the need for EXITT, but questions some of the behavioral rules. As the program develops, we hope that these inconsistencies will be corrected.

> "The manuals are of a very generous length. However, this does mean that a lot of effort is required to become conversant with the package. I think many people would not have the patience to read the manuals in much detail. A short user-guide would be useful."

A new format will be used for the release version documentation. The software use information will be separate from the supporting technical reports. The latter will then serve as a reference base to be consulted only when needed.

APPENDIX B. TECHNICAL REFERENCE GUIDE FOR FAST VERSION 18

Technical Reference Guide for FAST Version 18

Walter W. Jones
Richard D. Peacock

Center for Fire Research
National Institute of Standards and Technology

FAST (fire and smoke transport) is a zone model capable of predicting the environment in a multi-compartment structure subjected to a fire. This reference guide provides a detailed description of the source terms used in the model, data input requirements, and the output produced by version 18 of the model.

Key words: compartment fires; fire growth; mathematical models; numerical models; room fires; smoke; toxicity

1. INTRODUCTION

Considerable research has been done regarding the spread of fire and smoke from a room of fire origin to connected compartments. The work is motivated by a need to understand and predict the environmental conditions which occur as a fire develops and spreads. Much of the attention has focused on the development of numerical models which are able to make a reasonably accurate assessment of the environment resulting from a specified fire. We have built such a model, FAST [1][1].

FAST is a model to describe fire growth and smoke transport in multi-compartment structures. The implementation consists of a set of programs to describe the structure to be modeled, run the model and produce usable output. This reference guide describes the equations which constitute the model, data which are used by the model and explains how to operate the model. The physical basis of zone models, their limitations, and development of the predictive equations are described elsewhere [1] and are only summarized here. The intent of this paper is to provide a complete description of the way the model is structured. In

[1] Numbers in brackets refer to literature references listed in section 9 at the end of this report.

particular the relationship between the equations and the numerical implementation of the equations is laid out. It is intended as a complete description of the parameters and key words available to control various aspects of a simulation. It is hoped that there is sufficient information provided that one could adapt the model for specialized applications.

Functionality is provided by the following programs:

FAST	the model itself
FAST_in	interactive input
FASTplot	interactive output to display data produced by the model
BUILD	generate descriptor files for graphics output

FAST, FASTplot, and BUILD work on a wide variety of hardware, from supercomputers through microcomputers. FAST_in is specific to MS DOS based microcomputers, although it does generate an ASCII data file which can be used to run FAST on other computers.

Section 2 describes the structure of the model. Section 3 deals with the mathematical basis of the model. Section 4 is a discussion of source terms which appear in section 3, and the titles of the subsections reference the modules within the program which actually performs the respective calculations. Section 5 documents the relevant source code modules described in section 4. Section 6 describes the files used by the model. Every attempt has been made to maintain a correspondence between the terms in the mathematical formulae and those used in the computer programs. There are differences, but the correspondence should be clear. The final sections describe the interactive programs which help put the input and output data into usable forms. In the appendices, examples of input data files and corresponding output are given.

The utility BUILD is not described in this paper. It is documented in reference [2], including the file structure of the picture descriptor files, the mathematical basis and the command structure. The salient difference between the PC version and that on a mainframe is that in the former case the interaction as well as the display are on the same screen. Otherwise, they are identical.

There are several calculations presented to illustrate particular points. The calculations refer to the sample #5 data file. These examples are data that can not be obtained from other models, and so show some of the unique features of FAST. A more complete description of the model can be found in the paper by Jones [3] and the experimental work in Peacock et. al. [4].

2. STRUCTURE OF THE MODEL

The primary element of the model is a compartment. The interest in these predictive schemes lies in the environment within the compartments, so the model is structured around variables such as temperature, pressure, etc., in the compartment. Predictive equations for the gas layers in each compartment are derived from conservation of mass, momentum and energy, an equation of state, and the boundary conditions to which each compartment is subject. The term "boundary condition" refers to the transfer points at the boundaries of the compartments; examples are vents, air conditioning ducts, etc. The actual physical phenomena which drive the transport are then couched as source terms. Such a formulation allows the greatest flexibility in adding, modifying, or deleting terms which are appropriate to the problem at hand.

The conservation equations used are for mass, momentum and energy. These equations are fundamental to predictive models, and must hold in all cases. These conservation equations are rearranged to form a set of predictive equations for the sensible variables in each compartment. An important concession which is made for computational speed is that the fluid momentum between the compartments is calculated, but not within a compartment. The work term (volumetric expansion and contraction) is included in the energy equation, however. The result is that we can not follow acoustic waves anywhere, or gravitational waves within a compartment. The concomitant improvement is that we are not limited by the Courant time step condition for wave motion within a compartment.

Each compartment is subdivided into a few "control volumes," which we call zones. The premise is that the details which occur within such volumes do not concern us (at present), but their interaction does. We base this simplification on the observation that when a fire grows and spreads, the gases in a compartment stratify into distinct zones. In the present calculation we use only two zones per compartment. There is reasonably good agreement between theory and experiment for this choice, and there are other phenomena which put a more severe constraint on the validity of the model. An example of a compartment which might reasonably contain more than two zones would be a long corridor whose aspect ratio (length to width or height) is greater than 10 [17]. The general layout of the zones and the form of the conservation equations is discussed elsewhere [1] and will not be repeated here.

FAST is formulated as a set of ordinary differential equations. It was the first model of fire growth and smoke spread to cast the entire model in this form and was done because of the efficiency of solving the conservation equations this way. In addition, as discussed in the section on the form of the equations, the entire model is implemented in single precision arithmetic. It is the only fire growth and smoke transport model done this way. Single precision arithmetic is faster and more compact than the equivalent code in double precision, and often the algorithms for calculation are better[2].

It is important to keep in mind that this model is based on a control volume concept. To that end, one gives up knowledge of some of the details of the internal structure of the problem being modeled, such as temperature variation within a zone. The model must be used cautiously for situations where these approximations may not be valid, such as the initial filling of a tall shaft, or a very long corridor.

[2] Implementation of Algorithms by W. Kahan - notes for a lecture given at the University of California at Berkeley, 1971 and 1972.

3. THE PREDICTIVE EQUATIONS USED BY THE MODEL

The space with which we are concerned usually consists of several compartments with a hot upper zone and a relatively cool lower zone for each compartment, and objects such as chairs, plumes and fires. Interactions occur at the boundary of these zones. Examples of possible interactions are the flow through vents connecting compartments, the radiation from one compartment through a vent to another compartment and a plume which connects the upper zone and the lower zone of a compartment.

Using the nomenclature in section 10, the predictive equations can be written [1]:

$$\frac{dP}{dt} = \frac{\dot{s}}{(\beta - 1)\, V} \tag{1}$$

$$\frac{dT_u}{dt} = \frac{1}{\beta}\left(\frac{T_u}{PV_u}\right)\left[\dot{E}_u + \frac{V_u}{(\beta - 1)V}\,\dot{s}\right] \tag{2}$$

$$\frac{dT_\ell}{dt} = \frac{1}{\beta}\left(\frac{T_\ell}{PV_\ell}\right)\left[\dot{E}_\ell + \frac{V_\ell}{(\beta - 1)V}\,\dot{s}\right] \tag{3}$$

$$\frac{dV_u}{dt} = \frac{1}{P\beta}\left[c_p\dot{m}_uT_u + \dot{E}_u - \frac{V_u}{V}\,\dot{s}\right] \tag{4}$$

where $\dot{s} = c_p\dot{m}_uT_u + c_p\dot{m}_\ell T_\ell + \dot{E}_u + \dot{E}_\ell$ and $\beta = c_p/R = \gamma/(\gamma-1)$ with the assumption for the pressure $P_R = P_u = P_\ell = \rho_u R\, T_u = \rho_\ell R\, T_\ell$ and the constraint that the total volume of a compartment is fixed $V = V_u + V_\ell$. There is a set of these equations for each compartment.

The form of the energy terms ($\dot{E}_u$, $\dot{E}_\ell$) is important. With the choice that the reference temperature is the ambient, we obtain

$$\dot{E}_j = \dot{Q}_f(j) + \dot{Q}_r(j) + \dot{Q}_c(j)$$

$$+ \sum_i c_p \dot{m}_{i,j}^{in} (T_i - T_u) + R(T_a - T_u)\dot{m}_{i,j} \tag{5}$$

$$+ \sum_i c_p \dot{m}_{i,j} (T_j - T_k)$$

and the source term "s" becomes

$$\dot{s} = \sum_j \dot{Q}_f(j) + \dot{Q}_r(j) + \dot{Q}_c(j) \tag{6}$$

$$+ \sum_j \sum_i c_p \dot{m}_{i,j}^{in} (T_i - T_j) + c_p \dot{m}_j (T_j - T_a) + c_v \dot{m}_j T_j$$

The index "j" is for the layers "u" and "ℓ" and "i" is for the compartments which have connections to the compartment under consideration. If there is more than one connection between the compartments, then this latter summation is multi-valued. The mass flow terms are written as

$$\dot{m}_{i,j} = \dot{m}_{i,j}^{in} - \dot{m}_{i,j}^{out}$$

$$\dot{m}_j = \sum_i \dot{m}_{i,j}^{in} - \dot{m}_{i,j}^{out}$$

and $$T_k = \begin{cases} T_u & \text{if } j = \text{"}\ell\text{"} \\ T_\ell & \text{if } j = \text{"u"} \end{cases}$$

In addition, for each compartment in which a plume is present there is a term for the reduction in the energy release for bringing the fuel and entrained air from its initial temperature to that of the upper layer.

This form is important, especially for eq (6), as it is the means by which the numerical implementation is done in single precision. The equations are now in a form that allows us to consider all physical phenomena as source terms in the conservation equations.

4. SOURCE TERMS

The conserved quantities in each compartment are described by the set of predictive equations shown above. The form of the equations is such that the physical phenomena are source terms on the right-hand-side of these equations. Such a formulation makes the addition (and deletion) of physical phenomena and changing the form of algorithms a relatively simple matter.

4.1 Source Terms: Radiation (Implemented in FIRRAD)

Objects such as walls, gases and fires radiate as well as absorb radiation. Each object has its own properties, such as temperature, emissivity, etc. As we are solving the energy equation for the gas temperature, the primary focus is in finding out how much energy is gained or lost by the gas layers due to radiation. In order to calculate the net radiation absorbed in a zone, a heat balance must be done which includes all surfaces which radiate to and absorb radiation from a zone. The form of the terms which contribute heat to an absorbing layer are the same for all layers. We assume that all zones in these models are similar so we can discuss them in terms of a general layer contribution. In order for this calculation to be done in a time commensurate with the other sources, some approximations are necessary.

Radiation can leave a layer by going to another layer, by going to the walls, by exiting through a vent, by heating an object, or by changing the pyrolysis rate of the fuel source. Similarly, a layer can be heated by absorption of radiation from these surfaces and objects as well as from the fire itself. The formalism which we employ for the geometry and view factor calculation is that of Siegel and Howell [5]. Although the radiation could be done with a great deal of generality, we assume that the zones and surfaces radiate and absorb like grey bodies.

The fire is assumed to be a point source and the view factor into the upper and lower layers is calculated as a tetrahedron from the fire base to the zone interface. A plume is assumed not to radiate, and at present we do not have defined objects other than the fire. We use a simplified geometrical equivalent of the compartment in order to calculate the radiative transfer between the ceiling, floor and layer(s). We assume that the upper wall and ceiling, and the lower wall and floor are equivalent to two flat plates with the gas layers in between. See figure 5.1. Thus, this is a two wall radiation model. A difficulty arises in arriving at consistent boundary conditions commissural with the four wall convective heat transfer model. The extended ceiling (ceiling plus upper wall) has two temperatures associated with it, and similarly for the extended floor (floor plus lower wall). The ambiguity of chosing the temperature to use for the radiative transfer calculation can cause the upper and lower wall temperatures to be reversed in some cases. This most commonly occurs for highly conductive floor material and well insulated walls. Energy is conserved, but the radiative flux boundary condition for the upper and lower walls is partitioned incorrectly. For the remaining discussion we use the following notation

F_{jk} = Geometrical view factor of surface j by surface k
σ = Stefan-Boltzmann constant = 5.67×10^{-8} W/m^2K^4
α = Absorption coefficient of the upper gas layer, m^{-1}
$\epsilon_{u/\ell}$ = Emissivity of the upper/lower walls
ϵ_g = Emissivity of the upper gas layer

Using the formalism of Siegal and Howell [5] we have

$$\begin{aligned} D = {} & [1 - (1-\epsilon_u)(1-\epsilon_g) F_{uu}][1 - (1-\epsilon_\ell) F_{\ell\ell}] \\ & - [(1-\epsilon_u)(1-\epsilon_\ell)(1-\epsilon_g)^2 F_{u\ell}F_{\ell u}] \end{aligned} \tag{7}$$

$$\begin{aligned} \Pi_u = {} & \{[(1 - (1-\epsilon_g) F_{uu}][1 - (1-\epsilon_\ell) F_{\ell\ell}] \\ & - [(1-\epsilon_\ell)(1-\epsilon_g)^2 F_{u\ell}F_{\ell u}]\}\sigma T_{uw} - (1-\epsilon_g) F_{u\ell}\epsilon_\ell\sigma T^4_{\ell w} \\ & - \{1 + (1-\epsilon_\ell)[(1-\epsilon_g) F_{u\ell}F_{\ell u} - \overset{4}{F}_{\ell\ell}]\}\epsilon_g\sigma T_g \end{aligned} \tag{8}$$

$$\begin{aligned} \Pi_\ell = {} & \{[1 - (1-\epsilon_u)(1-\epsilon_g) F_{uu}](1-F_{\ell\ell}) \\ & - (1-\epsilon_u)(1-\epsilon_g)^2 F_{u\ell}F_{\ell u}\}\sigma T^4_{\ell w} - (1-\epsilon_g) F_{\ell u}\epsilon_u\sigma T^4_{uw} \\ & - \{[1 - (1-\epsilon_u)(1-\epsilon_g) F_{uu}] F_{\ell u} + (1-\epsilon_u)(1-\epsilon_g) F_{\ell u}\} \epsilon_g\sigma T^4_g \end{aligned} \tag{9}$$

As formulated in Siegal and Howell, the equations for radiative transfer are written in terms of transmissivity. We use the "equivalent" sphere analogy to relate this to an emissivity for the gas layer. If we assume that the gas layer is equivalent to a gaseous sphere of equivalent volume, then we can calculate an effective radius from R=4V/A, where V is the volume, and A the area of the ceiling plus upper wall. The transmission factor is approximately exp($-\alpha$R). The absorptivity is then 1-exp($-\alpha$R) and becomes the emissivity of an equivalent grey body which radiates as σT^4.

With these definitions we can calculate the energy radiated from the upper gas layer to the upper and lower walls respectively as

$$\dot{Q}(\text{upper}) = A_u\ \epsilon_u\ \Pi_u\ /\ D \tag{10}$$

$$\dot{Q}(\text{lower}) = A_\ell \, \epsilon_\ell \, \Pi_\ell \, / \, D$$

By summing these two terms together with the energy radiated by the fire, we obtain the negative of the heat flux absorbed by the upper layer. A heat balance with the fire is not done simply because the amount of heat radiated by the fire is usually much greater than that absorbed by the fire (from external sources). In other words, the radiation balance in the compartments does not affect the temperature of the flames.

For the case when $\epsilon_u = \epsilon_\ell = 1$ we have a simple expression for the energy absorbed by the gas layer, namely

$$\dot{Q}_g = -\sigma \left[\epsilon_g T_u^4 A + (1-\epsilon_g) T_{uw}^4 (A_u + A_{uv}) - T_{uw}^4 A_u - \epsilon_g T_u^4 A_d - T_\ell^4 A_{uv} \right] + F_f Q_f \tag{11}$$

where

A_{uv} = Area of the vents which the gas layer "sees"

F_f = fraction of the released heat which radiates times its view factor for the gas layer

$A = A_u + A_d$.

A schematic of this is shown in section 5.1

Note that although radiation can exit a vent, we do not do specific heating of a wall or object in an adjacent compartment. Further, there is no attempt to acccount for radiation blockage by objects or flames. The algorithm is appropriate for a compartment where the joints are concave, so that no surface is hidden from any other surface. For "L" shaped compartments, our view factor calculation would not be appropriate, and would overestimate the amount of radiative transfer. All of these phenomena require a much more extensive model which includes a ray tracing algorithm.

4.2 Source Terms: Convective Heating (Implemented in CONVEC)

Convection is one of the mechanisms by which the gas layers lose (or gain) energy to walls, objects or through openings. Conduction is a process which is intimately associated with convection, but as it does not show up directly as a term for heat gain or loss, it will be discussed separately. Convective heating describes the energy transfer between solids and gases. The enthalpy transfer associated with flow through openings will be discussed in the section on flow through vents.

Convective heat flow is energy transfer across a thin boundary layer. The thickness of this layer is determined by the temperature difference between the gas zone and the wall or object being heated [6]. We can write the heat flux term as

$$\dot{Q}_c = h_c(T_g - T_w)A_w \tag{12}$$

where the transfer coefficient can be written as

$$h_c = \frac{\kappa}{\ell} C_o (Gr\ Pr)^{1/3}. \tag{13}$$

The terms are

A_w = area of surfaces in contact with the zone

Gr = Grashof number = $g\ell^3|T_g - T_w|/\nu^2 T_g$,

Pr = Prandtl number = 0.72,

κ = thermal conductivity of the gas = $2.72\times10^{-4}\left(\frac{T_g + T_w}{2}\right)^{4/5}$,

ℓ = length scale $\approx \sqrt{A_w}$,

C_o = coefficient which depends on orientation [6],

$\nu = 7.18\times10^{-10}\left(\frac{T_g + T_w}{2}\right)^{7/4}$.

For the cases of interest we use the coefficients shown below. The coefficients for horizontal surfaces apply to a slab over a zone (such as ceiling surfaces). For a floor, the conditions (T_g and T_w) are reversed. For the outside boundary condiction, the condition is reversed, at least for the ceiling and floor. Physically, outside a compartment, the ceiling of a compartment will behave as if it were the floor of a compartment over it, and similarly for the floor of a compartment. Thus, we use the floor boundary coefficient for the outside boundary of the ceiling and the ceiling coefficient for the outside boundary of a compartment floor. For vertical boundaries, the coefficient remains the same on the interior and exterior.

Orientation	Coefficient[C_0]	Condition
Vertical	0.130	all
Horizontal	0.210	$T_g > T_w$
Horizontal	0.012	$T_g < T_w$

These coefficients are for turbulent boundary layer flow. Thus they overestimate the heat transfer which can occur in a quiescent compartment.

The boundary condition which connects the interior of the wall to the zone is fairly straightforward. This convective heating generates a flux from the gas layer which becomes a derivative boundary condition for the conduction algorithm. A similar boundary condition must be applied on the exterior of the walls. The assumption made is that the exterior portion of a wall is truly facing the ambient. This precludes a fire in one compartment heating a connected compartment through conduction. The omission is due to the difficulty of specifying how compartment walls are connected and not to the difficulty of specifying the boundary conditions or solving the equations. So the boundary condition for the exterior of a wall is similar to the interior, except that the exterior surface is assumed to be convecting and radiating to the ambient. With this caveat in mind, we can use the convection routine to calculate the boundary condition for the exterior wall also.

The current model allows for a ceiling, floor and two walls. Actually the two walls are the same material, but a separate temperature profile is maintained for the wall in contact with the upper and lower zones respectively. Therefore we have four components for convective heat transfer. See section 5.2 for a schematic of this division and a discussion of how it is implemented.

4.3 Source Terms: Plumes (Implemented in FIRPLM)

Buoyancy generated by the combustion processes in a fire causes the formation of a plume. Such a plume can transport mass and energy from the fire into the lower or upper layer of a compartment. In the present implementation, we assume that both mass and energy from the fire are deposited only into the upper layer. In addition the plume entrains mass from the lower layer and transports it into the upper layer. This yields a next enthalpy flux between the two layers. Actually, the flame and plume will generally radiate somewhat into the lower layer, at least if it is not diathermous. So our approximation causes the upper layer to be somewhat hotter, and the lower layer somewhat cooler than is the case, at least in a well developed fire.

A fire generates energy at a rate $\dot{Q}$. Some fraction, χ_R, will exit the fire as radiation, some into heating additional fuel for burning, χ_c, and the remainder will be available to drive the plume. This quantity is $(1-\chi_R)\dot{Q}$. Defining this quantity to be the convective heat release rate, we can use the work of McCaffrey [7] to estimate the mass flux from the fire into the upper layer.

This correlation divides the flame/plume into three regions as shown below. This prescription agrees with the work of Cetegen et al. [8] in the intermittent regions but yields greater entrainment in the other two regions. This difference is particularly important for the initial fire since the upper layer is far removed from the fire.

$$
\begin{array}{lll}
\text{flaming:} & \dot{m}_e/\dot{Q} = 0.011\ (Z/\dot{Q}^{2/5})^{0.566} & 0.00 \le Z/\dot{Q}^{2/5} < 0.08 \\
\text{intermittent:} & \dot{m}_e/\dot{Q} = 0.026\ (Z/\dot{Q}^{2/5})^{1.85} & 0.08 \le Z/\dot{Q}^{2/5} \le 0.20 \\
\text{plume:} & \dot{m}_e/\dot{Q} = 0.124\ (Z/\dot{Q}^{2/5})^{1.895} & 0.20 \le Z/\dot{Q}^{2/5}
\end{array}
\tag{14}
$$

McCaffrey's correlation is in general valid for all fires, everywhere. It is an extension of the common point source plume model, with a different set of coefficients for each region. These coefficients are experimental correlations, and are not based on theory. The theory appears only in the form of the fitted function. The binding to the point source plume model is for the value for Z where the mode changes, namely from flaming to intermittent to plume.

4.4 Source Terms: Vent Flow (Implemented in FLOW, FRFLOW, and ENTRFL)

Mass flow (in the remainder of this section, the term "flow" will be used to mean mass flow) is the dominant source term for the predictive equations because it fluctuates most rapidly and transfers the greatest amount of enthalpy on an instantaneous basis of all the source terms. Also, it is most sensitive to changes in the environment. One of the improvements which we have incorporated into the model is a means of calculating these flow fields with the correct number of neutral planes. In these situations, it is possible to have up to three neutral planes [10].

Flow at vents is governed by the pressure difference across a vent. In the control volume approximation, it is not calculated by solving the momentum equation directly. Rather, momentum transfer at the zone boundaries is included by using Bernoulli's solution for the velocity equation. This solution is augmented for restricted openings by using flow coefficients [9]. The flow coefficients allow for an effective constriction of fluid flow which occurs for vents with sharp edges, that is for openings for which the size of the orifice changes abruptly, such as a window in a room. The coefficients embodied in FAST are for rectangular openings in walls of compartments whose surface area is much larger than the opening.

There are two situations which give rise to flow through vents. The first, and most usually thought of in fire problems, is that of air or smoke which is driven from a compartment by buoyancy. The second type of flow is due to a piston effect which is particularly important when conditions in the fire environment are changing rapidly. Rather than depending on density differences between the two gases, the flow is forced by volumetric expansion, mostly caused by changes in gas density or pressure. Atmospheric pressure is about 100 000 Pa, fires produce pressure changes from 1 to 1 000 Pa, and mechanical ventilation systems typically involve pressure changes about 1 to 100 Pa. In order to solve these interactions correctly, we must be able to follow pressure differences of about 0.1 Pa out of 10^5.

The general form for the velocity field is given by

$$V = C\ S\ (2\rho|P_i - P_o|)^{1/2} \tag{15}$$

where C is an orifice coefficient (≈0.65 to 0.75), S is the opening area, ρ is the gas density on the source side and P is the pressure on the source(i) and destination(o) sides, respectively.

We apply the above equation to rectangular openings which allows us to remove the width from the mass flux integral. That is

$$\text{flow} = \int_{\text{width}} \int_{\text{height}} \rho V\ dzdb \rightarrow \text{width} \int_{z_1}^{z_2} \rho V\ dz \tag{16}$$

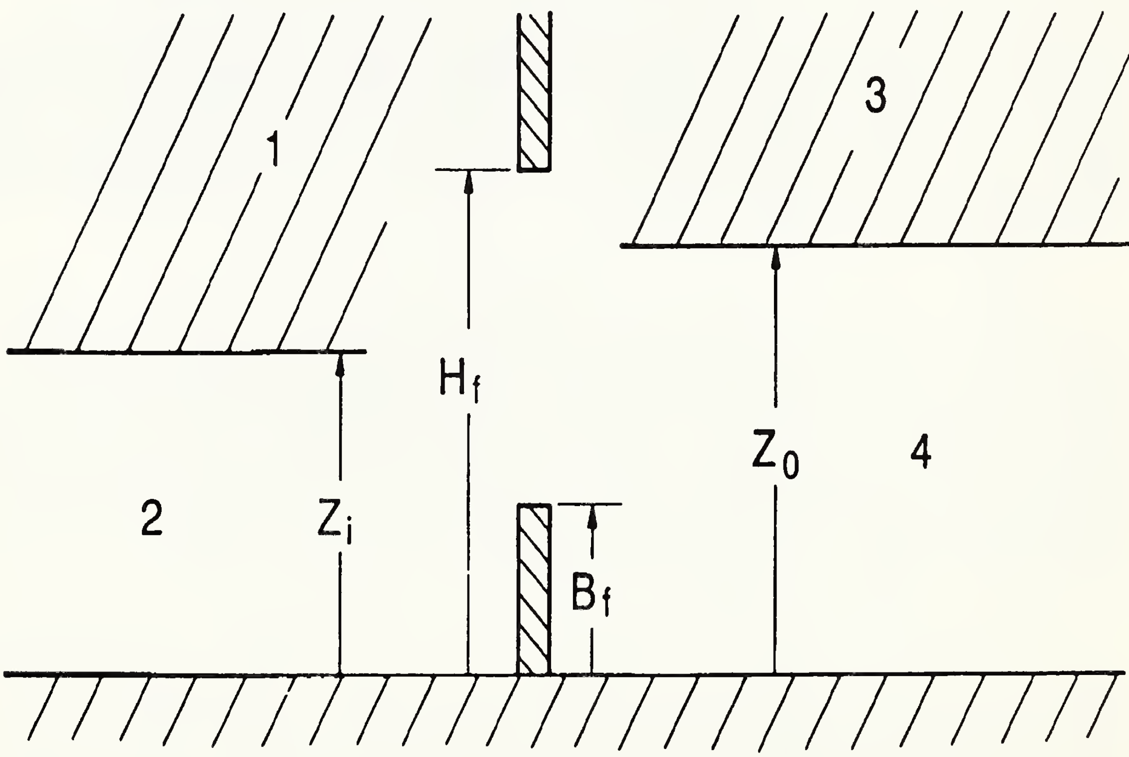


Figure 1. Notation convention for interface, sill, and soffit.

The simplest means to define the limits of integration is with neutral planes, that is the height at which flow reversal occurs, or physical boundaries such as a sill or soffit. By breaking the integral into intervals defined by flow reversal, a soffit, a sill, or a zone interface, the integral itself can be done analytically. We have for the internal pressure on each side of the opening as shown in figures 1 and 2:

$$P_i(z) = P_i(0) - \min(z, Z_i)\, \rho_2 g - \max(z - Z_i, 0)\, \rho_1 g \tag{17}$$

$$P_o(z) = P_o(0) - \min(z, Z_o)\, \rho_4 g - \max(z - Z_o, 0)\, \rho_3 g \tag{18}$$

where P(0) represents the base (reference) pressure at the floor. The pressure then appears only as a difference of these two terms, namely $F(z) = P_i(z) - P_o(z)$. These equations form an inordinately large family of curves as a function of the parameters ρ and Z. However, if the restrictions found in fire scenarios are imposed then we end up with only a five possibilities as shown below.

Restrictions		Maximum number of neutral planes
$\rho_2 \leq \rho_4$,	$Z_i \leq Z_o$	1
$\rho_2 > \rho_4$,	$Z_i \leq Z_o$	2
$\rho_3 \leq \rho_2 \leq \rho_4$,	$Z_i > Z_o$	3
$\rho_2 > \rho_4$,	$Z_i > Z_o$	2
$\rho_2 < \rho_3$,	$Z_i > Z_o$	1

If there were no soffits or sills to consider, then the calculation would be fairly straightforward. However, the possibility of soffit/sill combinations requires many numerical tests in the calculation. The first condition allows 44 different flow combinations, depending on the relative position of H_f, B_f, Z_i and Z_o. It contains at most a single neutral plane. Twenty-four of these combinations are without a neutral plane and 20 with a neutral plane. For the other cases, the interval $[B_f, H_f]$ can be partitioned into intervals which contain at most a single neutral plane. An important caveat is to be sure that the inequalities as shown above are treated consistently.

The approach we have used to calculated the flow field is of some interest because of the way it is implemented numerically. The general flow equation is

$$\dot{m}_{i \to o} = \frac{2}{3} C\, S\, (2\rho)^{1/2}\, (z_2 - z_1)\, \frac{1}{(P_2 - P_1)}\, \left(P_2^{3/2} - P_1^{3/2}\right) \tag{19}$$

For the situation when one of the endpoints (z_1, or z_2) defines a neutral plane, then this expression simplifies. As a specific example, let $P_1 \rightarrow 0$, whence the expression becomes

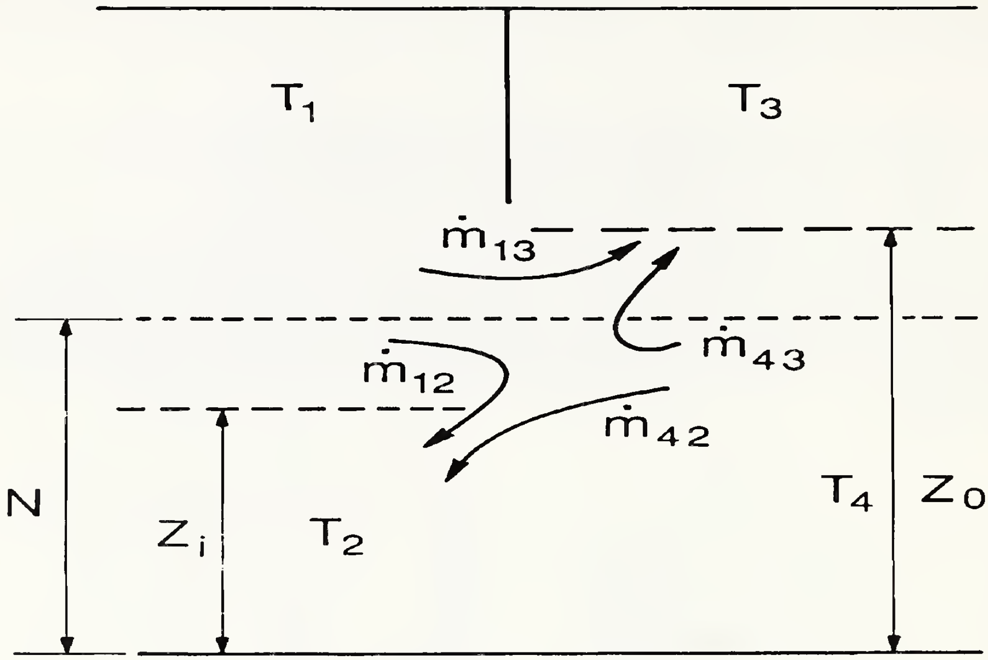


Figure 2. Example of a possible flow pattern and layer numbering convention.

$$\dot{m}_{i \to o} = \frac{2}{3} C\ S\ (z_2 - z_1)\ (2\rho\ P_2)^{\frac{1}{2}}. \tag{20}$$

The latter expression is much faster to evaluate than the former. We can partially ameliorate the difference in computation speed by rewriting eq (19) in a better form, using a continued fraction, as

$$x \equiv \text{minimum} \left\{ P_2^{\frac{1}{2}}, P_1^{\frac{1}{2}} \right\}$$

$$y \equiv \text{maximum} \left\{ P_2^{\frac{1}{2}}, P_1^{\frac{1}{2}} \right\}$$

$$\dot{m}_{i \to o} = \frac{2}{3} C\ S\ (2\rho)^{\frac{1}{2}}\ (z_2 - z_1) \left[x + \frac{y}{1 + x/y} \right]. \tag{21}$$

This form is considerably faster to evaluate, approaching the time required to evaluate eq (20).

The integration is started at the lowest point at which flow can occur, the sill or floor. Then the next change point is found. It is either a soffit or a change in the relative gas density. Within this interval there is either a neutral plane or not. The appropriate form, eq (20) or (21) is used. Then a check is then made to see if there is more opening through which flow can occur. If so, then the integration process starts from the last endpoint (z_2) and continues until the soffit is reached.

A mixing phenomenon occurs at vents which is similar to entrainment in plumes. As hot gases from one compartment leave that compartment and flow into an adjacent compartment a door jet can exist which is analogous to a normal plume. Mixing of this type occurs for $\dot{m}_{13} > 0$ as shown in figure 2. To calculate the entrainment ($\dot{m}_{43}$ in this example), once again we use a plume description, but with an extended source point. The estimate for the point source extension is given by Cetegen et al. [8]. This virtual point source is chosen so that the flow at the door opening would correspond to a plume with the heating (with respect to the lower layer) given by

$$\dot{Q}_o = c_p(T_1 - T_4)\dot{m}_{13}$$

The concept of the virtual source is that the enthalpy flux from the virtual point source should equal the actual enthalpy flux in the door jet at the point of exit from the vent using the same prescription. Thus the entrainment is calculated the same way as was done for a normal plume. The height of the plume is

$$z_p = z_3/eq^{2/5} + v_p,$$

where v_p, the virtual source point, is defined by inverting the entrainment process to yield

$$
\begin{aligned}
xq &= eq / \dot{m} & & \\
v_p &= (90.9/xq)^{1.76} & & \text{if } 0.00 < v_p <= 0.08 \\
v_p &= (38.5/xq)^{1.1001} & & \text{if } 0.08 < v_p <= 0.20 \\
v_p &= (8.10/xq)^{0.528} & & \text{if } 0.20 < v_p.
\end{aligned}
$$

The units of this height, z_p and v_p, are not length, but rather in the reduced notation of McCaffrey [7]. That is, the z_p defined here is the term $z/\dot{Q}^{2/5}$ used earlier. The agreement between experiment and theory is quite good even though we are outside of the normal range of validity of a plume model. In particular, a door jet forms a flat plume whereas a normal fire plume will be approximately circular.

The other type of mixing is much like an inverse plume and causes contamination of the lower layer. It occurs when there is flow of the type $\dot{m}_{12} > 0$. The shear flow causes vortex shedding into the lower layer and thus some of the particulates end up in the lower layer. The actual amount of mass or energy transferred is usually not large, but its effect can be large. For example, even minute amounts of carbon can change the radiative properties of the gas layer, from negligible to something finite. It changes the rate of radiation absorption by orders of magnitude which invalidates the notion of a diathermous lower layer. This term is predicated on the Kelvin-Helmholz flow instability and requires shear flow between two separate fluids. The mixing is enhanced for greater density differences between the two layers. However, the amount of mixing has never been well characterized. Quintiere et al. [11] discuss this phenomena for the case of crib fires in a single room, but their correlation does not yield good agreement with experimental data in the general case. So we have assumed that the incoming cold plume behaves like the inverse of the usual door jet between adjacent hot layers; thus we have a descending plume. It is possible that the entrainment is overestimated in this case, since buoyancy, which is the driving force, is not nearly as strong as for the usually upright plume.

4.5 Source Terms: Fire (Implemented in PYROLS and CHEMIE)

At present, the model has only a specified fire implemented. A specified fire is one for which the time dependent characteristics are specified as a function of time. Under development are pool fire and burning furniture algorithms. The specified fire can be unconstrained or constrained. These fires are later referred to as type 1 and type 2, respectively. The meaning of this assignment will become clearer in the discussion of the algorithm itself (sec. 5.5) and the data file structure (sec. 6.7). For the constrained fire, the constraint is based on the minimum of the fuel and oxygen available for combustion. For either, the pyrolysis rate is specified as $\dot{m}_f$, the burning rate as $\dot{m}_b$ and the heat of combustion as h_c so that the nominal heat release rate is

$$\dot{Q}_f = h_c \dot{m}_b - c_p (T_u - T_v) \dot{m}_b . \tag{22}$$

For the unconstrained fire, $\dot{m}_b = \dot{m}_f$, whereas for the constrained fire, the burning rate will be less than the pyrolysis rate. Models of specified fires generally use a heat of combustion which is obtained from an experimental apparatus such as the Cone Calorimeter [12]. The shortcoming of this approach is that the pyrolysis rate is not connected to radiative feedback from the flame or compartment. In an actual fire, this is an important consideration, and the specification used should match the experimental conditions as closely as possible.

The energy which is released goes into radiation and enthalpy flux

$$\dot{Q}_r(\text{fire}) = \chi_R \dot{Q}_f$$

$$\dot{Q}_c(\text{fire}) = (1-\chi_R)\dot{Q}_f.$$

The term $\dot{Q}_c$(fire) then becomes the driving term in the plume flow. In the actual implementation these formulas are modified somewhat. For a specified fire there is radiation to both the upper and lower layers, whereas the convective part contributes only to the upper layer. For the radiative portion a view factor must be calculated. Currently we do this on the basis of the view factor for the interface as seen from the fire source. The view factor is calculated on the basis of a tetrahedron formed by the point source fire, and the interface rectangle.

If the fire is constrained by the amount of available oxygen, then we can calculate a species balance. The scheme is applied in three places. The first is burning in the portion of the plume which is in the lower layer of the room of fire origin (region #1). The second is the portion in the upper layer, also in the room of origin (region #2). The third is in the vent flow which entrains air from a lower layer into an upper layer in an adjacent compartment (region #3). Figure 3 is a schematic of the concept of division of burning regions.

The species which are affected by this scheme are O_2, CO_2, CO, H_2O, unburned hydrocarbons (TUHC), and soot (OD). In a chemical equation, the individual atoms on the left and right hand sides must balance. This is true regardless of whether the reaction is considered to be stoichiometric. We apply this idea to the combination of fuel and oxygen to yield a balance of number density (#/volume) as follows:

$$(C_{N_C} H_{N_H} O_{N_O}) + N_{O_2} \rightarrow N_{CO_2} + N_{H_2O} + N_{CO} + N_S^{3}. \tag{23}$$

Equating like species (take the separate components of the orthonormal set representing the constituent atoms),

[3] In the present context soot consists only of carbon. Also we do not maintain a separate variable for the number density of soot as opposed to the mass density, so N_S is actually the production rate of carbon atoms. Thus, $m_S = 12\ N_S$.

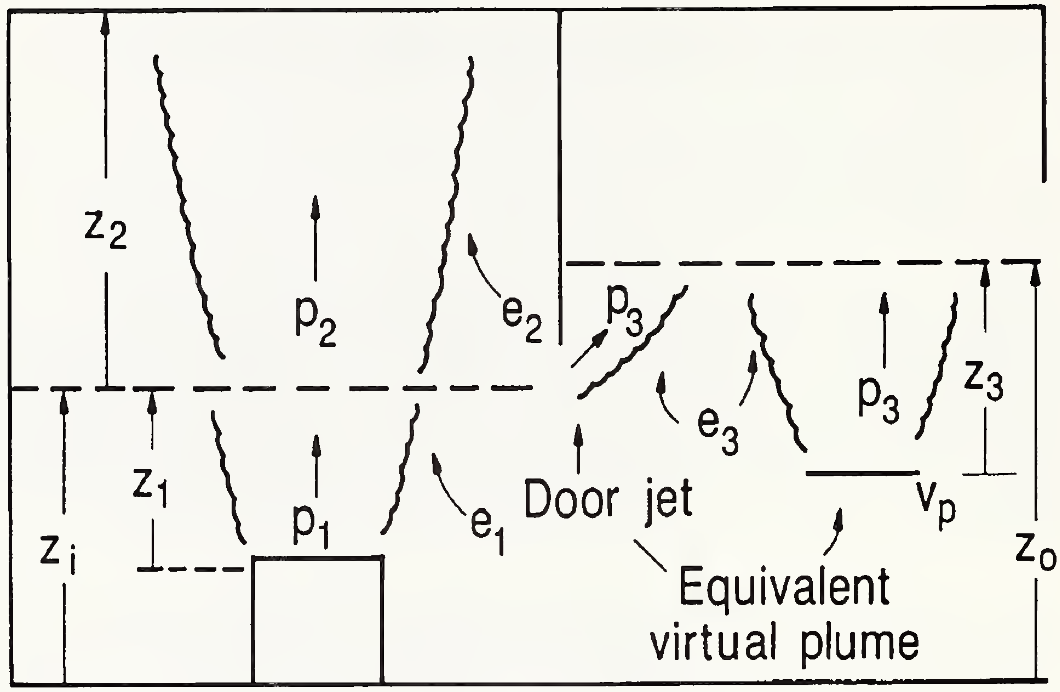


Figure 3. Schematic of entrainment and burning regions.

$$N_H = 2\ N_{H_2O} \tag{24}$$

$$N_C = N_{CO_2} + N_{CO} + N_S \tag{25}$$

$$N_O = 2\ N_{CO_2} + N_{H_2O} + N_{CO} - 2\ N_{O_2}\ . \tag{26}$$

This is the most general scheme which will be considered at present. The third equation (for O_2 balance) is not actually used in the following discussion but is included for completeness. Later there is a discussion of a more general scheme and the difficulties which might be encountered. A point to note is that we assume that the oxygen content of the fuel is negligible. If oxygen is a significant component of the fuel, the mass pyrolysis rate which is used to specify the fire should be reduced by the percentage of oxygen present.

The relative amounts of carbon and carbon monoxide are then specified with respect to the amount of carbon dioxide produced as

$$\frac{N_S}{N_{CO_2}}, \quad \frac{N_{CO}}{N_{CO_2}}, \text{ with } \frac{N_H}{N_C} \text{ giving the hydrogen/carbon ratio of the fuel.}$$

These parameters are functions of time and the type of fuel. With these definitions in mind, equate like species and take first order time derivatives to obtain

$$\dot{N}_{CO_2} = \frac{\dot{N}_C}{1 + \frac{N_{CO}}{N_{CO_2}} + \frac{N_S}{N_{CO_2}}}$$

$$\dot{N}_{H_2O} = \tfrac{1}{2}\, \dot{N}_C \left(\frac{N_H}{N_C} \right). \tag{28}$$

Time derivatives of the densities rather than the actual densities themselves are used. Although the balance is done for the atoms, the primary interest is in how the number of each species is changing. Obviously, if the number density is correct for all time, then the time rate of change of this density is also always correct.

For consistency in the model, it is more convenient to express these numbers in terms of masses rather than mole or number density. After the transformation from number density to mass density we have[4]

input:

$\dot{m}$(fuel) = pyrolysis rate of the source (kg/sec) (region #1)

or

$\dot{m}$(fuel) = $\dot{m}$(tuhc) from a previous region (kg/sec) (region #2 and #3)

[4] The terms in parenthesis (burn, fuel, tuhc etc.) are equivalent to the subscripts (b, f, tuhc, etc.) but are written out in the form found in the parameterization in the FORTRAN implementation. It is hoped that this will clarify the use of these equations in the code itself.

with the constraint:

$$\dot{m}(\text{burn}) = \min\left([O_2]_{\text{entrained}} \frac{1.32\text{x}10^7}{h_c}, \dot{m}(\text{fuel})\right) \tag{29}$$

and results:

$$\dot{m}(\text{tuhc}) = \dot{m}(\text{fuel}) - \dot{m}(\text{burn}) \tag{30}$$

$$\dot{q} = \dot{m}(\text{burn}) \times h_C \tag{31}$$

$$\dot{m}(\text{oxygen}) = - \frac{\dot{q}}{1.32\text{x}10^7} \tag{32}$$

$$\dot{m}(H_2O) = 9 \frac{\dot{m}(\text{burn})}{\left[1 + \left(\frac{m_H}{m_C}\right)\right]} \left(\frac{m_H}{m_C}\right) \tag{33}$$

$$\dot{m}(CO_2) = \frac{3.67\ \dot{m}(\text{burn})}{\left[1 + \left(\frac{m_H}{m_C}\right)\right]\left[1 + 1.57 \frac{m_{CO}}{m_{CO_2}} + 3.67 \frac{m_S}{m_{CO_2}}\right]} \tag{34}$$

$$\dot{m}(CO) = \dot{m}_{CO_2} \left(\frac{m_{CO}}{m_{CO_2}}\right) \tag{35}$$

$$\dot{m}(S) = \dot{m}_{CO_2} \left(\frac{m_S}{m_{CO_2}}\right). \tag{36}$$

The term $[O_2]$ is the amount of entrained oxygen multiplied by a factor to force cutoff of burning at the limiting oxygen index. The term $[O_2]$ is calculated as follows:

o2index = max (0.,(o2frac-limo2)*4.83)
o2mass = o2entr * 0.995 * (1-exp(-10*o2index))

where 4.83 is the inverse of 20.7%. The term "fuel" implies no oxygen in the present context. If there is oxygen in the original fuel, then the net production of unburned hydrocarbons will be incorrect. If this is the case, the prescribed fuel production must be decreased by the fraction of oxygen present. The energy balance is not affected by this change.

For region #1, the source will be the fuel source itself; for regions #2 and #3, the source will be the $\dot{m}$(tuhc) flowing from the previous region. The number $1.32\text{x}10^7$ is the heat release rate per kilogram of oxygen consumed as discussed by Huggett [13]. Thus for each region, the burning rate is the minimum of the two possible rates, the rate due to the fuel present, and the rate due to the oxygen present. Note that the production and fuel ratios are now in terms of masses. The limit on the hydrogen-carbon ratio should be zero to one third. Obviously this is not quite the correct effect for a general fuel such as a piece of furniture or a cable, but should suffice at least to get started. Given the above production rates, the carbon monoxide and soot fraction can be calculated in terms of carbon dioxide. These latter two are just the terms in the denominator of the CO_2 production rate. As pointed out earlier, an assumption has been made that soot is composed primarily of carbon. A more complete description should be undertaken, but this would complicate the above scheme considerably.

4.6 Source Terms: Conduction (Implemented in CNDUCT)

Conduction of heat through solids is not a source term in the sense discussed earlier. That is, loss or gain of energy from solids occurs by convective heating, which in turn is influenced by subsequent gain or loss through the solids. However, as much of the net heat loss from a compartment occurs through loss to the walls and heating of interior objects, the form of the heat propagation will be discussed here.

The equation which governs the heat transfer in solids is

$$\frac{\partial T}{\partial t} = \frac{k}{\rho \ c} \nabla^2 T \tag{37}$$

and is a linear parabolic equation. As such it must be solved by a different technique than is used for the ordinary differential equations which describe mass and enthalpy flux. The equation is linear only if the coefficients k, ρ and c are constant throughout the material. This may not be the case, especially for some materials such as gypsum for which the value of k may vary by a factor of two or more. However, to the accuracy that we know the thermal properties, it is a reasonable approximation. For a given wall we allow multiple layers (slabs) whose properties can differ. As explained in section 5.6, eq (37) is then solved for each layer as a linear system with the appropriate boundary conditions between the layers.

In order to couple these systems in a reasonable way, we appeal to the principle of time splitting. Simply stated we have two systems of equations which can be decoupled and solved independently as long as the time step used is short compared to the characteristic time scale for either set of equations. For fires of interest, wall temperatures change on the order of minutes. By using a time step of no more than 0.2 seconds, the applicability of time splitting is assured. This decoupling breaks down for very large fires (larger than 50 MW) when the radiant flux to a wall can cause its surface and subsurface temperatures to change in seconds rather than minutes. Of greater interest is the number of nodes used for the actual numerical calculation. As discussed below, we use 48 nodes (36 in the PC version) for this calculation. This is a compromise between computer memory required and the computation time required. The method used (discussed later) is referred to as a Crank-Nicholson scheme and is absolutely stable and convergent. The only difficulty is that with only a few nodes, iteration may be required if the heat flux boundary condition is changing rapidly. With a sufficient number of nodes, a single pass through the solver is sufficient. However, this requires additional computer memory. Most of the time, a single pass is sufficient with our choice of node structure.

Heat conduction is calculated on a compartment by compartment basis, with each bounding surface specified and calculated independently. Any combination of compartments and surfaces within a compartment can be specified. For example, both the ceiling and walls might be done in the room of fire origin and only the walls in the adjacent hallway. At present conduction is one dimensional only, perpendicular to the bounding surface. It is a limitation in moving from compartments near the fire source to distant spaces. In particular, the mechanism for complete mixing is flow down the walls and the degree of mixing is affected by heat conduction parallel to the wall, especially in the direction in which the interface is moving. A corollary is that the wall in contact with the gas layer changes temperature instantaneously as the layer interface moves up and down. This inconsistency would be removed with the introduction of a two dimensional heat flow calculation. As discussed by Goldman et al. [14] the phenomena can be important, especially as the thermocline in the wall will influence the direction in which the wall boundary flow propagates.

Conduction through solids occurs in two places: the compartment walls and interior objects. The technique used is the same in both cases, although the boundary conditions on the equation may be different. Generally a slab is cut into N intermediate slices or N+1 nodes. Then the one dimensional form of the heat equation is solved for each slice. It is the choice of the maximum number of nodes that is a compromise between precision and computation time. The finite difference implementation of the equation is a time-centered, implicit scheme which is symmetric about the nodes. For interior nodes we have

$$T'_i(1+\eta) = \frac{\eta}{2}(T'_{i+1} + T'_{i-1}) + \left(T_i + \frac{\eta}{2}(T_{i+1} - 2T_i + T_{i-1})\right) \tag{38}$$

and for boundary or edge nodes we have

$$T'_1\left(1+\frac{\eta}{2}\right) = \frac{\eta}{2}\left(T'_2 + \frac{\Delta x\dot{Q}_c}{k}\right) + \left(T_1 + \frac{\eta}{2}\left(T_2 - T_1 + \frac{\Delta x\dot{Q}_c}{k}\right)\right) \tag{39a}$$

$$T'_N\left(1+\frac{\eta}{2}\right) = \frac{\eta}{2}\left(T'_{N-1} - \frac{\Delta x\dot{Q}_c}{k}\right) + \left(T_N + \frac{\eta}{2}\left(T_{N-1} - T_N - \frac{\Delta x\dot{Q}_c}{k}\right)\right) \tag{39b}$$

where $\eta = \frac{\Delta t}{(\Delta x)^2} \frac{k}{\rho c}$.

The former is for the interior boundary and the latter for the exterior boundary (i=N). The temperature at the starting time at node "i" is T_i and at time $t+\delta t$ is $T_{i'}$.

To solve this system of equations, two boundary conditions must be specified. For this problem mixed boundary conditions are used. For the inside edge (adjacent to the gas layer) there is a heat flux which is comprised of convective and radiative components. On the outside the ambient is fixed and an outflow boundary condition is calculated based on an average convective heat flow coefficient and the temperature of the last node. Both boundary conditions are represented symbolically as $\dot{Q}_c$.

One limitation of our implementation of conduction is that it serves only as a loss term for energy. Heat lost from a compartment by conduction is assumed to be lost to the outside ambient. In reality, compartments adjacent to the room which contains the fire can be heated, possibly catastrophically, by conducted energy not accounted for in the model. Although solving the conduction equations for this situation is not difficult, the geometrical specification is. For this reason, we have chosen to assume that the outside of a boundary is always the ambient.

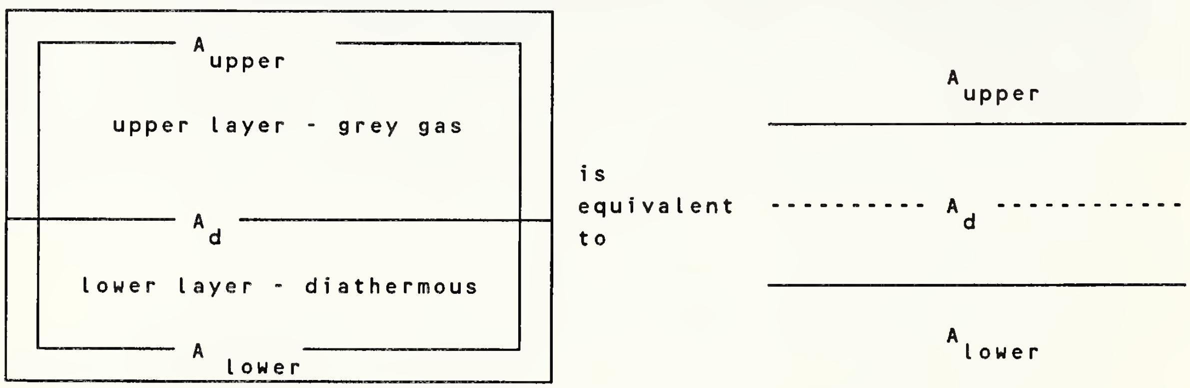
We allow for multi-layered walls, floors and ceilings. This requires additional internal boundary conditions at each material interface. Two additional nodes are necessary. These are used to force continuity of the heat flux across each interface.

5. SOURCE MODULES

The routines described below come directly from the FAST program. The modules have been annotated to make them more understandable. For example, comments within the code which are directives for changing the routines are not included. There are also comments which appear here which are not shown in the actual code. The part that is strictly in upper case is FORTRAN code, whereas text in lower or mixed case are extra comments.

5.1 FIRRAD (sec. 4.1)

This routine calculates the quasi-steady radiative flux between one gas layer and two walls. The wall surfaces are the extended floor and ceiling. That is, the extended ceiling is the sum of the areas of the ceiling and upper wall, and similarly for the extended floor. This routine is coded from the work of Siegal and Howell [5]. It assumes two flat plates facing a single grey sphere. The view factor for a hemisphere facing a flat plate can be integrated analytically. The lower layer is assumed to be diathermous, so it need not be taken into account. However, the interface between the lower wall and the atmosphere in the upper layer is the actual discontinuity area, so the view factors correspond to appropriate areas.



There are three surface areas of interest: A_{upper}, the area of the extended upper surface; A_{lower}, the area of the extended lower surface; and A_d the area of the interface, that is the separation between the upper and lower layers.

```
SUBROUTINE FIRRAD(T, TG, AW, AD, EPR, EG, QSRAD, QRADG, NC)

FAST COMMON BLOCK GOES HERE
```

```
      DIMENSION T(4),AW(2),EP(2),PI(2),QRAD(4),QSRAD(4,NC),QRADG(2,NC)
      DIMENSION TG(2),EPR(4)
```

aw(1) = A_{upper}

aw(2) = A_{lower}

ad = area of the discontinuity - generally same as floor area
t and tg are the wall and gas temperatures, respectively
epr and eg are the emissivities of the walls and gas layer, respectively
f11, f12, f21 and f22 are the view factors between the surfaces

```
      F11=1.-AD/AW(1)
      F12=AD/AW(1)
      F21=AD/AW(2)
      F22=1.-AD/AW(2)
      EP(1) = MAX(EPR(1), EPR(3))
      EP(2) = MAX(EPR(2), EPR(4))
      S0 = EG * SIGM * TG(UPPER)**4
```

use of the "max" function resolves the conflict between four walls in convection and two walls in radiation

```
      S1 =      SIGM * MAX(T(1),T(3))**4
      S2 =      SIGM * MAX(T(2),T(4))**4

      D=(1.-(1.-EP(1))*(1.-EG)*F11)*(1.-(1.-EP(2))*F22)
     1  -(1.-EP(1))*(1.-EP(2))*(1.-EG)**2*F12*F21
      PI(1)=((1.-(1.-EG)*F11)*(1.-(1.-EP(2))*F22)
     1  -(1.-EP(2))*(1.-EG)**2*F12*F21)*S1
     2  -(1.-EG)*F12*EP(2)*S2
     3  -(1.+(1.-EP(2))*((1.-EG)*F12*F21-F22))*S0
      PI(2)=((1.-(1.-EP(1))*(1.-EG)*F11)*(1.-F22)
     1  -(1.-EP(1))*(1.-EG)**2*F12*F21)*S2
     2  -(1.-EG)*F21*EP(1)*S1
     3  -((1.-(1.-EP(1))*(1.-EG)*F11)*F21+(1.-EP(1))*(1.-EG)*F21)*S0

      ONED = 1. / D
      DO 10 I = UPPER, LOWER
```

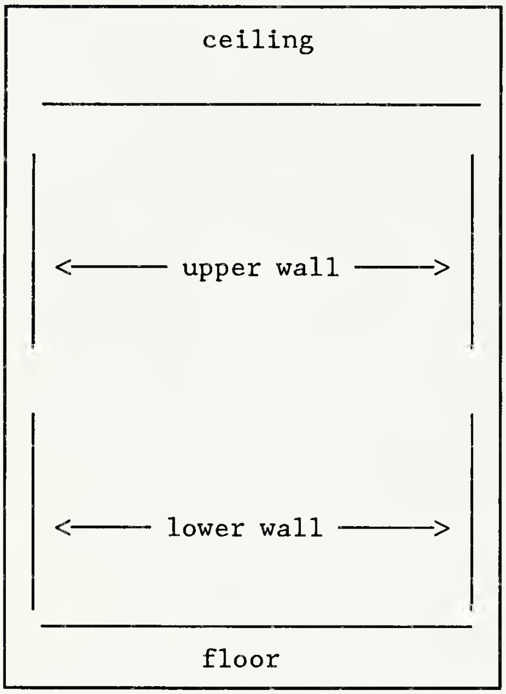
qsrad is the radiation to the surfaces, and qradg is the total radiative heat flux into the gas

```
      QSRADL       = -EP(I) * PI(I) * ONED
      QSRAD(I,NC) = QSRADL
   10 QRAD(I)      = QSRADL * AW(I)
      QRADG(UPPER,NC) = - (QRAD(UPPER) + QRAD(LOWER))
```

```
      QRADG(LOWER,NC) = 0.0
      RETURN
      END
```

5.2 CONVEC (sec. 4.2)

The model allows for a ceiling, floor and two walls. Actually the two walls are always the same material, but a separate temperature profile is maintained for the wall in contact with the upper and lower zones, respectively. Therefore we have four components for convective heat transfer.



Division of Boundaries for Convective Heating Routine

$$h = \frac{lmd}{l}\ NU = \frac{lmd}{l}\ C\ (Gr\ Pr)^{1/3}$$

Orientation	Coefficient	Condition
walls	0.130	all
ceiling and floor	0.210	$T_g > T_w$
ceiling and floor	0.012	$T_g < T_w$

The coefficient in the above table is the "C" in the previous equation.

Reference [6] discusses this aspect.

```
      SUBROUTINE CONVEC(IW, TG, TW, AW, QDINL, QCNVGO)
C     TG = GAS LAYER TEMPERATURE
C     TW = WALL TEMPERATURE OF WALL "IW"
C     AW = AREA OF THIS WALL
C     ANET = TOTAL AREA OF WALL "IW" IN CONTACT WITH THE GAS LAYER (TG)
C     QDINL = HEAT CONVECTIVE FLUX TO THE WALL BOUNDING THIS GAS LAYER
C     QCNVGO = NET CONVECTIVE HEAT FLUX TO THE GAS LAYER
```

```
      FAST COMMON BLOCK GOES HERE
      REAL LMD,NU
```

pr = Prandtl number = 0.72 for air
nu = Nusselt number
lmd = lambda = an equivalent conductivity for air
v = viscosity of air

The power law for turbulent flow is 1/3 and for laminar flow it is 1/4. We have simplified the convection calculation by using only the turbulent flow power law. If a more general relationship is used, then the following note shows how to convert the final "q" to yield the correct relationship between the heat transfer and the heat transfer coefficient as formulated by the Nusselt number.

```
      PR=0.72
      V=7.18E-10*((TW+TG)/2.)**(7./4.)
      LMD = 2.72E-4 * ((TW+TG)*0.5)**0.8

C     NOTE: GRASHOF NUMBER HAS THE L**3 DIVIDED OUT TO
C           PREVENT DIVIDE BY ZERO ERRORS AS THE SURFACE
C           VANISHES - DEPENDS ON THE NU(1/3) POWER.
C           RESULT MUST BE MULTIPLIED BY (L**3)**(1/A)*L/(L**2) WHERE
C           A IS THE POWER IN THE NUSSELT NUMBER CALCULATION AND
C           L = SQRT(AW)

      GR=G*ABS(TG-TW)/(V**2*TG)

      GO TO (20,30,10,10),IW

C     VERTICAL WALL

   10 NU=0.13*(GR*PR)**(1./3.)
      GO TO 40

C     CEILING

   20 IF(TG.LT.TW) GO TO 21
      NU=0.21*(GR*PR)**(1./3.)
      GO TO 40
   21 NU=0.012*(GR*PR)**(1./3.)
      GO TO 40

C     FLOOR

   30 IF(TG.LT.TW) GO TO 31
      NU=0.012*(GR*PR)**(1./3.)
```

```
      GO TO 40
   31 NU=0.21*(GR*PR)**(1./3.)

   40 QDINL = LMD * NU * (TG-TW)
      QCNVGO = QCNVGO - QDINL * AW
      RETURN
      END
```

5.3 FIRPLM (sec. 4.3)

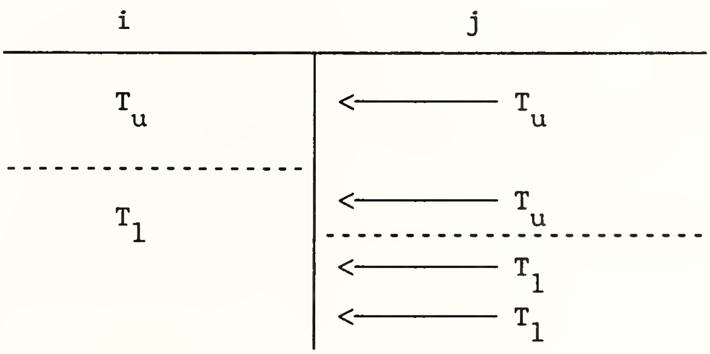
```
      SUBROUTINE FIRPLM(QJL, Z, R, FMZ, EMZ, LFBT)

C     "Momentum Implications for Buoyant Diffusion Flames"
C     Combustion and Flame 52,149(1983)

C     LFBT = FIRE TYPE FOR ENTRAINMENT MODIFICATION
C     QJ = FIRE SIZE (W)
C     R  = MASS LOSS RATE OF THE FIRE
C     FMZ = TOTAL MASS TRANSFER RATE AT THE TOP OF THE PLUME
C     EMZ = NET MASS ENTRAINMENT RATE
C     Z = PLUME HEIGHT

      DIMENSION F(4)
      DATA F/1.,2.,4.,1./

C     NOTE UNITS CONVERSION JOULES->KILOJOULES

      QJ = 0.001 * QJL
      IF(Z.GT.0.) THEN
        IF(QJ.GT.0) THEN
          ZDQ=Z/(F(LFBT)*QJ)**0.4
          IF(ZDQ.GT.0.2) THEN
            FMZ = 0.124* ZDQ**1.895 * QJ
          ELSE IF (ZDQ.GT.0.08) THEN
            FMZ = 0.026 * ZDQ**0.909 * QJ
          ELSE
            FMZ = 0.011 * ZDQ**0.566 * QJ
          ENDIF
          FMZ = MAX (R, FMZ/F(LFBT))
          EMZ = MAX (FMZ-R, 0.0)
        ELSE
          FMZ = R
          EMZ = 0.0
        ENDIF
      ELSE
        FMZ=R
```

```
  EMZ=0.0
ENDIF
RETURN
END
```

5.4 FLOW, FRFLOW AND ENTRFL (sec. 4.4)

Fluid flow is the primary mechanism for transport of mass and enthalpy from one compartment to another. We divide flow into two classes which we refer to as horizontal and vertical flow. The terms are symbolic of the approximate direction of the flow with respect to gravity. Vertical flow is parallel to the direction of gravity and horizontal flow is perpendicular. Vents are then named by the same convection, so HVENT is the acronym for vents through which there will be horizontal flow and are referred to as "horizontal vents," and VVENT is the equivalent specification for vertical flow and "vertical vents." Unlike the plume model, there is no constraint on the amount of gas entrained, except that it must satisfy the equivalency principle discussed earlier. So it is possible for short (low soffit) vents in tall compartments to overestimate the amount of gas entrained.

The following three routines calculate fluid movement which nominally is in a horizontal direction. The following schematic illustrates the normal rule used to deposit fluid which flows from one compartment to another.



This selection rule is that the upper layer gases flow into an upper layer, and similarly for the lower layer. However, for an outside ambient that is warmer or colder than either layer, the in-flow must force air into one or the other, respectively. As an example, if we are modeling a warm building in a winter scenario, the air which infiltrates the building should go into the lower layer. The modified selection rules become

$T_\ell(j) < T_u(j) < T_\ell(i) < T_u(i)$ ——— all into lower layer

$T_\ell(j) < T_\ell(i) < T_u(j) < T_u(i)$

$T_\ell(i) < T_\ell(j) < T_u(j) < T_u(i)$

$T_\ell(j) < T_\ell(i) < T_u(i) < T_u(j)$

$T_\ell(j) < T_\ell(i) < T_u(i) < T_u(j)$

——> usual selection rules (see above)

$T_\ell(i) < T_u(i) < T_\ell(j) < T_u(j)$ ——— all into upper layer

The first routine (FLOW) simply adjusts the boundary conditions for interior or exterior flow and does the redundancy check mentioned earlier on the symmetry aspects of the bidirectional flow.

```
      SUBROUTINE FLOW(I, J, K, TU, Z, TL)

i and j specify two compartments, and k is the vent number (1->4)
tu and tl are the upper and lower layer temperatures respectively
z is the interface height

      DIMENSION TU(N), Z(N), TL(N), R(4) , TM(4,4), ZN(6)
      RG(I) = (RAMB(I) * TAMB(I)) / (PAMB(I)+POFSET)

C     IF WE REFER TO THE OUTSIDE COMPARTMENT, THEN THE INTERFACE
C     MUST REFER TO THE EXTERNAL AMBIENT, WIND INCLUDED

      IF (I.LT.N) THEN
        R(1) = (RAMB(I)*TAMB(I))/(PAMB(I)+POFSET) * (P(I)+POFSET)/TU(I)
        R(2) = (RAMB(I)*TAMB(I))/(PAMB(I)+POFSET) * (P(I)+POFSET)/TL(I)
        PI =   P(I)
        ZAI =  HRP(I) - Z(I)
        HFI =  HFLR(I)
      ELSE
        R(1) = ERA(J)
        R(2) = ERA(J)
        PI =   EPA(J)
        ZAI =  1.E+5
        HFI =  HFLR(J)
      ENDIF
      IF (J.LT.N) THEN
        R(3) = (RAMB(J)*TAMB(J))/(PAMB(J)+POFSET) * (P(J)+POFSET)/TU(J)
```

```
    R(4) = (RAMB(J)*TAMB(J))/(PAMB(J)+POFSET) * (P(J)+POFSET)/TL(J)
    PJ =   P(J)
    ZAJ =  HRP(J) - Z(J)
    HFJ =  HFLR(J)
  ELSE
    R(3) = ERA(I)
    R(4) = ERA(I)
    PJ =   EPA(I)
    ZAJ =  1.E+5
    HFJ =  HFLR(I)
  ENDIF

C     START WITH THE ASSUMPTION THAT R(I) < R(J) - THIS REMOVES THE
C     SYMMETRY

      IF(R(1).GT.R(3)) RETURN

C     FIND THE WIDTH BY MULTIPLYING THE OPENING BY THE WIDTH FRACTION FROM
C     CVENT

      IF (ITERPT.EQ.1) THEN
         FACTOR = (QCVENT(I,J,K,ITIME1)*TIMEI1-QCVENT(I,J,K,ITIME2)*
     .            TIMEI2) * TIMEI3
      ELSE
         FACTOR = QCVENT(I,J,K,LFMAX+1)
      ENDIF

      HHO = HHP(I,J,K)
      HLO = HLP(I,J,K)
      BWO = BW(I,J,K) * FACTOR
      CALL FRFLOW(PI,PJ,HFI,HFJ,ZAI,ZAJ,R,HLO,HHO,BWO,TM,IZN,ZN)

C     KEEP TRACK OF THE NUMBER OF NEUTRAL PLANES, BUT NOT THE ACTUAL
C     POSITION OF THE NEUTRAL PLANE(S)

      NEUTRAL(I,J) = IZN

      RETURN
      END
```

The routine FRFLOW does the actual integration along the vertical axis of the vent, that is from z_1 to z_2 (see eq (16)). A more detailed discussion of the algorithm is given in reference [15]. The effects of wind are included in the external pressure applied to a vent which is connected to the outside ambient. As such, it does not explicitly show up in the calculations, but is part of the term EPA above. We use the equation for pressure as a function of height as given in reference [17]. Starting with an initial temperature and pressure of T_a, P_a for the ambient at the station, we can calculate the pressure at a height H_i. The station information is at a reference height H_r, and the wind speed is V_w at a relative height H_w above the reference height H_r. The form for the pressure with the wind added is

$$P_w \rightarrow P_a \left(\frac{T_a - 0.0065\ H_i}{T_a + 0.0065\ H_r}\right)^{5.26} \left(1 + \frac{C_w * V_w}{2\ R\ (T_a - 0.0065 H_i)} \left(\frac{H_i}{H_w}\right)^{p_w}\right).$$

The power law p_w defines the lapse rate for the pressure, and the coefficient C_w is the relative effect that the wind will have on an opening. It varies from -1 to +1 and is the dot product of the wind direction vector and the vent direction.

```
      SUBROUTINE FRFLOW(PIO,PEO,HI,HE,ZI,ZE,RH,BF,HF,ALF,TM,IZN,ZN)

C     PIO = PRESSURE AT A CERTAIN REFERENCE LEVEL, SIDE I
C     PEO =  " " " " "  THE SAME   " " " " " " , SIDE E
C     ZI  = DISCONTINUITY HEIGHT, SIDE I (OVER REF. LEVEL)
C     ZE  =  " " " " " " " " " " " " " E   " " " " " " "
C     RH(1)= GAS DENSITY OF THE UPPER LAYER, SIDE I
C     RH(3)=  " " " " " " " " " " " " " " " " " " E
C     RH(2)=  " " " " " " " " " LOWER " " " " " " I
C     RH(4)=  " " " " " " " " " " " " " " " " " " E
C     BF  = OPENING SILL HEIGHT (OVER REF. LEVEL)
C     HF  =  " "  SOFFIT " " " " " " " " " " " "
C     ALF = " " "  WIDTH
C     CD  = CONSTRICTION COEFFICIENT

C     ZN  = TABLE OF THE NEUTRAL PLANE HEIGHTS COMPUTED IN THE
C           THE OPENING: AS TWO OF THESE MAY BE EQUAL, THE DIMENSION
C           IS 6, BUT THERE ARE AT MOST THREE NEUTRAL PLANE HEIGHTS.
C           THE INITIAL VALUES ARE 100000 METERS.

C     TM  = TABLE(4,4) OF THE MASS FLOW RATES THROUGH OPENING, EACH
C           ELEMENT TM(I,J) REPRESENTING THE ABSOLUTE VALUE OF THE MASS
C           FLOW RATE (IF ANY) FROM I TO J (IF NOT: TM(I,J)=-0)
C            1 IS RELATIVE TO THE UPPER GASEOUS LAYER, SIDE I
C            2  " " " " " " " " " LOWER " " " " " " " " " " "
C            3  " " " " " " " " " UPPER " " " " " " ", SIDE E
C            4  " " " " " " " " " LOWER " " " " " " " " " " "

      DIMENSION RH(4),TM(4,4),ZN(6)
      DATA G/9.80665/ , CD/0.7/, DMP/1.0/
      DATA ZERO/0./

C    INITIALIZATION
```

```
      DO 1 K=1,4
      DO 1 L=1,4
1     TM(K,L)=0
      DO 2 K=1,6
2     ZN(K) = 100000.
      IZN = 0
      I=2
      J=4
      DPO = PIO - PEO
      DPI = G * (MIN(ZI,BF-HI)*RH(2) + MAX(ZERO,BF-ZI)*RH(1))
      DPE = G * (MIN(ZE,BF-HE)*RH(4) + MAX(ZERO,BF-ZE)*RH(3))
      DP =  DPO + DPE - DPI
      TTCA = 0.6666667 * CD * ALF

C     MAIN LOOP: INTEGRATION OVER INTERVALS [ZA,ZB] FROM BF TO HF

      ZA = BF
10    ZB = HF

C     FLOW RATE FROM OR TO ZONE 1 IF ZI <= ZA

      IF(ZI.LE.ZA)THEN
        I = 1

C     MAKE ZB=MIN(HF,ZI) IF ZA < ZI < ZB

      ELSE IF (ZI.LT.ZB)THEN
        ZB = ZI
      END IF

C     FLOW RATE TO OR FROM ZONE 3 IF ZE <= ZA

      IF(ZE.LE.ZA)THEN
        J = 3

C     MAKE ZB=MIN(HF,ZI,ZE) IF ZA < ZE < MIN(HF,ZI)

      ELSE IF (ZE.LT.ZB)THEN
        ZB = ZE
      ENDIF

C     EXPRESSION OF PRESSURE DIFFERENCES IN ZA AND ZB

      DPA = DP
      DPB = DPA+(RH(J)-RH(I))*G*(ZB-ZA)

C     NO NEUTRAL PLANE IN [ZA,ZB]
```

```
      IF (DPA*DPB.GT.ZERO)THEN
C     .....FROM I TO J

        IF (DPA.GT.ZERO)THEN
          X = SQRT(DPA)
          Y = SQRT(DPB)
          XX = MIN(X,Y)
          YY = MAX(X,Y)
          Y2 = YY * YY
          TM(I,J) = TTCA * SQRT(2.*RH(I))*(ZB-ZA)*(XX+YY/(1.+XX/YY))
                  * TTCB(DMP,Y2) + TM(I,J)

C     .....FROM J TO I

        ELSE
          X = SQRT(-DPA)
          Y = SQRT(-DPB)
          XX = MIN(X,Y)
          YY = MAX(X,Y)
          Y2 = YY * YY
          TM(J,I) = TTCA * SQLRT(2.*RH(J))*(ZB-ZA)*(XX+YY/(1.+XX/YY))
                  * TTCB(DMP,Y2) + TM(J,I)
        ENDIF

C     NEUTRAL PLANE HEIGHT IN [ZA,ZB]

      ELSE IF (DPB.EQ.ZERO.AND.DPA.EQ.ZERO)THEN
        IZN = IZN + 1
        ZN(IZN) = (ZA+ZB)/2
      ELSE
        IZN = IZN+1
        ZN(IZN) = ZA-(DPA/(DPB-DPA))*(ZB-ZA)

C     ..BOTTOM FLOW I TO J

        IF(DPA.GT.DPB)THEN
          TM(I,J) = TTCA*(ZN(IZN)-ZA)*SQRT(2.*RH(I)*DPA)
     .            * TTCB(DMP,DPA) + TM(I,J)
          TM(J,I) = TTCA*(ZB-ZN(IZN))*SQRT(-2.*RH(J)*DPB)
     .            * TTCB(DMP,-DPB) + TM(J,I)

C     ..BOTTOM FLOW J TO I

        ELSE
          TM(J,I) = TTCA*(ZN(IZN)-ZA)*SQRT(-2.*RH(J)*DPA)
                  * TTCB(DMP,-DPA) + TM(J,I)
```

```
        TM(I,J) = TTCA*(ZB-ZN(IZN))*SQRT(2.*RH(I)*DPB)
                * TTCB(DMP,DPB) + TM(I,J)
      ENDIF
    ENDIF

C   REASSIGN LOWER BOUND AND LOWER BOUND PRESSURE DIFFERENCE

    IF (ZB.GE.HF) RETURN
    ZA = ZB
    DP = DPB
    GO TO 10
    END
```

We now can do the entrainment for the flow through vents.

```
    SUBROUTINE ENTRFL(TU, TL, FMD, Z, FMZ)
```

the conversion from Watts used by FAST to the units of McCaffrey [7] is the factor .001.

```
    XQJ = CP * (TU-TL) * 0.001
    QJ = XQJ * FMD
    FMDQJ = 1. / XQJ
    Z0DQ = (FMDQJ/0.011)**1.767
    IF(Z0DQ.LE.0.08) GO TO 10
    Z0DQ = (FMDQJ/0.026)**1.1001
    IF(Z0DQ.LE.0.20) GO TO 10
    Z0DQ = (FMDQJ/0.124)**0.528

 10 ZDQ = Z/QJ**0.4 + Z0DQ
    IF(ZDQ.GT.0.2) THEN
      FMZ = 0.124 * ZDQ**1.895 * QJ
    ELSE IF (ZDQ.GT.0.08) THEN
      FMZ = 0.026 * ZDQ**0.909 * QJ
    ELSE
      FMZ = 0.011 * ZDQ**0.566 * QJ
    ENDIF
```

the following statement insures that the entrainment is physical. We are limited by the correlation that we use of momentum driven jets are strictly functions of the heat release rate.

```
    FMZ = MAX (0.0, FMZ-FMD)
    RETURN
    END
```

5.5 PYROLS, CHEMIE (sec. 4.5)

A specified quantity is any quantity for which there is a specified time history. The specification is set of data of the quantity of interest as a function of time. To obtain values between the specified points, we use an interpolating polynomial. The routine PYROLS calculates the coefficients of the interpolating polynomial and most of the specified quantities. The values for CVENT are actually done in FLOW, but with the same interpolation coefficients. The output from PYROLS is then used by CHEMIE to calculate the burning rate. If a type 1 fire is selected (unconstrained) then the burning rate is set to the pyrolysis rate, and the heat release rate is found by multiplying the burning rate by the heat of combustion. Otherwise, the prescription discussed in section 4.5, and shown below, is used to constrain the burning rate based on both the fuel and oxygen available.

```
      SUBROUTINE PYROLS(TIME, BFIRET, AFIRET, HFIRET, QFIRET,
     . HCOMBT)

C     PYROLYSIS RATE OF THE FUEL - HCRATT IS IN COMMON SINCE IT IS USED
C     IN SEVERAL PLACES

      FAST COMMON BLOCK GOES HERE

      IF(TIME.GE.TFMAXT) GO TO 20
    1 TI0 = TFIRET
      TI = TI0 + TFIRED(IFIRED)
      I = IFIRED
      IF(TIME.LE.TI) GO TO 10
      IFIRED = IFIRED + 1
      IF(IFIRED.GT.LFMAX) GO TO 20
      TFIRET = TI
      GO TO 1

C     TYPE 1 INTERPOLATION - ITERPT = 1

these are the interpolating coefficients

   10 TI1 = TI - TIME
      TI2 = TI0 - TIME
      OVTFD = 1. / TFIRED(I)
      ITERPT = 1

this is the interpolating polynomial

      BFIRET = (TI1 * BFIRED(I) - TI2 * BFIRED(I+1)) * OVTFD
      AFIRET = (TI1 * AFIRED(I) - TI2 * AFIRED(I+1)) * OVTFD
      HFIRET = (TI1 * HFIRED(I) - TI2 * HFIRED(I+1)) * OVTFD
```

```
      QFIRET = (TI1 * QFIRED(I) - TI2 * QFIRED(I+1)) * OVTFD
      HCRATT = (TI1 * HCRATIO(I)- TI2 * HCRATIO(I+1)) * OVTFD
      CCO2T = (TI1 * CCO2(I) - TI2 * CCO2(I+1)) * OVTFD
      COCO2T = (TI1 * COCO2(I)  - TI2 * COCO2(I+1)) * OVTFD
      HCOMBT = (TI1 * HOCBMB(I) - TI2 * HOCBMB(I+1)) * OVTFD
      DO 15 J = 1, NS
      IF(.NOT.ACTIVS(J)) GO TO 15
      MFIRET(J) = (TI1*MPRODR(I,J) - TI2*MPRODR(I+1,J)) * OVTFD * BFIRET
   15 CONTINUE
      TIMEI1 = TI1
      TIMEI2 = TI2
      TIMEI3 = OVTFD
      ITIME1 = I
      ITIME2 = I+1
      RETURN
```

```
the following is done at an end point
```

```
C     TYPE 2 INTERPOLATION - ITERPT = 2 - NOW TIMEI* HAS NO MEANING

   20 ITERPT = 2
      BFIRET = BFIRED(LFMAX+1)
      AFIRET = AFIRED(LFMAX+1)
      HFIRET = HFIRED(LFMAX+1)
      QFIRET = QFIRED(LFMAX+1)
      HCRATT = HCRATIO(LFMAX+1)
      CCO2T = CCO2(LFMAX+1)
      COCO2T = COCO2(LFMAX+1)
      HCOMBT = HOCBMB(LFMAX+1)
      DO 30 J = 1, NS
      IF(.NOT.ACTIVS(J)) GO TO 30
      MFIRET(J) = BFIRET * MPRODR(LFMAX+1,J)
   30 CONTINUE
      RETURN
      END
```

CHEMIE is the routine which calculates the heat release rate and species production. The primary input is the mass pyrolysis rate, and the primary output is the heat generation rate. This routine is only used for a type 2 (constrained) fire.

```
      SUBROUTINE CHEMIE (QPYROL, PYROL, ENTRAIN, NETFUEL, TARGET, LAYER)
```

"pyrol" is the mass pyrolysis rate from the PYROL routine, and qpyrol the heat generation rate, "entrain" is the entrainment rate (we are dealing with diffusion limited combustion) and "netfuel" is the fuel actually burned as opposed to the possible "pyrol" value. "netxx" then are the species production rates, based on the formulae discussed in section 4.5

```
      FAST COMMON BLOCK GOES HERE

      REAL NETFUEL, NEWNET, NETH2O, NETCO2, NETCO, NET
      REAL TMASS, NETFUL, XMASS(NS)
      EQUIVALENCE (NETO2,XMASS(2)),(NETCO2,XMASS(3)),(NETCO,XMASS(4))
      EQUIVALENCE (NETFUL,XMASS(7)),(NETH2O,XMASS(8)),(NETC,XMASS(9))
      INTEGER SOURCE, TARGET
      DATA XMASS/NS*0.0/
```

"source" specifies the compartment of origin of the flow, and "layer" is the corresponding layer from which the fuel and oxygen originate.

```
      SOURCE = TARGET
      TMASS = 0.0
      DO 2 LSP = 1, 9
    2 TMASS = TMASS + MASS(LAYER,SOURCE,LSP)
      TMASS = MAX (TMASS, MINMAS)
      O2FRAC = MASS(LAYER,SOURCE,2) / TMASS
      O2ENTR =  ENTRAIN * O2FRAC
```

4.83 is the inverse of 20.6 %

```
      O2INDEX = MAX(0.,(O2FRAC-LIMO2)*4.83)
      O2MASS =  O2ENTR * 0.995 * (1-EXP(-10*O2INDEX))
      OOSTOK =  13200000. / HCOMBA
      QPYROL =  MAX(0.,MIN(PYROL, OOSTOK*O2MASS)) * HCOMBA
      NETFUEL = QPYROL / HCOMBA

C     THIS IS THE REAL KINETICS SCHEME AS DRIVEN BY DIFFUSION

      NETFUL = - NETFUEL      NETO2 = - QPYROL / 1.32E+7
      NETH2O = 9.0 * NETFUEL * HCRATT / (1+HCRATT)
      NETCO2 = 3.67 * NETFUEL / ((1+HCRATT)*(1.+1.57*COCO2T+3.67*CCO2T))
      NETCO = NETCO2 * COCO2T
      NETC =  NETCO2 * CCO2T

    1 NETMAS(UPPER,TARGET,I) = NETMAS(UPPER,TARGET,I) + XMASS(I)

C     NO POINT IN ENTRAINING FROM THE UPPER LAYER INTO THE UPPER LAYER

      IF (LAYER.EQ.UPPER) RETURN

C     ADD IN THE FLOW ENTRAINED BY THE PLUME

      DO 8 LSP = 1, NS
      IF (.NOT.ACTIVS(LSP)) GO TO 8
```

```
C       PLUME CONTRIBUTION FOR ALL ENTRAINED GASES

        NEWNET = ENTRAIN * MASS(LOWER,SOURCE,LSP) / OLDMAS(LOWER,SOURCE)
        NETMAS(UPPER,TARGET,LSP) = NETMAS(UPPER,TARGET,LSP) + NEWNET
        NETMAS(LOWER,TARGET,LSP) = NETMAS(LOWER,TARGET,LSP) - NEWNET
      8 CONTINUE
        RETURN
        END
```

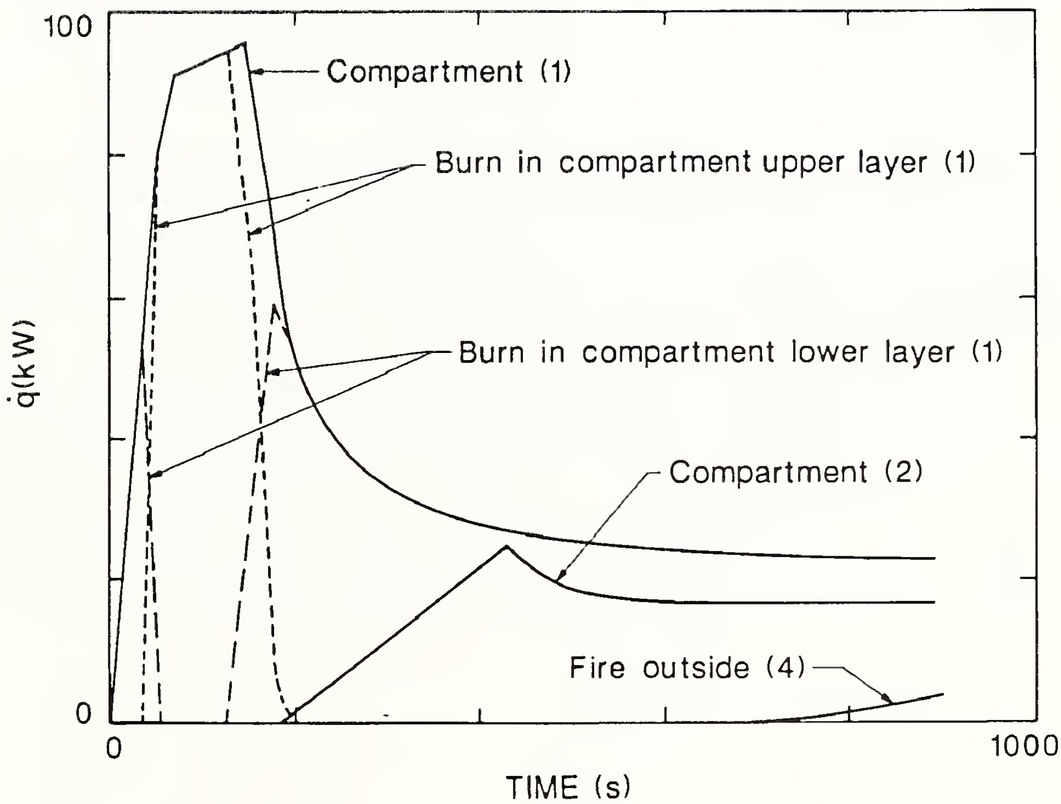


Figure 4. Heat release rate in a vitiated atmosphere.

An example of what happens in a vitiated atmosphere can be demonstrated by example. The data file used is the three compartment model shown in Appendix A with door heights modified to accentuate the effect of vitiation. The building was a nominal two compartment structure connected by a door, with another door to the outside. The door to the third compartment was shut as part of this calculation. The fire simulated a free burn going from zero to 100 kW over 30 seconds, and then remaining fixed at that level. That is, the pyrolysis rate was such that if no constraint existed, the fire would burn at the 100 kW level. The effect of vitiation is shown in figure 4. During the process of filling, the effect of vitiation is such that the total heat release in all spaces is less than the 100 kW nominal value. Eventually there will be no accumulation of fuel, and the burning outside of the structure will make up the difference. Compartment (3) is effectively cut off.

Figure 4 shows the total heat release rate in compartment (1) together with the contribution of the release in the lower layer and the upper layer. As the interface approached the fire source, the entrainment and relative contribution from the lower layer (region #1) decreased until the fire was in the upper layer only (region #2). Subsequently, the fire burned only in the upper layer and depleted the oxygen of this layer. Since no fuel is then burned in the lower layer, all is available to burn in the upper layer. Also, since there was no plume in the lower layer to pump oxygen into the upper layer, the oxygen level decreased until the fire was extinguished in regions #1 and #2 in compartment (1).

As the burning rate was constricted in compartment (1), unburned fuel began to spill into the adjacent compartment (2) and burned in the flow from the doorway. Once again, burning took place until the layer in this compartment reached a point where there is not sufficient oxygen to support burning of all the fuel. At this point fuel began to flow to the outside and burn. This sequence of events is also illustrated in figure 4.

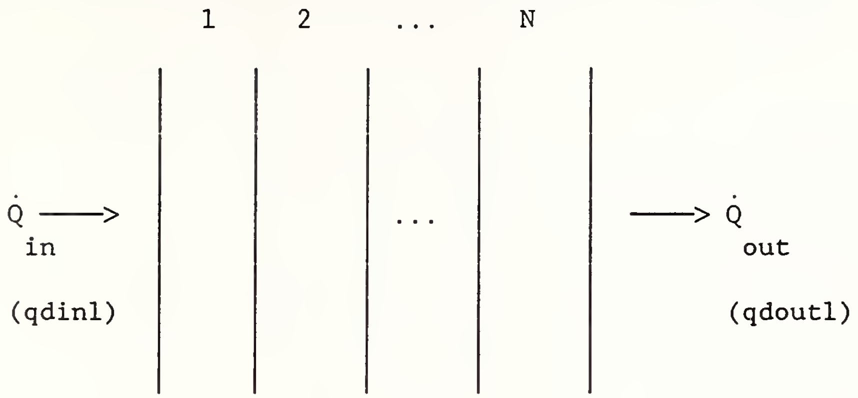
Note that the burning in the compartments was never fully extinguished. As the fire decreased in compartment 1, and fuel began to flow out, the layer moved up somewhat so that burning once again took place in the lower layer. After 400 seconds, a steady state was reached where some fuel was burned in the lower layer, and the remaining fuel is deposited in the upper layer. This then became a source of fuel to burn upon exiting to compartment (2) and subsequently to the outside, compartment (4). A steady state was reached in compartment #2 at about 600 seconds. From this time on, the vent fire to the outside grew. The calculation was terminated prior to the latter reaching a steady state.

The vent specification for this calculation is

```
HVENT   1  2   1 0.81   0.55   0.00
HVENT   2  4   1 0.79   0.75   0.00
HVENT   2  3   1 0.00   0.00   0.00
```

5.6 CNDUCT (sec. 4.6)

"CNDUCT" solves a series of linear parabolic equations which describe heat flow through a solid. Each boundary is partitioned into N+1 nodes (N slabs) and looks something like



A set of these nodes exists for each boundary. The boundary can consist of up to three materials, whose properties can differ. The solver is applied to each layer (slab) of the boundary, with appropriate boundary conditions at the real physical boundaries, and between the slabs. The solver uses a time centered, space centered (Crank-Nicholson) successive over relaxation method to solve the temperature field for given boundary conditions. The boundary conditions are the heat flux at the interior and exterior nodes. Because of the possible change in material properties, we imposed the additional constraint that both the temperature and gradient of the temperature must be continuous across the interior interfaces. We do not allow for a film resistance between the various materials. The "B" coefficients are defined in Mitchell and Griffiths [16]. The specific form is not transparent because of the time and space centering formulation of the solver.

```
      SUBROUTINE CNDUCT(QDINL,QDOUTL,DT,NC,NWW)

C     NSLB.....NUMBER OF SLABS.IN.WALL.NWW......
C     FLW......SLAB THICKNESS..........(M)......
C     CW.......SPEC HEAT...............(J/KG/K).
C     RW.......DENSITY.................(KG/M*3).
C     FKW......CONDUCTIVITY............(J/M/S/K)
C     QDOT.....HEAT FLUX...............(J/S/M*2)
C     TWJ......TEMP PROFILE............(K)......
C     DT.......TIME STEP...............(S)......
```

nmaxit is the maximum number of iterations allowed for the solver.

```
      PARAMETER (NMAXIT=100)

      FAST COMMON BLOCK GOES HERE

      INTEGER NODE(0:MXSLB)
      REAL XM(MXSLB),MAXDIF,B(NN),DX(MXSLB),FK(MXSLB)
      REAL EPS, NEWT(NN), OLDT(NN), R1(MXSLB), R2(MXSLB)
      DATA EPS/0.9/, MAXDIF/0.0/
```

```
C     PRECALCULATE CONSTANTS

      NTOT = 0
      NSL = NSLB(NWW,NC)
      DO 4 I = 1, NSL
    4 NTOT = NTOT + NDIV(I,NWW,NC)
      DO 1 I = 1, NTOT
      NEWT(I) = TWJ(NWW,NC,I)
    1 OLDT(I) = TWJ(NWW,NC,I)

      DO 2 I = 1, NSL
      FK(I) = 1. / FKW(I,NWW,NC)
      DX(I) = FLW(I,NWW,NC) / FLOAT(NDIV(I,NWW,NC))
      XM(I)=FKW(I,NWW,NC)*DT/(DX(I)*DX(I)*RW(I,NWW,NC)*CW(I,NWW,NC)*2.)
      R1(I) = 1. / (1.+XM(I))
      R2(I) = 1. / (1.+2.*XM(I))
      IF (XM(I).GT.(.5)) THEN
        diagnostic write
        STOP 'CNDUCT'
      ENDIF
  2   CONTINUE

C     NOTE THE CHANGE IN QDOUTL TO OBTAIN EXTERIOR CONVECTION FROM
C     THE "CONVEC" ROUTINE - ALSO THERE IS A SIGN CHANGE REQUIRED TO
C     MAINTAIN CONSISTENCY WITH IMPLEMENTATION OF THE B COEFFICIENTS

      DUMY = 0.0
      CALL CONVEC(NWW, TWE(NWW,NC), TWJ(NWW,NC,NTOT), 1.0, QDOUTL, DUMY)
      QDOUTL = -QDOUTL

      NODE(0) = 0
      DO 3 I = 1, NSL
    3 NODE(I) = NDIV(I,NWW,NC) + NODE(I-1)
      NODE(0) = 1
      NODE(NSL) = NODE(NSL) - 1

      ITER = 0

C     CALCULATE B VALUES

      B(1)=(OLDT(1)+XM(1)*(OLDT(2)-OLDT(1)+QDINL*DX(1)*FK(1)))*R1(1)
      DO 15 J = 1,NSL
      DO 15 I = NODE(J-1)+1, NODE(J)
   15 B(I)=(OLDT(I)+XM(J)*(OLDT(I-1)-2.*OLDT(I)+OLDT(I+1)))*R2(J)
      B(NTOT) =(OLDT(NTOT)-XM(NSL)*(OLDT(NTOT)-OLDT(NTOT-1)+QDOUTL
               * DX(NSL)*FK(NSL)))*R1(NSL)
```

```
C     NOW CALCULATE THE NEW TEMPERATURE FOR THE NEXT TIME STEP

 20   ITER = ITER + 1
      MAXDIF = 0.0
      IF (ITER.GT.NMAXIT) GOTO 300

C     CALCULATE THE FIRST NODE DATA

      TCHK = NEWT(1)
      NEWT(1)=(XM(1)*(NEWT(2)+DX(1)*QDINL*FK(1)))*R1(1) + B(1)
      MAXDIF = MAX(MAXDIF,ABS(NEWT(1)-TCHK))

C     CALCULATE THE INTERIOR NODE DATA

      DO 35 J = 1, NSL
      DO 30 I = NODE(J-1)+1, NODE(J)
      TCHK = NEWT(I)
      NEWT(I) =(XM(J)*(NEWT(I-1)+NEWT(I+1)))*R2(J) + B(I)
   30 MAXDIF = MAX(MAXDIF,ABS(NEWT(I)-TCHK))
   35 CONTINUE

C      CALCULATE THE LAST NODE DATA

      TCHK = NEWT(NTOT)
      NEWT(NTOT) = (-XM(NSL) * (QDOUTL*DX(NSL)*FK(NSL) - NEWT(NTOT-1)))
     .      * R1(NSL) + B(NTOT)
      MAXDIF = MAX(MAXDIF,ABS(NEWT(NTOT)-TCHK))

C     CHECK THE CONVERGENCE CRITERION

      IF (MAXDIF.GT.EPS) GOTO 20

C     CONVERGENCE ACHIEVED IF WE GET TO HERE

      DO 7 I = 1,NTOT
    7 TWJ(NWW,NC,I) = NEWT(I)
      RETURN

C     NO CONVERGENCE AFTER NMAXIT ITERATIONS

  300 diagnostic output
      STOP 'CNDUCT'
      END
```

Figure 5 shows a comparison of measured and calculated temperatures of a wall for the three compartment data file in Appendix A. The experimental data is discussed by Peacock et al. [4].

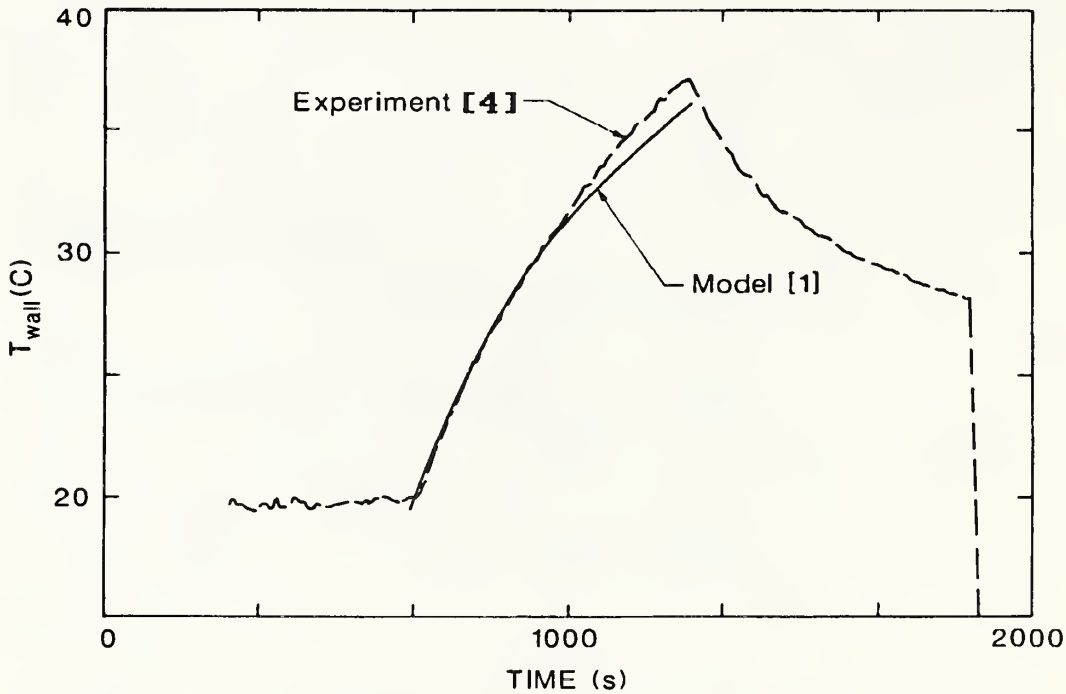


Figure 5. Comparison of measured and calculated wall temperatures.

6. DESCRIPTION OF THE DATA FILE USED BY FAST

The computer model requires a description of the problem to be solved. The following description is for the input data used by the model. In general, the order of the data is not important. The one exception to this is the first line which specifies the version number and gives the data file a title.

The data are grouped as

- Version and title (6.1)
- Time specification (6.2)
- Ambient conditions (6.3)
- Floor plan data (6.4)
- Connections (6.5)
- Thermophysical properties of the enclosing surfaces (6.6)
- Fire specifications (6.7)
- Species production (6.8)
- Files (6.9)
- Graphics specification (6.10).

The number of lines in a given data set will vary depending for example on the number of openings or the number of species tracked. A sample input data file is given in Appendix A. A number of parameters such as heat transfer and flow coefficients have been set within the program as constants. Please refer to the section on source terms to ascertain the values for these parameters.

Each line of the input data file begins with a key word which identifies the type of data on the line. The key words which are currently available are

CEILI	specify name of ceiling descriptor(s)	(N)
CHEMI	miscellaneous parameters for kinetics	(5)
CO	CO/CO_2 mass ratio	(lfmax+1)
CT	fraction of fuel which is toxic	(lfmax+1)
CVENT	opening/closing parameter	(lfmax + 4)
DEPTH	depth of compartments	(N)
DUMPR	specify a file name for saving time histories	(1)
EAMB	external ambient	(3)
FAREA	area of the base of the fire	(lfmax+1)
FHIGH	height of the base of the fire	(lfmax+1)
FLOOR	specify the name of floor property descriptor(s)	(N)
FMASS	pyrolysis rate	(lfmax+1)
FQDOT	heat release rate	(lfmax+1)

FTIME	length of time intervals	(lfmax)
HCL	hcl/pyrolysis mass ratio	(lfmax+1)
HCN	hcn/pyrolysis mass ratio	(lfmax+1)
HCR	hydrogen/carbon mass ration of the fuel	(lfmax+1)
HEIGH	interior height of a compartment	(N)
HI/F	absolute height of the floor of a compartment	(N)
HVENT	specify vent which connect compartments horizontally	(7)
INTER	initial height of the upper/lower interface	(2)
LFBO	compartment of fire origin	(1)
LFBT	type of fire	(1)
LFMAX	number of time intervals	(1)
LFPOS	position of the fire in the compartment	(1)
OD	C/CO_2 mass ratio	(lfmax+1)
RESTR	specify a restart file	(2)
TAMB	ambient inside the structure	(3)
TIMES	time step control of the output	(5)
VVENT	specify a vent which connects compartments vertically	(3)
VERSN	version number and title	(fixed format 2)
WALLS	specify the name of wall property descriptor(s)	(N)
WIDTH	width of the compartments	(N)
WIND	scaling rule for wind effects	(3)

The number in parenthesis is the maximum number of entries for that line. "N" represents the number of compartments being modeled and "lfmax" is the number of time intervals used to describe the fire, detailed below in section 6.7. The outside (ambient) is designated by one more than the number of compartments, N+1. So a three compartment model would refer to the outside as compartment four.

Each line of input consists of a label followed by one or more alphanumeric parameters associated with that input label. The label must always begin in the first space of the line and be in capital letters. Following the label, the values may start in any column and all values must be separated by either a comma or a space. Values may contain decimal points if needed or desired. They are not required. Units are standard SI units. Most parameters have default values which can be utilized by omitting the appropriate line. These will be indicated in the discussion. The maximum line length is 128 characters, so all data for each key word must fit in this number of characters. For each entry which requires more than one type of data, the first entry under the column "parameter" indicates the number of data required.

6.1 Version and Title

This line must be the first line in the file. It is the line that FAST keys on to determine whether it has a correct data file. The format is fixed, that is the data must appear in the columns specified in the text.

Label	Parameter	Comments
VERSN	(2)	The VERSN line is a required input.
	Version Number	The version number parameter specifies the version of FAST for which the input data file was prepared. Normally, this would be 18. It must be in columns 8-9.
	Title	The title is optional and may consist of letters, numbers, and/or symbols that start in column 11 and may be up to 50 characters. It permits the user to uniquely label each run.

Example:

```
VERSN   18 Simulation for Building XYZ
```

6.2 Time Specification

Label	Parameter	Comments	Units
TIMES	(5)	The TIMES line is required data.	
	Simulation Time	Simulation time is the length of time over which the simulation takes place. The maximum value for this input is 86400 seconds (1 day). The simulation time parameter is required.	s

Print Interval	The print interval is the time interval between each printing of the output values. If omitted or less than or equal to zero, no printing of the output values will occur.	s
Dump Interval	The dump interval is the time interval between each writing of the output to the dump file. The dump file stores all of the output of the model at the specified interval in a format which can be efficiently retrieved for use by other programs. Section 6.9 provides details of the dump file. A zero must be used if no dump file is to be used. There is a maximum of 50 intervals allowed. If the choice of this parameter would yield more than 50 writes, it is adjusted so that this limit is not exceeded.	s
Display Interval	The display interval is the time interval between each graphical display of the output as specified in the graphics specification, section 6.10. If omitted, no graphical display will occur. There is a limit on the display of 50 for the microcomputer versions and 100 for the mainframe versions of FAST. This parameter is not adjusted; rather graphs will be truncated to the first 50 or 100 points, respectively.	s
Copy Count	Copy count is the number of copies of each graphical display to be made on the selected hard copy device as specified in the graphics specification, section 2.9. If omitted, a value of zero (no copies) is assumed.	

Examples:

```
TIMES  360  0  0
TIMES  360 10 30
TIMES  900    30    10    10    0
```

In the first example, a simulation time of 360 seconds is specified. The output values will not be printed or stored in a dump file. No graphical display of the output will occur. In the second example, a 360 second simulation with printed output every 10 seconds and output to a dump file every 30 seconds is specified. No graphical display of the output values will be generated. In the third example, all parameters are specified. A 900 second simulation with printed output every 30 seconds, output to a dump file every 10 seconds and a graphical display with no copies will occur every 10 seconds. Note the free field format of these parameters - multiple spaces between parameters are permitted.

6.3 Ambient Conditions

The ambient conditions section of the input data allows the user to specify the temperature and pressure and station elevation of the ambient atmosphere, as well as the absolute wind pressure to which the structure is subjected. There is an ambient for the interior and for the exterior of the building. The key word for the interior of the building is TAMB and for the exterior of the building is EAMB. The form is the same for both. The key word for the wind information is WIND. The wind modification is applied only to the vents which lead to the exterior. Pressure interior to a structure is calculated simply as a lapse rate based on the NOAA tables [17]. For the exterior, the nominal pressure is modified by

$$\delta(p) = C_w \rho V^2, \qquad \text{where} \quad V = V_w \left(\frac{H_i}{H_w}\right)^{p_w}$$

This modification is applied to the vents which lead to the exterior ambient. The pressure change calculated above is modified by the wind coefficient for each vent. This coefficient, which can vary from -1.0 to +1.0, nominally from -0.8 to +0.8, determines whether the vent is facing away from or into the wind. The pressure change is multiplied by the vent wind coefficient and added to the external ambient for each vent which is connected to the outside.

Label	Parameter	Comments	
TAMB or EAMB	(3)	These data are optional.	
	Ambient Temperature	Ambient temperature is the temperature of the ambient atmosphere. Default is 300.	K
	Ambient Pressure	The ambient pressure is the pressure of the ambient atmosphere. Default is 101300.	Pa

	Station Elevation	The station elevation is the elevation of the point at which the ambient pressure and temperature (see above) are measured. The reference point for the elevation, pressure and temperature must be consistent. This is the reference datum for calculating the density of the atmosphere as well as the temperature and pressure inside and outside of the building as a function of height. Default is 0.	m
WIND	(3)	This line is optional.	
	Wind Speed	Wind speed at the reference elevation. The default is 0.	m/s
	Reference Height	Height at which the reference wind speed is measured. The default is 10 meters.	m
	Lapse Rate Coefficient	The power law used to calculate the wind speed as a function of height. The default is 0.16.	

The choice for the station elevation, temperature and pressure must be consistent. Outside of that limitation, the choice is arbitrary. It is often convenient to choose the base of a structure to be at zero height and then reference the height of the building with respect to that height. The temperature and pressure must then be measured at that position. Another possible choice would be the pressure and temperature at sea level, with the building elevations then given with respect to mean sea level. This is also acceptable, but somewhat more tedious in specifying the construction of a building. Either of the these choices works though because consistent data for temperature and pressure are available from the Weather Service for either case.

Examples:

```
TAMB 300
TAMB 288 101000 200.
```

The first example sets the ambient temperature to 300 Kelvin, but leaves the ambient pressure at 101300 and the reference elevation at 0 meters. The second specifies a temperature of 15 degrees Celsius at 200 meters and a pressure of 101000 Pa. In both of these cases the external ambient is set to the same values. An example of different inside and outside values is a warm building in a winter setting and might be described as

```
TAMB  288 101305 0.0
EAMB  270 101315 0.0
```

6.4 Floor Plan Data

The floor plan data section allows the user to portray the geometry of the structure being modeled. The size and location of every room in the structure MUST be described. The maximum number of rooms is dependent upon the local implementation of FAST. Usually a total of 10 rooms (plus the outdoors) is available for a single simulation. For the PC versions, a maximum of six compartments (plus the outdoors) is allowed. The structure of the data is such that the compartments are described as entities, and then connected in appropriate ways. It is thus possible to have a set of rooms which can be configured in a variety of ways. In order to specify the geometry of a building, it is necessary to give its physical characteristics. Thus the lines labelled HI/F, WIDTH, DEPTH AND HEIGH are all required. Each of these lines requires "N" data entries, that is one for each compartment.

Label	Parameter	Comments	Units
HI/F	**Floor Height**	The floor height is the height of the floor of each room with respect to station elevation specified by the TAMB parameter. The reference point must be the same for all elevations in the input data. The number of values on the line must equal the number of rooms in the simulation.	m
WIDTH	**Room Width**	Room width specifies the width of the room. The number of values on the line must equal the number of rooms in the simulation.	m
DEPTH	**Room Depth**	Room depth specifies the depth of the room. The number of values on the line must equal the number of rooms in the simulation.	m
HEIGH	**Room Height**	Room Height specifies the height of the room. The number of values on the line must equal the number of rooms in the simulation.	m

Example:

```
HI/F   0.0   0.0   0.0
```

```
WIDTH  6.1   4.6   4.6
DEPTH  9.1  14.3   4.3
HEIGH  3.6   2.4   2.4
```

This floor plan data specifies the sizes for a three room simulation with rooms sizes of 6.1 x 9.1 x 3.6 m, 4.6 x 14.3 x 2.4 m, and 4.6 x 4.3 x 2.4 m, respectively. All rooms are at the same elevation at a reference height of 0.0 m.

6.5 Connections

The connections section of the input data file describes any horizontal or vertical vents between rooms in the structure. These may include doors between rooms in the structure, windows in the rooms (between rooms or to the outdoors), or vertical openings between floors of the structure. Openings to the outside are included as openings to the room with a number one greater than the number of rooms described in the floor plan data section. Doors, windows, and the like are called horizontal vents because the direction of the vent, or vent connection, is in the horizontal direction. The key word is HVENT. Horizontal vents may be opened or closed during the fire with the use of the CVENT key word. For vertical vents, such as scuddles, the key word is VVENT; at present there is not an equivalent mechanism for opening or closing the vertical vents. The form for horizontal and vertical vents is necessarily different.

Label	Parameter	Comments	Units
HVENT	(7)	Required to specify connections between compartments. No openings prevents flow. Each HVENT line in the input file describes one horizontal vent between rooms in the structure (or between a room and the outdoors). The first six entries on each line are required. There is an optional seventh parameter to specify a wind coefficient.	
	First Room	The first room is simply the first connection.	
	Second Room	The second room is the room number to which the first room is connected. The order has one significance. The height of the sill and soffit are with respect to the first compartment specified.	

	Vent Number	There can be as many as four vents between any two compartments. This number specifies which vent is being described. It can range from one to four.	
	Width	The width of the opening.	m
	Soffit	Position of the top of the opening above the floor of the room number specified as the first room.	m
	Sill	Sill height is the height of the bottom of the opening above the floor of the room number specified as the first room.	m
	Wind	The wind coefficient is the cosine of the angle between the wind vector and the vent opening. This applies only to vents which connect to the outside ambient (specified with EAMB). The range of values is -1.0 to +1.0. If omitted, the value defaults to zero.	
VVENT	(3)	Required to specify a vertical connection between compartments. Each VVENT line in the input file describes one vertical vent between rooms in the structure (or between a room and the outdoors). There are three parameters, the connected compartments, and the effective area of the vent.	
	First Room	The first room is simply the first connection.	
	Second Room	The second room is the room number to which the first room is connected. The order has one significance. The height of the sill and soffit are with respect to the first compartment specified.	
	Area	This is the effective area of the opening. For a hole, it would be the actual opening. For a diffuser, then the effective area will be somewhat less than the geometrical size of the opening.	

Examples:

```
HVENT 1  2  1 1.1  2.1  0.0
HVENT 1  3  1 1.1  2.1  0.0
HVENT 2  4  1 1.3  2.1  0.6
VVENT 1  3  3.0
```

Assuming the three room structure as described in the floor plan data section, the above examples describe two openings 1.1 x 1.5 m betweens rooms 1 and 2 and between rooms 1 and 3. An 1.3 x 2.1 m opening between room 2 and the outside (room 4 for a three room simulation) is raised 0.6 m off the floor of room 2.

```
HVENT 2  4  2 1.3  2.1  0.6 1.0
```

This specifies vent #2 between compartment (2) and the outside, with a wind coefficient of 1.0, which implies that the vent is facing directly into the wind.

CVENT is a parameter which is used to open a close vents. It multiples the width in the vent flow calculation. The default is 1.0 which is a fully open vent. A value of 0.5 would specify a vent which was halfway open.

Label	Parameter	Comments	Units
CVENT	(LFMAX+4)	Specify closing value. Each CVENT line in the input file describes one horizontal vent between rooms in the structure (or between a room and the outdoors).	
	First Room	The first compartment.	
	Second Room	The second room is the room number to which the first room is connected.	
	Vent Number	This number specifies which vent is being described. It can range from one to four. These parameters correspond to the first three parameters in HVENT.	
	Width (LFMAX+1)	Fraction that the vent is open. This applies to the width only. The sill and soffit are not changed.	%

CVENT has a form similar to HVENT but in addition contains the opening data. The additional data is in the same form as all the time dependent specifications, namely a value for each endpoint in the heat release curve. The form is

CVENT C#1 C#2 V# x x x x,...

By way of example, the default value for CVENT for the example show above with LFMAX=5 would be

```
CVENT 1 2 1 1.0 1.0 1.0 1.0 1.0 1.0
```

and would specify that the first vent between compartments (1) and (2) would be open at all times. Another example would be

```
CVENT 1 3 1 0.5 0.5 0.5 0.5 0.5 0.5
```

and would specify that the first vent between compartments (1) and (3) would be half open all of the time. These fractions refer to the width given in the HVENT specification and for the cases above would be 1.1 meters.

6.6 Thermophysical Properties of Enclosing Surfaces

The thermophysical properties of the enclosing surfaces are described by specifying the thermal conductivity, specific heat, emissivity, density, and thickness of the enclosing surfaces for each room. If the thermophysical properties of the enclosing surfaces are not included, FAST will treat them as adiabatic (no heat transfer). Since most of the heat conduction is through the ceiling and since the conduction calculation takes a significant fraction of the computation time, it is recommended that initial calculations be made using the ceiling only. Adding the walls generally has a small effect on the results and the floor contribution is usually negligible. Clearly, there are cases where the above generalization does not hold, but it may prove to be a useful screening technique. Currently, thermal properties for materials are read from a thermal database file unique to FAST. The data in the file for FAST simply gives a name (such as CONCRETE) which is a pointer to the properties in the thermal database. (For computers which do not support extensions, the ".DAT" is dropped.) For the PC version, this is an installation parameter. All of these specifications are optional. The thermal properties are assumed to be constant; that is, we do not account for the variation with temperature or water content.

The thermophysical properties are specified at <u>one</u> condition of temperature, humidity, <u>etc</u>. There can be as many as three layers per boundary, but they are specified in the thermal database itself.

Label	Parameter	Comments	Units
CEILI	(N)	The label CEILI indicates that the names of thermophysical properties on this line describe the ceiling material. If this parameter is present, there must be an entry for each compartment.	
WALLS	(N)	The label WALLS indicates that the names of thermophysical properties on this line describe the wall material. If this parameter is present, there must be an entry for each compartment.	
FLOOR	(N)	The label FLOOR indicates that the names of thermophysical properties on this line describe the floor material. If this parameter is present, there must be an entry for each compartment.	

Examples:

```
CEILI OFF        REDOAK     CONCRETE
WALLS CONCRETE   CONCRETE   CONCRETE
```

The corresponding thermal data base might appear as

```
CONCRETE   1.75  1000.   2200.   0.1500  0.94
BRICK      0.18   900.    790.   0.016   0.90
REDOAK     0.15  1300.    640.   0.025   0.99
```

The names of the materials can be any ASCII string up to 8 characters. So a valid name is $%#@**% although this admittedly does not convey much information. The key word "OFF" is used to tell the model not to compute the heat loss for the ceiling in compartment (1). In this case the FLOOR parameter is not present at all, so there will be no heat transfer through the floor in any room and the calculation will not be done for the ceiling in compartment (1), where the key word "off" is present. This is most useful for doing the heat transfer calculation in the burn room and adjacent rooms and then turning it off in distant compartments. See Appendix D for a complete description of the form of the thermal database.

6.7 Fire Specifications

The fire specifications allow the user to describe the fire source in the simulation. The location and position of the fire is specified along with the chemical properties of the fuel. Finally, the fire is described with a series of mass loss rate, fuel height, and fuel area inputs. All of these specifications are optional and each line requires a single number. The defaults for the fire specification is a methane burner in the center of compartment (1). The defaults shown for each key word reflect the values for methane.

Label	Parameter	Comments	Units
LFBO	**Room of Fire Origin**	Room of fire origin is the room number in which the fire originates. Default is 1.	
LFBT	**Fire Type**	This is a number indicating the type of fire. 1 Unconstrained fire 2 Constrained fire. The default is 1. See sections 4.5 and 5.5 for a discussion of the implications of this choice.	
LFPOS	**Fire Position**	The fire position is the area of the room in which the fire originates and is one of the following values: 1 Center of the room, 2 Corner of the room, or 3 Along a wall of the room, but not near a corner of the room. The fire position is used to account for the entrainment rate of the plume, which depends on the location of the fire plume within the compartment. Fire positions 2 and 3 should only be used when the fire is very close to the corner or wall respectively. The default is 1.	

CHEMI	(6)	Chemical kinetics and miscellaneous parameters.	
	Molar Weight	Molecular weight of the fuel vapor. This is the conversion factor from mass density to molecular density for "tuhc." Default is 16. It is used only for conversion to ppm, and has no effect on the model itself.	
	Relative Humidity	The initial relative humidity in the system. This is converted to kilograms of water per cubic meter from the table from "Dynamical and Physical Meteorology" by Haltiner and Martin (1957)	%
	Limiting Oxygen Index	The limit on the ratio of oxygen to other gases in the system below which a flame will not burn. This is applicable only to type (LFBT) 2 or later fires. The default is 10.	%
	Heat of Combustion	Heat of combustion of the fuel. Default is 50000000.	J/kg
	Initial Fuel Temperature	Typically, the initial fuel temperature is the same as the ambient temperature as specified in the ambient conditions section.	K
	Gaseous Ignition Temperature	Minimum temperature for ignition of the fuel as it flows from a compartment through a vent into another compartment. The default is the initial fuel temperature.	K

LFMAX	**Number of Intervals**	This is the number of time intervals for the mass loss rate, fuel height and species inputs. The mass loss rate, fuel height and species are entered as series of points with respect to time. This is referred to in this document as a specified fire. A sufficient number of intervals should be selected to provide a reasonable approximation (using straight line segments) for the input variables which specify the fire. A example of this is shown in figure 6. The mass loss rates P_1-P_7 are specified over the time intervals I_1-I_6. The number of points specified must be one greater than the number of time intervals. For example, if there are six mass loss points there should be a total of five time intervals (or one interval between every two consecutive points). The maximum number of intervals allowed in version 18 of FAST is 21.	
FTIME	**Time Interval (LFMAX)**	Time interval is the time between each point (mass loss rate, fuel height and species) specified for the fire. The total duration of the fire is the sum of the time intervals. This time is independent of the simulation time which is specified for the TIMES label. If the simulation time is longer than the total duration of the fire, the final values specified for the fire (mass loss rate, fuel height, fuel area, and species) will be continued until the end of the simulation. The number of values on the line must equal the number of time intervals specified by LFMAX, above.	s
FMASS	**Mass Loss Rate (LFMAX+1)**	The rate at which fuel is pyrolyzed at times corresponding to each point of the specified fire.	kg/s
FHIGH	**Fuel Height (LFMAX+1)**	The height of the base of the flames above the floor of the room of fire origin for each point of the specified fire.	m
FQDOT	**Heat Release Rate (LFMAX+1)**	The heat release rate of the specified fire.	W

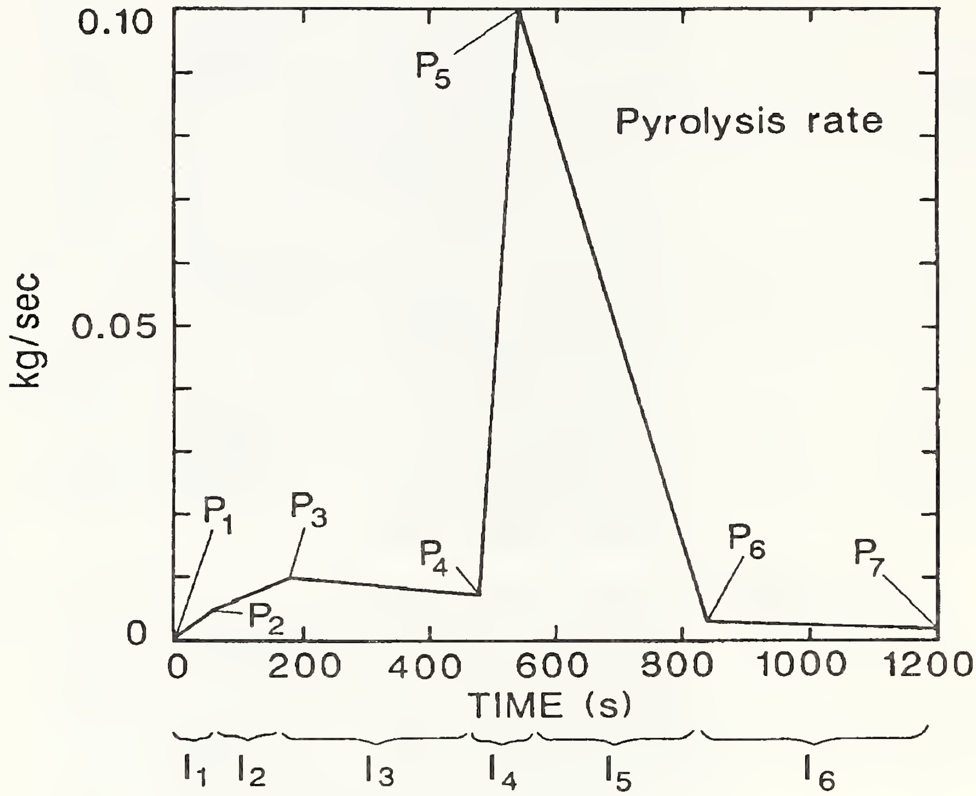


Figure 6. Pyrolysis rate for LFMAX=6.

With the three parameters, the heat of combustion (HOC) from CHEMI, FMASS and FQDOT, the pyrolysis and heat release rate are over specified. The model uses the last two of the three to obtain the third parameter. That is, if the three were specified in the order HOC, FMASS and FQDOT, then FQDOT would be divided by FMASS to obtain the HOC for each time interval. If the order were FMASS, FQDOT and HOC, then the pyrolysis rate would be determined by dividing the heat release rate by the heat of combustion. If only two of the three are given, then those two will determine the third, and finally, if none or only one of the parameters is present, the defaults shown will be used.

Example:

```
LFBO     1
LFBT     1
LFPOS    1
CHEMI    0.0  0.0 10.  18100000. 300.
LFMAX    7
```

```
FMASS  .014  .0014 .025  .045  .050  .0153 .0068 .0041
FAREA  .5    .5    .5    .5    .5    .5    .5    .5
FHIGH  .25   .25   .25   .25   .25   .25   .25   .25
FTIME      20.   20.   50.   50.  100.  100.  400.
```

In the example, a specified fire (LFBT 1) originates in room number 1 (LFBO 1) in the center of the room (LFPOS 1). A seven segment (LFMAX) fire is specified. The fuel burns with a heat of combustion of 18100000 J/kg. The initial relative humidity is 0%, the molecular weight is 16 (zero is not allowed, so the default is used) and the limiting oxygen index is 10%. Since the type of fire is 1, an unconstrained fire, this latter parameter has no meaning in this context.

```
LFBT    2
LFMAX   7
FMASS  .014  .0014 .025  .045  .050  .0153 .0068 .0041
FAREA  .5    .5    .5    .5    .5    .5    .5    .5
FHIGH  .25   .25   .25   .25   .25   .25   .25   .25
FTIME      20.   20.   50.   50.  100.  100.  400.
```

In this example, the specified fire is constrained with a limiting oxygen index of 1%. Since LFBO is not given, the default compartment (1) is used, and the position of the fire is in the center of the room. The default heat of combustion of 50000000 kJ/kg is used.

6.8 Species Production

Species production rates are specified in the manner similar to the fire, entering the rates as a series of points with respect to time. The species which are followed by FAST are

- Carbon Dioxide
- Carbon Monoxide
- Concentration-Time Product
- Hydrogen Cyanide
- Hydrogen Chloride
- Nitrogen
- Oxygen
- Soot (Smoke Density)
- Total Unburned Hydrocarbons
- Water

For a type one (LFBT=1) fire, only the concentration-time product of pyrolysate(ct), hydrogen cyanide(hcn) and hydrogen chloride(hcl) can be specified. No other species are followed. For a type two (LFBT=2) fire, nitrogen, oxygen, carbon dioxide, carbon monoxide, soot, unburned fuel and water are followed. In all cases, the unit of the production rates is kg/kg. However, the meaning of the production rates is different for the several types of species. For either fire, the production rates for ct, hcn and hcl are with respect to the pyrolysis rate of the fuel. For the others, carbon monoxide, water, etc., the production rate is specified with respect to the basic carbon production in the form of a ratio with carbon dioxide. For carbon monoxide, for example, the specification will be CO/CO_2. Thus we can not consider a pure hydrogen flame, but this is unlikely in the situations of interest.

Label	Parameter	Comments	Units
SPECIES	(LFMAX+1)	For each species desired a series of production rates are specified for each of the time points input for the specified fire. The program performs a linear interpolation between these points to determine the time of interest.	
HCN, HCL and CT	Production Rate	Units are kilogram of species produced per kilogram of fuel burned. The input for CT is the kilograms of "toxic" combustion products produced per kilogram of fuel burned.	kg/kg
HCR	Production Rate of the Fuel	The mass ratio of hydrogen to carbon as it becomes available from the fuel. This parameter affects primarily the rate of production of water.	kg/kg
OD	Yield	The ratio of the mass of carbon to carbon dioxide produced by the oxidation of the fuel.	kg/kg
CO	Yield	The ratio of the mass of carbon monoxide to carbon dioxide produced by the oxidation of the fuel.	kg/kg

6.9 Files

There are several files which FAST uses to communicate with its environment. They are 1) a configuration file, 2) the thermal database, 3) a "dump" file, and 4) a restart file. The output of the simulation may be written to a disk file for further processing by programs such as FASTplot or to restart FAST. At each interval of time as specified by the dump interval in the TIMES label, the output is written to the file specified. For efficient disk storage and optimum speed, the data is stored in an internal format and cannot be read directly with a text editor.

Label	Parameter	Comments	Units
DUMPR	**Dump File**	The name specifies a file (up to 17 characters) to which the program outputs for plotting are written. **Dump file** is an optional input. If omitted, the file will not be generated. Note that in order to obtain a history of the variables, this parameter must be specified and also the dumper interval (under TIMES) must be set to a non-zero value.	
RESTR	**Restart File**	The name specifies a file (up to 17 characters) from which the program reads data to restart the model. This data must have been generated (written) previously with the dump parameter discussed earlier. A time step is given after the name of the file and specifies at what time the restart should occur.	
THRMF	**Thermal Database**	The name specifies a file (up to 20 characters) from which the program reads thermophysical data. If this parameter is not specified, then either the default (THERMAL.DAT) is used, for the name is read from the configuration file.	
DEFCG	**Configuration File**	The name specifies a file (up to 20 characters) from which the program reads configuration information data.	

Example:

```
DUMPR FAST1.DAT
RESTR filename n
THRMF thermal.tpf
```

where "filename" was created in a previous run using the DUMP parameter. "n" specifies the starting time and must be one of the times at which a dump was generated. As an example, if a data set were run with

```
VERSN   18 title...
TIMES   360 60 10 0 0
```

```
.
.
DUMPR   MYFILE
```

then every 10 seconds a snap shot of the time histories of all variables would be generated. So a restart might be done at 300 seconds with the following

```
VERSN   18 new title
TIMES   900 60 0 0 0
.
.
RESTRT  MYFILE 300
```

with no requirement that the restart must be at the last dump point. The only caveat is to check the listings to be sure that a dump was generated at the desired point. For those cases where too many dump intervals are requested, the interval is recalculated, and a message is written to the output device.

6.10 Graphics Specification

A graphics specification can be added to the data file. Details of the meaning of some of the parameters is best left to the discussion of the device independent graphics software used by FAST [2]. However, the information necessary to use it is straightforward. The general structure is similar to that used for the building and fire specification. One must tell the program "what to plot," "how it should appear," and "where to put it."

The key words for "where to put it" are

DEVICE	where to plot it
BAR	bar charts
GRAPH	specify an x-y plot
TABLE	put the data into a table
PALETTE	specify the legend for CAD views
VIEW	show a perspective picture of the structure
WINDOW	the size of the window in "user" space.

The complete key word is required. That is, for the "where to put it" terms, no abbreviations are allowed. Then one must specify the variables to be plotted. They are

VENT, HEAT, PRESSUR, WALL, TEMPERA, INTERFA,
H_2O, CO_2, CO, OD, O_2, TUHC, HCN, HCL, CT

As might be expected, these are the similar key words to those used in the plotting program, FASTplot. In this case, we have a reduced set. The application and use of FAST and FASTplot are different.

For each key word there are parameters to specify the location of the graph, the colors and finally titles as appropriate. For the variables, there is a corresponding pointer to the graph of interest.

The form of each "where to put it" variable is described below

Label	Parameter	Comments
DEVICE	**Plotting Device**	The **Plotting Device** specifies the hardware device where the graphics is to be displayed. For the PC version, this key word should be omitted. If it must be included for compatibility reasons, set it to 4. For other computers, it is installation dependent. In general it specifies which device will receive the output.
WINDOW	(6)	The window label specifies the **user space** for placement of graphs, views,...
	Xl	left hand side of the graph in any user desired units.
	Yb	bottom of the graph in any user desired units.
	Zf	forward edge of the 3D block in any user desired units.
	Xr	right hand side of the graph in any user desired units.
	Yt	top of the graph in any user desired units.
	Zb	rear edge of the 3D block in any user desired units. These definitions refer to the 3D plotting block that can be seen. The most common values (which are also the default) are

Xl = 0.
Yb = 0.
Zf = 0.
Xr = 1279.
Yt = 1023.
Zb = 10.

This is not a required parameter; however, it is often convenient to define graphs in terms of the units that are used. For example, if one wished to display a house in terms of a blueprint, the more natural units might be feet. In that case, the parameters might have the values

Xl = 0.
Yb = 0.
Zf = 0.
Xr = 50.
Yt = 25.
Zb = 30.

GRAPH	(10)	Up to five graphs may be displayed at one time on the graphics display. Each graph is identified by a unique number (1-5) and placed in the window at a specified location. Xl,Yb,Zf,Xr,Yt and Zb have a meaning similar to WINDOW. However, here they specify where in the window to put the graph.
	Graph Number	The number to identify the graph. Allowable values are from 1 to 5. The graphs must be numbered consecutively, although they do not have to be given in order. It is acceptable to define graph 4 before graph 2 but if graph 4 is to be used, then graphs 1 through 3 must also be defined.
	Xl	Left hand side of the graph within the window in the same units as that of the window.
	Yb	Bottom of the graph within the window in the same units as that of the window.

	Zf	Forward edge of the 3D (three dimensional) block within the window in the same units as that of the window.
	Xr	Right hand side of the graph within the window in the same units as that of the window.
	Yt	Top of the graph within the window in the same units as that of the window.
	Zb	Back edge of the 3D block within the window in the same units as that of the window.
	Color	The color of the graph and labels which is specified as an integer from 1 to 15. Refer to DEVICE (NBSIR 85-3235) for the colors corresponding to the values for the color.
	Abscissa Title	Title for the abscissa (horizontal axis). To have blanks in the title, use the underscore character "_".
	Ordinate Title	Title for the ordinate (vertical axis). To have blanks in the title, use the underscore character "_".
TABLE	(7)	Up to five tables may be displayed at one time on the graphics display. Each table is identified by a unique number and placed in the window at a specified location. Xl,Yb,Zf,Xr,Yt and Zb have a meaning similar to WINDOW. However, here they specify where in the window to put the table.
	Table Number	The table number is the number to identify the table. Allowable values are from 1 to 5. The tables must be numbered consecutively, although they do not have to be given in order. It is acceptable to define table 4 before table 2 but if table 4 is to be used, then tables 1 through 3 must also be defined.

	Xl	Left hand side of the table within the window in the same units as that of the window.
	Yb	Bottom of the table within the window in the same units as that of the window.
	Zf	Forward edge of the 3D block within the window in the same units as that of the window.
	Xr	Right hand side of the table within the window in the same units as that of the window.
	Yt	Top of the table within the window in the same units as that of the window.
	Zb	Back edge of the 3D block within the window in the same units as that of the window.
VIEW	(24)	Up to five views may be displayed at one time on the graphics display. Each view is identified by a unique number and placed in the window at a specified location. Xl,Yb,Zf,Xr,Yt and Zb have a meaning similar to WINDOW. However, here they specify where in the window to put the view.
	View Number	View number is the number to identify the view. Allowable values are from 1 to 5. The views must be numbered consecutively, although they do not have to be given in order. It is acceptable to define view 4 before view 2 but if view 4 is to be used, then views 1 through 3 must also be defined.
	Xl	Left hand side of the view within the window in the same units as that of the window.
	Yb	Bottom of the view within the window in the same units as that of the window.
	Zf	Forward edge of the 3D block within the window in the same units as that of the window.

	Xr	Right hand side of the view within the window in the same units as that of the window.
	Yt	Top of the view within the window in the same units as that of the window.
	Zb	Back edge of the 3D block within the window in the same units as that of the window.
	File	**File** is the filename of a compatible "BUILD" file, as discussed later.
	Transform Matrix	The **Transform Matrix** is a 16 number matrix which allows dynamic positioning of the view within the window. The matrix (1 0 0 0 0 1 0 0 0 0 1 0 0 0 0 1) would show the image as it would appear in a display from BUILD.
PALETTE	(15)	The PALETTE label performs a specialized function for showing colors on the views. A four entry table is created and used for each type of filling polygon used in a view. Up to five palettes may be defined. Each palette is identified by a unique number and placed in the window at a specified location. Xl, Yb, Zf, Xr, Yt and Zb have a meaning similar to WINDOW. However, here they specify where in the window to put the palette.
	Palette Number	Palette number is the number to identify the palette. Allowable values are from 1 to 5.
	Xl	Left hand side of the palette within the window in the same units as that of the window.
	Yb	Bottom of the palette within the window in the same units as that of the window.
	Zf	Forward edge of the 3D block within the window in the same units as that of the window.
	Xr	Right hand side of the palette within the window in the same units as that of the window.

	Yt	Top of the palette within the window in the same units as that of the window.
	Zb	Back edge of the 3D block within the window in the same units as that of the window.
	Color and Label	There are four pairs of color/text combinations, each corresponding to an entry in the palette. The color number is an integer from 1 to 15 and the text can be up to 50 characters (but remember the 128 character maximum). As before, spaces are indicated with an underscore character "_".
BAR	(9)	Up to five bar charts may be displayed at one time on the graphics display. Each bar chart is identified by a unique number and placed in the window at a specified location. Xl,Yb,Zf,Xr,Yt and Zb have a meaning similar to WINDOW. However, here they specify where in the window to put the bar chart.
	Bar Chart Number	The number to identify the bar chart. Allowable values are from 1 to 5.
	Xl	Left hand side of the bar chart within the window in the same units as that of the window.
	Yb	Bottom of the bar chart within the window in the same units as that of the window.
	Zf	Forward edge of the 3D block within the window in the same units as that of the window.
	Xr	Right hand side of the bar chart within the window in the same units as that of the window.
	Yt	Top of the bar chart within the window in the same units as that of the window.

	Zb	Back edge of the 3D block within the window in the same units as that of the window.
	Abscissa Title	Title for the abscissa (horizontal axis). To have blanks in the title, use the underscore character "_".
	Ordinate Title	Title for the ordinate (vertical axis). To have blanks in the title, use the underscore character "_".
LABEL	(10)	Up to five labels may be displayed at one time on the graphics display. Each label is identified by a unique number and placed in the window at a specified location. Xl, Yb, Zf, Xr, Yt, and Zb have a meaning similar to WINDOW. However, here they specify where in the window to put the label. It is assumed that time is always to be displayed if any labels are present. To this end, label 1 is always used for the time in the units HH:MM:SS.
	Label Number	Label number is the number to identify the label. Allowable values are from 1 to 5.
	Xl	Left hand side of the label within the window in the same units as that of the window.
	Yb	Bottom of the label within the window in the same units as that of the window.
	Zf	Forward edge of the 3D block within the window in the same units as that of the window.
	Xr	Right hand side of the label within the window in the same units as that of the window.
	Yt	Top of the label within the window in the same units as that of the window.
	Zb	Back edge of the 3D block within the window in the same units as that of the window.

Text	The text to be displayed within the label. To have blanks in the title, use the underscore character "_".
Angle1, Angle2	Angles for display of the label in a right cylindrical coordinate space. At present only the first angle is used and represents a positive counterclockwise rotation; set the second angle to zero. Both angles are in radians.

In order to see the variables, they must be assigned to one of the above displays. This is accomplished with the variable pointers as

```
(Variable) (nmopq) (Compartment) (Layer).
            12345
```

Variable is one of the available variables VENT, HEAT, PRESSUR, WALL, TEMPERA, INTERFA, N_2, O_2, CO_2, CO, HCN, HCL, TUHC, H_2O, OD, CT used as a label for the line. The species listed correspond to the variable "SPECIES" in FASTplot. In the variable list of FAST, all are contained in the variable TOXICT. **(nmopqr)** is a vector which points to

index	display in
(1) n	-> bar chart
(2) m	-> table
(3) o	-> view
(4) p	-> label
(5) q	-> graph

respectively. These numbers vary from 1 to 5 and correspond to the value of "n" in the "where to put it" specification. **Compartment** is the compartment number of the variable and **Layer** is "U" or "L" for upper and lower layer, respectively.

Examples:

```
WINDOW     0    0 -100  1280  1024    1100
GRAPH 1  250. 170.  0. 1220. 900.    10.  5 TIME  CELSIUS
LABEL 1  970. 960.  0. 1231. 1005.   10. 15 00:00:00                0.  0.
LABEL 2  690. 960.  0.   987. 1005.   10. 13 TIME_[S]                0.  0.
LABEL 3  90.  920.  0.   730. 1020.   10. 4 Single_Compartment_demo  0.  0.
LABEL 4  400. 610.  0.   687. 660.    10. 1 U_layer_temperature     .1  0.
LABEL 5  400. 270.  0.   687. 320.    10. 1 1_layer_temperature     .0  0.
TEMPERA 0 0 0 0 1   1 U
TEMPERA 0 0 0 0 1   1 L
```

In this case, a new window is defined, along with one graph and five labels. Both temperature variables are assigned to graph 1. One quirk is not obvious. It is assumed that time is always to be displayed if any labels are present. To this end, label 1 is always used for the time in the units HH:MM:SS. Graph 1 has the label "TIME" on the abscissa and "CELSIUS" on the ordinate.

```
WINDOW        0     0  -100  1280  1024    1100
GRAPH   1  120.  300.    0.   600.  920.    10.  3 TIME  PPM
GRAPH   2  740.  300.    0.   1220. 920.    10.  3 TIME  CELSIUS
LABEL   1  970.  960.    0. 1231. 1005.    10. 15 00:00:00       0.     0.
LABEL   2  690.  960.    0.  987. 1005.    10. 13 TIME_[S]       0.     0.
LABEL   3  200.  050.    0.  520.  125.    10.   14 CO¦D2¦O_CONCENTRATION 0. 0.
CO      0 0 0 0 1    1 U
TEMPERA 0 0 0 0 2    1 U
TEMPERA 0 0 0 0 2    1 L
```

This file sets up two graphs with the CO data from the upper layer of compartment (1) in the first graph and both the upper and lower layer temperatures displayed on the second graph.

```
WINDOW        0     0  -100  1280  1024    1100
GRAPH   1  150.  300.    0.  620.  920.    10.  3 TIME  PPM
LABEL   1  390.  960.    0.  651. 1005.    10. 15 00:00:00       0.     0.
LABEL   2  110.  960.    0.  407. 1005.    10. 13 TIME_[S]       0.     0.
LABEL   3  200.  050.    0.  520.  125.    10.   14 O¦D2¦O_CONCENTRATION 0. 0.
TABLE   1  700.  300.    0. 1200.  920.    10.
HEAT    0 1 0 0 0    1 U
O2      0 1 0 0 1    1 U
TEMPERA 0 1 0 0 0    1 U
TEMPERA 0 1 0 0 0    1 L
```

Here the four variables HEAT, O2, and TEMPERATURE are displayed in table 1 and O2 is shown in graph 1.

```
WINDOW        0     0  -100  1280  1024    1100
VIEW    1  800.  390.  150. 1200.  900.  200. DEMOFA.DAT 1.41 .48 1.33 0....
VIEW  2  420.  200.   50.  720.  500.  100. DEMOFA.DAT 1.53 -.46 1.21 0. ...
GRAPH   1   50.  290.    0.  300.  490.    10. 13 TIME  PPM
GRAPH   2  150.  650.    0.  500.  850.    10. 13 TIME  m¦U-1
GRAPH   3  510.  690.    0.  740.  890.    10. 13 TIME  CELSIUS
GRAPH   4  810.  120.    0. 1160.  320.    10. 13 TIME  HEIGHT
```

```
LABEL    1  760.  960.   0. 1021. 1005.   10. 14 00:00:00         0.      0.
LABEL    2   50.   10.   0.  250.   70.   10.  2 TEST_IN_ONE_ROOM    0.57079 0.
LABEL    3   70.  960.   0.  367. 1005.   10. 13 FIRE_[W]         0.      0.
LABEL    4  480.  960.   0.  777. 1005.   10. 13 TIME_[S]         0.      0.
LABEL    5  300.  960.   0.  475. 1005.   10. 14 ________         0.      0.
TABLE    1  220.   50.   0.  520.  250.   10.
HEAT     0 0 0 5 0   1 U
OD       0 1 1 0 0   1 U
OD       0 0 2 0 2   1 U
CO       0 1 1 0 1   1 U
CO       0 0 2 0 0   1 U
TEMPERA  0 1 1 0 3   1 U
TEMPERA  0 0 2 0 0   1 U
INTERFA  0 1 1 0 4   1 U
INTERFA  0 0 2 0 0   1 U
```

Two views are specified, both emanating from the file "demofa.dat" with different transforms. Four graphs, three labels and one table will be displayed. All variables will be taken from the upper layer in compartment (1), and they will go to both views, in determining the hazard calculation. The variables will also be shown in table 1 and in the four graphs, respectively.

7. FASTplot

The FAST model predicts the environment produced by a fire in one of several compartments, or rooms, and follows smoke and toxic gases from one compartment to another, separately predicting values for each of the variables in both the upper and lower layers. The results for "FAST" are written to a special data file (the "dump" file) after each prescribed time step. FASTplot is intended to provide a post processing visual interface to generate graphs and tables from the time histories saved by the model. FASTplot has the capability to form a list of variables, read in their values at each time interval, list the values in tabular form, plot the values, and save the variables in a formatted file for use with other software. In addition, it has the capability to read dump files created by other programs to plot along with FAST data.

For the FAST dump files, the variables currently available are

boundary surface temperature (ceiling, floor)	WALL	°C
entrained mass flow in the plume	ENTRAIN	kg/s
hcl wall surface concentration	HCL	kg/m^2
heat release in lower layer	LPLUME	kW
heat release in upper layer	UPLUME	kW
heat release in flame out a vent	VFIRE	kW
heat release rate of the fire	HEAT RELEASE	kW
layer height	INTERFACE	m
layer temperature	TEMPERATURE	°C
mass flux from the plume into the upper layer	PLUME	kg/s
pyrolysis rate of the fuel	PYROLYSIS	kg/s
pressure	PRESSURE	Pa
radiation field to a target	TARGET	W/m^2
species density[5]	SPECIES	%,ppm
total radiative heat flux into the layer	RADIATION	W
total convective heat flux into the layer	CONVECTION	W
vent flow	VENT	kg/s
vent entrainment	JET	kg/s
volume of the upper layer	VOLUME	m^3

The command for starting the program is simply FASTPLOT. After identifying information, a "command prompt" appears and commands to direct the generation of the tables and graphs may be entered.

[5] For nitrogen, oxygen, carbon dioxide, fuel (tuhc) and water, the units are percent. For carbon monoxide and hydrogen cyanide, the units are parts per million. For optical depth the unit is inverse meters, and CT is gram-minutes per cubic meter.

Commands available at the "command prompt" are

ADD	LIST
ASCII	PLOT
AGAIN	RAPID
CLEAR	READ
DEFAULT	REVIEW
DELETE	SAVE
END	SHIFT
HELP	TENAB
FILE	VARIABLE

These commands can be broken into five major groups that describe the process used to generate tabular or graphical output with FASTplot. The following is a description of each of the commands. At least three characters must be used to identify a command.

7.1 Entering Data Into FASTplot

FASTplot can currently read three types of data files:

- data created by the FAST model (FAST dump files),
- data created by the TENAB model[6] (TENAB dump files), and
- data created in specially formatted ASCII text files from other programs including RAPID, a program developed by CFR for analysis of large-scale fire tests.

Several commands are available within FASTplot to read these data files. They are FILE, AGAIN, and ADD (for FAST files), ASCII and RAPID (for ASCII text files), and TENAB (for TENAB files). In addition, several commands provide ancillary functions to support data entry.

[6] Hazard I Technical Reference Guide, NIST Handbook.

7.1.1 Commands for Reading Data

ADD

This command is used to build a list of FAST variables to be read into the active list. When an option is requested, ADD may be entered by itself or together with a list of variables that are to be added. If it is entered alone, there will be a request for the variables that are to be added to the list. For example:

```
> ADD
- INPUT VARIABLES TO BE ADDED>
        or
> ADD TEMP,PRES,......
```

For each variable selected there is a series of questions that will be asked to identify the type of that variable wanted. A question asked about all variables is:

```
WHICH COMPARTMENT? ->
```

For layer dependent variables, the user is asked to input the layer (U for upper or L for lower):

```
WHICH LAYER? ->
```

If VENTFLOW is chosen the compartment origin and destination will be requested as will the vent number; if SPECIES is selected the species name (O_2, CO_2,...) will be requested.

The maximum number of variables allowed in the active list at any one time is 20. If the list is full or the variable is presently in the active list the addition will be disallowed and another option requested.

ASCII

Read a file in columnar ASCII format. The next query will be for the columns to read. In order for this to work, there must be a column which corresponds to the default column as selected the "DEFAULT" command. Normally this will be time, but can be any other column as desired.

FILE

The FILE command allows the user to specify the FAST dump file name for subsequent ADD commands. FILE applies only to FAST dump files.

RAPID — Read a file in the RAPID format. The next query will be for the channels to read. In order for this to work, there must be a channel which corresponds to the default channel as selected the "DEFAULT" command. Normally this will be the time channel, but can be any other channel as desired.

TENAB — Read a file in the TENAB format. The TENAB program produces estimates for a number of tenability criteria for persons exposed to a fire environment predicted by the FAST model. The user must enter the "person number" and the desired criteria to be read from the file. The possibilities are:

Tenab Variable List
1. Fractional Effective Dose Due to Gases - Bukowski
2. Fractional Effective Dose Due to Gases - Purser
3. Fractional Effective Dose Due to CO2 - Purser
4. Temperature - Deg C
5. Fractional Effective Dose Due to Convective Heat
6. CT (G-MIN/M3)
7. Flux (KW-MIN/M2)
8. Derksen Curve

7.1.2 Support Commands for Data Entry

The AGAIN, CLEAR, DELETE, READ, and REVIEW commands allow the user to view and manipulate the list of variables read with the data entry commands.

AGAIN — This will repeat the input of a list of variables for a new file. The program maintains a list of the most recently acquired FAST variables. First, get a file with "FILE," then get a set of variables. Once again using "FILE," get a new file and then use AGAIN to get the same list of variables on this new file. This function simplifies direct comparisons between runs of FAST.

CLEAR — This command empties the current variable list.

DELETE — When this option is entered the present list of variables will be printed to the screen and the user will be asked to input the variables to delete by the number associated with them on the list. They must be entered on a single line separated by commas or blanks. If the variable number that is input does not correspond to one that is currently on the list it will be skipped. After the deletions have been processed a new list is presented and another option requested. If the list is presently empty then that fact will be stated in an error message. One caution is in order. The variables are deleted by the number in the list, rather then by rank ordering within a group. This is important in conjunction with use of the AGAIN command.

READ — READ is used to force a read of the data files. This is most useful for script files which can be processed automatically to display data. It is equivalent to pressing an <enter> at the "read prompt" in the interactive mode.

REVIEW — At times the user may wish to see what is presently on his list before entering a command. This may be done with the REVIEW command. It will print out the current list along with the compartment number, species, and layer of each of the variables. After the printing of the entire list, the option request is again displayed.

7.2 Generating Tables and Graphs With FASTplot

The commands LIST and PLOT allow the user to generate a table of values of selected variables or a graph of selected variables. The SHIFT command allows the user to shift the abscissa or ordinate axis of a variable.

LIST — List the values of any of the variables on the list to the screen. The variables to be listed and the time range of the list is entered. On PC versions, the list can be printed with the PRINT SCREEN key once it appears on the screen,.

PLOT — After entering the PLOT command, the current list of variables will be displayed along with their numbers. They should be entered in a string separated by commas or blank spaces. For example:

```
ENTER VARIABLES TO BE PLOTTED ->1,2,3,4
            or
ENTER VARIABLE TO BE PLOTTED ->1 2 3 4
```

Variables to be plotted together on a single graph are grouped in parenthesis. For example:

```
ENTER VARIABLES TO BE PLOTTED -> (1,2,3,4)
```

Normally, the program will scale the axes automatically. However, if the automatic formatting option has been turned off, then before the graph is drawn, the user is given the opportunity to change the range of the X and Y axes and the graph legends. The maximum and minimum value of the X and Y axes will be displayed, followed by a request for a change in each. If no change is desired simply enter an <enter> and the next axis change will be displayed:

```
The Min/Max for Temperature  are

  X =       0.00 TO    2000.00
  Y =       0.00 TO    1000.00

<enter> If no changes are desired.

  Xmin =       0.00, Change to =
  Xmax =    2000.00, Change to =
  Ymin =       0.00, Change to =
  Ymax =    1000.00, Change to =
```

Similar prompts are made for the legends for each graph. The user is allowed to change the text for each curve label and the position. If no changes are desired, the <enter> key may be pressed to accept the suggested values for the legend text and position:

```
Legend for  1 (Temperature  1 U  ) is |R 1 U|. :
<enter> For no change:
Legend for  2 (Temperature  2 U  ) is |R 2 U|. :
<enter> For no change:

Legend for graph 1 is at X=  40.00, Y= 945.49
<enter> If no changes are desired.
     X =      40.00, Change to =
     Y =     945.49, Change to =
```

When all the changes (if any) have been made the graph of that particular variable will be plotted. After the graph has been completed the option request will be displayed and a new option may be entered.

SHIFT

SHIFT is used to adjust the variable axes. The required input is a selection of the axis to shift, the amount of shift, and a list of channels. Please note that shifting the time axis for a single variable will shift the time axis for all variables associated with that particular file. Such an effect occurs because only one vector of values is kept for the time line for each file.

7.3 Saving Data With FASTplot

The save command allows the user to create an ASCII text file in one of two formats. These files may be used for future FASTplot runs or for exporting FAST or TENAB data to other programs.

SAVE

A command to save the values of the variables in the list into a file. The format used will depend on the option chosen in "DEFAULT," columnar data for spreadsheet and charting programs, or row data for making the data directly compatible with our data processing program (RAPID) designed for the reduction of experimental data in the Center for Fire Research.

The user will be asked for the name to be used for the file. A check will be made to see whether that file presently exists or not. If it does, the user will be asked if he wants to write over the old file with this new data. If his answer is NO, nothing will be placed in the file and other option requested. If, however, he does want the file rewritten, or the file does not already exist, the new file will be created and the data stored in it.

Columnar data is straightforward, with each variable listed. The time channel will be the first column. For files in the row format, each variable in the list will be saved with the following line at the beginning of each block of data:

```
I6,I6,A6,*-----------COMMENT----------
```

The first I6 will be for the number of data points for that variable, the next I6 is for the number given to that variable on the list, and the A6 is the actual variable name. Everything after the * is a comment block and will be filled with information relevant to that particular variable, such as species number, compartment number, layer, etc. The actual numerical data will be written using the format 7E11.5.

7.4 Changing the Default Parameters in FASTplot

The DEFAULTs command allows the user to change a number of default parameters within FASTplot. These defaults specify the format of the graphical output and assumed values for some of the input parameters (ones where the user may simply press the **<enter>** key).

DEFAULT — This enables the user to set default parameters for the following, with the system default show to the right in parenthesis:

COMPARTMENT NUMBER	(1)
VENTFLOW DESTINATION	(2)
LAYER	(U)
CHARACTER SET	(4)
OUTPUT (not appropriate for PC versions)	
GRAPHICS DEVICE (" ") - will be implemented in the future	
AUTO SCALING	(Y)
CHANNEL FOR ABSCISSA	(999)
FACTOR FOR ABSCISSA	(1)

The purpose of this option is to change the defaults available for other commands and data input. Output and Graphics Device should not be reset on the PC versions. Channel for abscissa refers to the RAPID data reduction program, NBS Special Publication 722 (1986). Factor for abscissa refers to the column used when reading ASCII data files.

7.5 Getting Online Help in FASTplot

The HELP and VARIABLES command provides some simple online help for using FASTplot.

HELP — This command may be entered at any time that the user is asked for an option. Its purpose is to list to the screen, the available commands and a brief explanation, after which another option will be asked for.

VARIABLES — Show the list of variables which are available. This list is identical to the one shown at the beginning of section 7.

7.6 Exiting FASTplot

The END command terminates the execution of FASTplot. If desired, any data which has been read into FASTplot should be saved prior to entering this command. Any data not saved will be lost upon exiting the program and must be reentered if it is to be used again.

8. FAST_in

FAST_in is an interactive interface (front end) for the FAST model. As such, it is designed to guide a user through the creation and modification of a data file which can be used in running the model. FAST_in is not a general purpose fire growth and smoke transport model, although it does have limited capability for doing calculations and estimates. Rather, it is a text oriented editor used to create FAST data files while FAST is a general purpose model with graphics display. While some of the more intricate inputs available with the FAST model are not available from within FAST_in, basic data files can be created with FAST_in and further edited with any general purpose text editor.

The user interface is organized into a series of screens, each of which addresses a general area of the process of modeling a fire. General and key word help is always available except within the key word help section itself. The top of the screen shows which section is active. These names are shown below and are roughly descriptive of the area which is covered. These correspond to sections in the data file discussed in section 5. The bottom of the screen shows what special keys are active, or indicates what action is expected. If data can be entered, then the range and units will be shown if appropriate. For example, room width will be in units of length, whereas a title has no dimensions.

The "screens" are

0	Initialization	only at the beginning
1	Overview	primary sections
2	Ambient Conditions	
3	Geometry	
4	Thermal Properties	
5	Thermal Database	
6	Fire Specification	
7	Calculations,...	
8	Results	show results of calculation
9	Information and Settings	show the current version numbers and make permanent changes in the colors ans units

Note that the Initialization screen (screen 0) and the output screens (screens 7-9) do not correspond to sections of the data file. Rather, they are used to retrieve and save the data file created with FAST_in or to run the model with the current data set. Refer to section 6 for the details of the data entered on each screen.

1. Overview	Title and time specifications from section 6.1 and 6.2
2. Ambient Conditions	Ambient conditions from section 6.3
3. Geometry	Floor plan data and connections from sections 6.4 and 6.5
4. Thermal Properties	Thermophysical properties of enclosing
5. Thermal Database	surfaces from section 6.6
6. Fire Specification	Fire specifications from sections 6.7 and 6.8

In general, the program requests either data from the keyboard, or selection information from the function keys (or mouse if present). Any active function keys will be shown at the bottom of the screen. If the meaning is not clear, the **show keys** function key, f9, will give further explanation. Otherwise, there will be directions as to what further actions are possible. If alphanumeric input (data) is being requested, the entry must always be completed by pressing the **<enter>** key. For function keys, only a single keystroke is required. Some of the function keys are active throughout FAST_in; others are specific to certain screens. Those specific to individual screens are described in more detail on the following pages. Those active throughout the program are presented below.

key	key label	function
f1	go to page	Allows you to move directly from one screen to another within FAST_in. From any screen, pressing <f1> brings up a menu listing all the screens in FAST_in. Using the mouse or the arrow keys, select the screen of interest and press <enter> or the left mouse button.
f2	return	Allows you to move directly from the current screen to the previous screen within FAST_in. As an example, if you are on the thermal properties screen and press <Page Down> to move to the thermal database screen, pressing <f2> will return you to the thermal properties screen. Pressing <f2> again will take you again to the thermal database screen. This switching may be continued as long as desired.
f3	help	You may press the HELP key, f3, at any time to receive context sensitive help describing the current screen or current quantity being entered. Pressing <f3> a second time brings up a list of keywords for which more detailed help is available.
f8	change units	You may temporarily change the working engineering units displayed by FAST_in and used for data entry at any time by pressing <f8> and selecting the quantity to be changed with the

		up and down arrow keys. Pressing the right or left arrow keys changes the working units of the currently selected quantity. To change the units permanently, you must modify the installation parameters.
f9	show keys	provides a brief description of the function keys currently active and can be used to provide a quick reference of the current function of each of the keys.
f10	quit	is used to end the program.

```
FAST_in v 2.1   Initialization                                    04/12/88

                     FILE: DATA.DAT




¦file¦   ¦help¦   ¦ 1R ¦ 3R ¦    ¦   ¦keys¦unit¦quit¦  input=>
```

On the Initialization screen, the FAST input file to be edited with FAST_in is selected. The name of any DOS file may be entered by typing in the name of the file or the user may press the select file key, f1, to see a list of files in the current working directory. By default, all files with an extension of `.DAT` are presented in the list. If desired, one may type a file matching pattern (such as `*.*` to see all files in the subdirectory) before pressing <f1>.

In addition to showing the name of the current screen, "Initialization" in this case, the name of the module, its version number and the current date are shown. The latter two can change, as the program is enhanced, and when run on dates different than shown in the figure.

If a completely new data file is to be created, two generic data sets are built into the program. Key <f5> may be pressed to use a single room case and key <f6> may be pressed to use a three room case.

```
FAST_in v 2.1 Overview                                                          04/12/88

File: DATA.DAT     Title:    demo #1 a single compartment

Geometry                     Time               AmbientConditions

____________             __________           ________________________
Compartments      1  Simulation    180     Temperature     26.9
    Vents...      1       Print      0        Pressure  1.0E+05
HVAC connect      0        Dump      5     Station elv.     0.0
                        Display      5      Wind speed      0.0
                                           Scale height    10.0
                                              Power law  0.1600
Fire Specification
__________________
              Type Specified fire(constrained)
   Species tracked    O2  CO2   CO TUHC  H2O   OD   CT



Range: Alphanumeric ( 50)     Units: Name or Title
|goto|rtrn|help|    |    |    |    |unit|keys|quit|  input=> single compartment
```

The Overview screen presents a summary of the FAST data file. The title, simulation time, print interval, dump interval, and display interval may be changed on the screen. See sections 5.1 and 5.2 for detailed information on the parameters. All other information presented is changed on other screens of the program and is included here (in the "protected text" color) to provide a summary of the data set.

```
FAST_in v 2.1 Ambient conditions                                                04/12/88

              (internal)  (external)

   Temperature     26.9        26.9
      Pressure  1.0E+05     1.0E+05
  Station elv.      0.0         0.0

    Wind speed                  0.0
  Scale height                 10.0
     Power law               0.1600

  Compartments        1     Maximum pressure differential      0.0
      Vents...        1          Maximum elevation change     2.30
  HVAC connect        0             Total internal volume     32.6



Range:     -73.1 to     76.9   Units: Temperature in CELSIUS
|goto|rtrn|help|    |    |    |    |unit|keys|quit|  input=>
```

On the Ambient Conditions screen, the internal and external ambient temperature, pressure, and station elevation along with information on external wind may be changed. Ambient conditions are detailed in section 5.3. The wind speed, scale height, and power law are used to calculate the wind coefficient for each vent connected to the outside. The wind velocity is specified at some reference height. The power law then provides a lapse rate for the wind speed. An assumption is that the wind velocity vanishes at the surface. The formula used to calculate the wind speed at the height of any vent is (wind speed) · ((vent height)/(scale height))$^{(\text{power law})}$. The wind is applied to each external opening as a change in pressure outside of the vent. It is further modified by the wind coefficient used for the openings.

```
FAST_in v 2.1 Geometry                                                                              04/12/88

           Dimensions

 Compartment Number:        1
              Width:     3.30
              Depth:     4.30
             Height:     2.30
    Floor elevation:      0.0

         Vents(doors...)

      with respect to first room      wrt second room    - absolute -
  #  width    sill  soffit  wind     #   sill  soffit    a_sil  a_sof Vent(1->4)
  1   1.07    0.0    2.0    0.0      2    0.0    2.0      0.0    2.0      1




Range:       0.0 to    150.0   Units: Distance in METER
|goto|rtrn|help|ADD |DEL |O/C |SWPG|unit|keys|quit|  input=>
```

On the Geometry screen, information on the sizes of all of the rooms and vents are entered. Sections 5.4 and 5.5 provide details. The screen is divided into an upper and lower "page," one for the room dimensions and one for the vent information. The SWITCH PAGE key, f7, toggles between the two pages. A room or vent may be added or deleted using the ADD key, f4 or the DELETE key, f5. The OPEN/CLOSE key, f6, allows specification of vent position over the course of the fire as detailed by the CVENT parameter in FAST.

```
FAST_in v 2.1 Thermal properties                                          04/12/88

 Compartment Number        1

 Ceiling properties:      OFF
   Floor properties:      OFF
    Wall properties:      OFF




Range: Alphanumeric (  8)     Units: Name or Title
| go |rtrn|help|ADD |DEL |    |    |unit|keys|quit|  input=>
```

The Thermal Properties screen details the materials used for the ceilings, walls, and floors of all of the rooms as detailed in section 5.6. The name of a material contained in the FAST Thermal Database may be entered by first positioning the highlighted selection bar over the entry of interest and typing the material name exactly as it appears in the FAST thermal database. To make the process easier, a material name may be selected on the Thermal Database screen below, and designated for the currently selected surface by pressing the ADD PICKED key, f4. To specify an adiabatic surface, press the DELETE key, f5, to turn OFF the heat transfer calculation for that surface. If the word NONE appears, it means that the name entered does not appear in the Thermal Database.

```
FAST_in v 2.1 Thermal Database                                            04/12/88

           Conduct Specifi Density Thickne Emissiv      * CODES *
DFIR30      0.0002  0.9000   790.0  0.0160  0.9000
PINEWOOD    0.0001    2.50   540.0  0.0160  0.8000
CONCRETE    0.0018    1.00  2200.0  0.1500  0.9400
REDOAK      0.0002    1.30   640.0  0.0160  0.9000
FIBER          0.0    1.25   240.0  0.0160  0.9000
GYPSUM      0.0002  0.9000   800.0  0.0160  0.9000
WOOD           0.0    1.00   250.0  0.0160  0.9800
DFIR0       0.0001    1.40   510.0  0.0127    1.00
DFIR10      0.0002    1.50   560.0  0.0160  0.9000
GLASS       0.0014  0.7600  2500.0  0.0160  0.9500
GLASFIBR       0.0  0.7200    32.0  0.0160  0.9000
KAOWOOL     0.0002    1.05   128.0  0.1160  0.9700
GYP1        0.0001  0.9000   800.0  0.0250  0.9000
GYP2        0.0001  0.9000   800.0  0.0500  0.9000
BRICK1      0.0002  0.9000   790.0  0.0160  0.9000
WB          0.0001    1.17  4050.0  0.0250  0.8000


Range:      0.0 to    0.0900   Units: Conductivity in KILOJOULE/SECOND/METER/CELS
| go |rtrn|help|ADD |DEL |PICK|    |unit|keys|quit|  input=>
```

The contents of the FAST thermal database may be examined or changed on the Thermal Database screen. A new material may be added by pressing the ADD key, **f4**, or an existing one deleted by pressing the DELETE key, **f5**. A material can be chosen (and later added in the Thermal Properties screen) by positioning the highlighted selection bar over the material and pressing the PICK MATERIAL key, **f6**. The thermophysical data file can not be changed (saved after editing) by FAST_in, although it will shown as changed on the "save files" screen if changes have been made at this point.

```
FAST_in v 2.1 Fire Specification                                                 04/12/88

      Heat of C    Lim O2    Rel Hum.    GMW        Pos       Room       Type
       1.8E+04      3.00       0.0      16.0         1          1          2



                    2.0E+04 +
 | 1  1.8E+04|              ***  *  *     *    *                    *
 | 2  1.8E+04|              |
 | 3  1.8E+04|              |
 | 4  1.8E+04|              |
 | 5  1.8E+04|      1.0E+04 +
 | 6  1.8E+04|              |
 | 7  1.8E+04|              |
 | 8  1.8E+04|              |
                            |
                        0.0 +---------+---------+---------+---------+---------+
                            0.       160.      320.      480.      640.      800.


   Pyrolysis Heat_release  Height  Area  H/C CO/CO2 C/CO2 HCN HCL Ct

Range:   0.0010 to  6.0E+04   Units: Heat of Combustion in KILOJOULE/KILOGRAM
| go |rtrn|help|ADD |DEL |MOD |     |unit|keys|quit|  input=>
```

All data pertaining to the combustion properties are entered on this screen. The heat of combustion, mass loss rate, and species yields are entered, along with selection of the fire room and fire type as described in the data file format section. Note that fire chemistry is only allowed for constrained (type 2) fires.

A species may be added or deleted from the calculation using the ADD key (**f4**) or the DELETE key, **f5**. The time intervals may be modified by pressing the MODIFY TIME key, **f6**.

```
FAST_in v 2.1 Calculate,...                                          04/12/88

    run this data set       <f4> time      0  maximum    180 (seconds)

    quick estimates         <f5> asks for a time interval

    run time graphics (FAST) <f6> no

    save data file(s)       <f7>

    write to log file       <f8> no



| go |rtrn|help|    |    |    |    |    |quit|
```

Once data for a test case has been entered or modified using FAST_in, you may run the data set using a version of the FAST model, or save the data to disk to run with the complete version of FAST. To run the model, press <f4>. To save the data to a disk file, press <f7>. You may also append a simple graphics descriptor to the FAST data file by pressing <f6>. The resulting display will show selected variables in a simple X-Y plot on the screen as the model calculates the results. If problems are encountered with FAST_in, you can document the problem by generating a log file with the <f8> function key and repeating the sequence of commands which generates the problem.

```
FAST_in v 2.1 Results - temp..                                      04/12/88

              Time:      0.0

 Compartment Number:       1

   Upper layer temp:     26.9
   Lower layer temp:     26.9
       Upper volume:   0.0326
        Layer depth:   0.0023
       Ceiling temp:     26.9
    Upper wall temp:     26.9
         Floor temp:     26.9
    Plume flow rate:      0.0
     Pyrolysis rate:      0.0
          Fire size:      0.0
          Vent fire:      0.0     0.0
           Pressure:      0.0



                                Units: Temperature in CELSIUS
¦ go ¦rtrn¦help¦ FF ¦    ¦    ¦    ¦unit¦keys¦quit¦
```

When the installation program is run, the default units are set. However, during a run of FAST_in, it is possible to change the units, for that session. The key to set units is <f8> when it is shown as active. This will allow a change for the current session. To change the units permanently, rerun the installation program. The screen for the units section looks like

```
FAST_in v 2.1 Set Units                                             04/20/89

  Base Unit      Current Units  Possible Units

  Temperature    KELVIN         KELVIN     CELSIUS     RANKINE     FAHRENHEIT

  Pressure       PASCAL
  Length         METER
  Energy         JOULE
  Mass           KILOGRAM
  Time           SECOND
  Time           SECOND

   |To change units, highlight the basic unit to be changed, then point to the|
   |unit desired.  Pointing is done either with the cursor keys or the mouse. |

<esc> to exit,  <f3> for help
```

The time scale for most phenomena is set with the first entry. This refers to rates such as mass per unit time. The second is to accommodate English units in a natural way. In these units, conductivity is in BTU/hour/... as opposed to Joules/second/... In most cases, they will be set to the same unit, but if the "English" option is used, then they will be different. Of course, they can be set to different values manually.

For the most part, the remaining screens follow the same type of format. When the function keys are active, one can move through the "screens" with the "go" command, or by using **<PgUp>** and **<PgDn>**. The "Home" key moves the program to the "Overview" section and the **<End>** key will go to the "Calculate,..." section.

After one has become familiar with FAST_in, it is desirable to use some additional feautures which are available. They include making permanent changes to units and colors within FAST_in itself rather than returning to the installation procedure. Also, one can run the model directly, as long as "run time" graphics are not desired. To activate these features, run the installation module and exit with the **<f9>** key instead of **<f10>**.

9. ANNOTATED REFERENCES

[1] Jones, W.W., A Multicompartment Model for the Spread of Fire, Smoke and Toxic Gases. Fire Safety Journal 9, 55 (1985).

The papers by Jones [1], and Jones and Peacock [10] are the most complete descriptions of the use of differential equations in the problem of modeling fire growth and smoke transport. The original work on multicompartment models was written by T. Tanaka, A Mathematical Model of a Compartment Fire, BRI (Japan) No. 70 (1977). It is somewhat difficult to follow, partly due to language and partly to notation.

[2] Jones, W.W. and Fadell, A.B., A Device Independent Graphics Kernel, NBSIR 85-3235 National Bureau of Standards (USA) (1988).

[5] Siegal, R. and Howell, J.R., Thermal Radiation Heat Transfer, McGraw Hill Book Co., New York (1981).

[6] Schlichting, H., Boundary Layer Theory, translated by J. Kestin, Pergammon Press, New York (1955).

Schlichting is the most complete of the works on boundary layer theory especially the 7th edition, but somewhat difficult to read due to its completeness. An alternative which is much easier to follow is by Pitts, D.R. and Sissom, L.E., Heat Transfer, McGraw Hill, New York (1977).

[7] McCaffrey, B.J., Momentum Implications for Buoyant Diffusion Flames, Combustion and Flame 52, 149 (1983).

There are several plume models for fires. The one that has proved to be most in agreement with experimental data is that of McCaffrey [7]. Cetegan et al. have studied the door jet entrainment phenomena in great detail and their virtual plume concept works very well when used with McCaffrey's correlation.

[8] Cetegan, B.M., Zukoski, E.E., and Kubota, T., Entrainment and Flame Geometry of Fire Plumes, Ph.D. Thesis of Cetegen, California Institute of Technology, Pasadena (1982).

[9] Quintiere, J.G., Steckler, K., and Corley, D., An Assessment of Fire Induced Flows in Compartments, Fire Science and Technology 4, 1 (1986).

[10] Jones, W.W. and Peacock, R.D., Refinement and Experimental Verification of a Model for Fire Growth and Smoke Transport, Proceedings of the Second International Symposium on Fire Safety Science, Tokyo (1988).

[11] Quintiere, J.G., Steckler, K., and McCaffrey, B.J., A Model to Predict the Conditions in a Room Subject to Crib Fires, First Specialist Meeting (International) of the Combustion Institute, Talence, France (1981).

[12] Babrauskas, V., Development of the Cone Calorimeter - A Bench Scale Heat Release Rate Apparatus Based on Oxygen Consumption, Fire and Materials 8, 81 (1984).

[13] Huggett, C., Estimation of Rate of Heat Release by Means of Oxygen Consumption Measurements, Fire and Materials 4, 61 (1980).

The papers by Babrauskas [12] and Huggett [13] deal with a very specific piece of the chemistry which is extant in fires. Their concept allows us to finesse the very difficult question of the composition of the fuel, by providing an experimental relation between the net oxygen used by the products of combustion and the heat released by the fire.

[14] Goldman, D. and Jaluria, Y., Effect of Buoyancy on the Flow in Free and Wall Jets, ASME Winter Annual Meeting, Miami (1985).

[15] Jones, W.W. and Bodart, X., Buoyancy Driven Flow as the Forcing Function of Smoke Transport Models, NBSIR 86-3329, National Bureau of Standards (USA) (1986).

[16] Mitchell, A.R. and Griffiths, P.F., The Finite Difference Method in Partial Differential Equations, J. Wiley & Sons, New York (1980).

[17] U.S. Standard Atmosphere (1976), a joint publication of the National Oceanographic and Atmospheric Administration and the National Aeronautics and Space Administration.

[18] Zukoski, E.E., Heat Transfer in Unwanted Fires, Proceedings of the ASME-JASME Thermal Engineering Joint Conference 1, Hawaii (1987).

10. NOMENCLATURE

The variables used in the formulae are listed here. There are a few exceptions for local variables which are used only in a section for expository purposes. In general, most of these variables can be indexed by compartment (single i) or by the layer in a given compartment (u or ℓ). The variables shown in the implementation section correspond roughly to the mathematical variables shown here. Due to the limitations of character sets for computers, there can not be an exact correspondence, but the crosswalk should be clear. The first list is for the earlier discussion. The next list is for the numerical model as it is currently implemented.

Variables used in the mathematical description of the model:

A area (m^2)

- A_{upper} - extended upper wall - ceiling plus wall contiguous to upper layer
- A_{lower} - extended lower wall - floor plus lower wall
- A_w - area of surfaces in contact with a zone (upper or lower)
- A_d - area of interface between the two layers (discontinuity)

B sill height of a vent (m)

C coefficient (dimensionless)

- C - flow coefficient ≈ 0.72 for doorways (nominal value: range is 0.55 to 1.0)
- C_o - convective heat transfer coefficient (which depends on orientation)
- C_w - wind coefficient - dot product of the wind vector and vent direction

c heat capacity

- c_p - heat capacity of a gas at constant pressure
- c_v - heat capacity of a gas at constant volume
- c - heat capacity of a solid

D denominator in radiative heat balance matrix

$\dot{E}$ rate of change of total energy (Joules/s) - consists of enthalpy plus specific energy - E is used because we are really referring to a change in the internal energy density of the gas; $h = \dot{m}\, c_p$ is part of this term

- $\dot{E}_u$ - upper layer
- $\dot{E}_\ell$ - lower layer

e_i rate of entrainment in plume in region (i) - used for vitiated combustion - refer to p_i

F view factor (dimensionless)

F_f product of the fraction of fire which goes into radiation and a view factor

Gr Grashof number - see eq (13)

g gravitational constant (9.80 m/s^2)

H height (m)

H - soffit height of a vent

H_w - height at which the wind speed is measured - relative to H_r.

H_r - station elevation

H_i - height at which to calculate the pressure (including wind effects)

h heat of combustion (J/kg) or convective heat coefficient (J/m^2/K)

I time interval in seconds

$\dot{m}$ time rate of change of mass (kg/s)

$\dot{m}_i$ - total (net) mass flow into compartment i

$\dot{m}_u$ - total (net) mass flow into the upper layer of a compartment

$\dot{m}_\ell$ - total (net) mass flow into the lower layer of a compartment

$\dot{m}^{in}_{i,j}$ - net flow from compartment j into compartment i

$\dot{m}^{out}_{i,j}$ - net flow from compartment i into compartment j

$\dot{m}_{i,j} = \dot{m}^{in}_{i,j} - \dot{m}^{out}_{i,j}$ - in eq (20), (21), i→o is used to indicate in to out

$\dot{m}_e$ - entrained mass

$\dot{m}_f$ - pyrolysis rate of the fire

$\dot{m}_b$ - burning rate of the fire ($\leq \dot{m}_f$)

m species mass density (kg/m^3)

m_{xx} where xx is H_2O,CO_2,CO,S(soot),H,O,C,O_2,THUC,HCL,HCN,N_2 and fuel

N species number density or molar density (#/m^3)

N_{xx} where xx is H_2O,CO_2,CO,S(soot),H,O,C,O_2,THUC,HCL,HCN,N_2 and fuel

N_U is the Nusselt number, a function of Gr and Pr. It is not used explicity in any calculation, but is to show the relationship with standard heat and mass transfer theory.

P pressure (Pa)
- P_u - upper layer
- P_ℓ - lower layer
- P_R - reference pressure (assumption $P_R = P_u = P_\ell$ for temperature and density calculations)
- P_i - pressure at the base of compartment i
- P_i - pyrolysis rate - used only in the explanation of the fire specification in figure 6
- P_a - ambient pressure at a given height H_r
- P_w - pressure at a height H_i including wind effects

p_i plume flow rate for the vitiated combustion calculation - subscript refers to the region (1,2 or 3), which are show in figure 3; corresponding term is e_i

p_w power for the pressure lapse rate in the equation for the pressure including wind

Pr Prandtl number (0.72)

$\dot{Q}$ heat release rate for a chemical or physical process - this does not include any enthalpy flux (Watts)
- $\dot{Q}_f$ - chemical heat release rate from a fire
- $\dot{Q}_r$ - radiation heating of a gas by a wall surface or other gas layer
- $\dot{Q}_c$ - convective heating of gas by a wall surface
- $\dot{Q}_k$ - from surface 'k'
- $\dot{Q}_g$ - net heating of a gas by all radiative processes

R "universal" gas constant (≈289 J/kg/K)

S surface area of a vent (m^2)

$\dot{s}$ rate of total energy change in a compartment (sum of $\dot{E}$'s)

T temperature (K)
- T_u - upper layer
- T_ℓ - lower layer
- T_{uw} - upper wall
- $T_{\ell w}$ - lower wall
- T_R - reference temperature - limit -> T_a
- T_a - ambient either inside or outside of the structure
- T_v - temperature of the volatiles (after gasification)

t time (s)

V total volume of a compartment (m^3)

V_u - upper layer
V_ℓ - lower layer
V_w - wind speed (m/s) given at a height H_w above the terrain

v_p length of the virtual plume in vent flow calculations - used with the virtual offset z_p - both are in reduced units - see page 17ff

Z length (m) used for plume length, layer thickness and height of neutral plane(m)-

z - same meaning as Z except used as an integration parameter
Z_i - height of the hot layer interface (room height - layer thickness)

γ ratio of heat capacities ≃1.4 for air

σ Stefan-Boltzmann constant (5.67×10^{-8} W/m^2K^4)

α absorption coefficient of the gas (m^{-1})

ϵ emissivity (dimensionless)

ϵ_u - upper gas layer in a compartment
ϵ_ℓ - lower gas layer in a compartment

κ thermal conductivity (J/m/s/K)

ν kinematic viscosity (m^2/s)

ρ mass density (kg/m^3)

ρ_u - upper layer
ρ_ℓ - lower layer
ρ_i - i varies from 1 to 4 which represents upper and lower layers, as shown in figures 1 and 2

η condition number in the conduction equation - eq (39)

χ fraction of heat release rate which goes into some process

χ_R fraction of heat release rate which goes into radiation
χ_C fraction of heat release rate which goes into convective motion
χ_e fraction of pyrolosate which burns

Π_u numerator of heat balance matrix for upper layer contribution

Π_ℓ numerator of heat balance matrix for lower layer contribution

In the flow calculation, the indices have a special meaning. The reference is from "i," the inside compartment, to "o" the outside compartment. In this case, the index is 1 for the upper layer of "i," 2 for the lower layer of "i," 3 for the upper layer of "o," and 4 for the lower layer in "o." This terminology applies to temperatures, densities and mass flow only for the flow calculation as done in section 4.4 The "i" and "o" are chosen by a selection rule discussed in section 6.4

Variables used by FAST in the common blocks mocola, mocolc, mocold and mocole

AA(NR,NR,4)	flow from lower layer to lower layer (kg/s)
ACTIVS(NS)	logical switch to tell which species are active (interacts with "allowed")
AFIRED(NV)	area of fire (m^2)
AO(IFT)	area of simple fitting ift (m^2)
APS(NR)	current area of the specified fire (m^2)
AR(NR)	floor area of a compartment (in current version ceiling=floor)
AS(NR,NR,4)	flow from lower to upper layer (kg/s)
ASL(NR,NR,4)	entrainment from upper into lower layer (kg/s)
BFIRED(NV)	burning rate (kg/s)
BFLO(IB)	mass flow rate through branch ib (kg/s)
BR(NR)	breadth of a compartment (m)
BW(NR,NR,4)	width of vent (m) (modified by qcvent)
CCO2(NV)	net carbon production rate (fraction relative to co2)
CE(IB)	effective mass flow coefficient for resistance branch ib
CNAME(NWAL,NR)	name (pointer) of thermal property specied for a boundary
CO(IFT)	flow coefficient for simple fitting ift
COCO2(NV)	relative co/co2 production rate
CONFGFIL	name of a configuration file (not required)
CP	heat capacity of AIR at constant pressure (J/kg/K)
CRDATE(3)	creation date of the model (day, month and year)
CW(MXSLB,NWAL,NR)	specific heat of a thermal material
DA(ID)	area of duct id (m^2)
DE(ID)	effective diameter of duct id (m)
DELTAT	time step used by the model, currently 1.0 seconds
DFMAX(K)	derivative of fan curve at hmax(k)
DFMIN(K)	derivative of fan curve at hmin(k)
DL(ID)	length of duct id (m)
DPZ(I,K)	hydrostatic pressure difference between node i and kth node
DR(NR)	depth of a compartment (m)
DUCTAR(ID)	absolute roughness of duct walls
EME(NR)	plume entrainment rate (kg/s)
EMP(NR)	pyrolysis rate of the fire source (kg/s)

EMS(NR) plume flow rate into the upper layer (kg/s)
EPW(NWAL,NR) emissivity of the interior wall surface (non)
ERA(NR),EPA(NR),ETA(NR) exterior equivalents of ramb, pamb, and tamb: era,epa,eta
EXxx exterior equivalents of ta, pa and ra: exta, expa, exra
FKW(MXSLB,NWAL,NR) thermal conductivity of a material slab
FLW(MXSLB,NWAL,NR) thickness of a slab (m)
G gravity constant (9.806 m/s)
GAMMA cp/cv for air - 1.4
GMWF gram molecular weight (in grams, default ->16)
HCOMBA heat of combustion - initialization only
HCRATIO(NV) hydrogen/carbon ratio in the fuel - time dependent
HEATLP(NR) heat release rate in the plume in the lower layer (W)
HEATUP(NR) heat release rate in the plume in the upper layer (W)
HEATVF(NR) heat release in a vent (sum of all vents between two compartments 1->4)
HFIRED(NV) height of the base of the fire - time dependent (m)
HFLR(NR) absolute height of the floor of a compartment (m)
HH(NR,NR,4) top of vent (soffit) - distance from floor (m)
HHP(NR,NR,4) absolute height of the soffit (m)
HL(NR,NR,4) height of the sill relative to the floor (m)
HLP(NR,NR,4)absolute height of the sill (m)
HMAX(K),HMIN(K) max and min head pressure for fan(k)
HOCBMB(NV) heat of combustion of a specified fire (J/kg)
HR(NR) interior height of a compartment (m)
HRL(NR) absolute height of the floor (m)
HRP(NR) absolute height of the ceiling (m)
HVBCO(K,J) coefficients of fan curve polynomial
HVELXT(II) elevation of exterior nodes relative to station (m)
HVEXCN(MEXT,NS) species concentration at external the nodes
HVFLOW(I,J) mass flow rate to node i from the jth node to which it is connected
HVGHT(I) elevation of node i
HVNODE(I,J) mapping between external and internal nodes (2,MNODE)
HVP(I) relative pressure at node i
HWJ(NW,NR) hcl density on the wall (grams/m^2, initialized to 0)
IBRD(ID) pointer to resistive branch with duct id
IBRF(IFT) pointer to resistive branch with fitting ift
IC(I,K) pointer to kth resistive branch connected to node i
IDIAG not used
IFIRED current interpolation time for specified fire - integer pointer
IN(I,K) pointer to kth node connected to node i in hvac system
ITMMAX maximum number of time steps (#)
ITMSTP current time step (#)
IVERS current version
LCOPY number of "hard" copies for each graphics output - used for movies
LCW(MXSLB,NTHMX) local heat capacity

LDIAGO	dump interval (#)
LDIAGP	display (graphics) interval (#)
LEPW(NTHMX)	local emissivity
LFBO	compartment of origin (1 to nr-1)
LFBT	type of fire (1, 2, ...)
LFKW(MXSLB,NTHMX)	local conductivity
LFLW(MXSLB,NTHMX)	local thickness (m)
LFMAX	number of intervals in a fire specification
LFPOS	position of the fire in a room (1 to 4) - affects entrainment only
LIMO2	limiting oxygen index in percent (default is 10%)
LNSLB(NTHMX)	local number of slabs in a material (used in reading from the database)
LOGERR	unit for error logging - set to zero if not to log erros
LPRINT	print interval
LRW(MXSLB,NTHMX)	local mass density of a material slab
MASS(2,NR,NS)	mass in a layer of species ns (1 to ns)
MAXCT	number of entries in the thermal database (max is 57 now)
MFIRET(NS)	mass release rate of species ns - transient
MINMAS	minimum mass in mass(...)
MPRODR(NV,NS)	species production rate for specified fire - see tech ref for details
MPSDAT(3)	date of this run
N	number of compartments in use (including the outside)
N2,N3,N4	n+1,2n+1,3n+1
NA(IB)	starting node for branch ib
NBR	number of branches
NCNODE(I)	number of branches coonnected to hvac node i
NCONFG	0 or 1 if a graphics descriptor is present
NDIV(MXSLB,NWAL,NR)	number of interior nodes in a wall material (of mxslb slabs)
NDT	number of ducts
NDUMPR	0 or 1 if a dump file specification is present
NE(IB)	exit node number of branch ib
NEUTRAL(NR,NR)	number of neutral planes for a vent - not very useful
NEXT	number of exterior nodes
NF(IB)	0 if duct, fan number if a fan
NFAN	number of fans
NFC(K)	number of polynomial coefficients for fan k
NFT	number of simple fittings
NLIST(NTHMX)	list of thermal names used by the current thermal database
NLSPCT	number of species in this run
NM1	actual number of compartments (N-1)
NNODE	number of nodes in the hvac system
NOPNMX	not used
NRESTR	restart time (0 means no restart)
NRFLOW	not used
NSLB(NWAL,NR)	number of slabs in a particular wall

NSMAX maximum simulation time (seconds)
NW(NR,NR) switch for horizontal vents - coded for 1 to 4 by powers of 2
NWV(NR,NR) switch for vertical vents
ONTARGET(NR) absolute radiation from the upper layer to a target (less ambient)
P(NT) solution vector of pressure, upper temperature, lower temperature, volume
PA ambient pressure at the measured station
PAMB(NR) ambient pressure in a compartment prior to the fire
PMAX(NT),PMIN(NT) limits on the values in p
POFSET a pressure offset to help solve the stiffness problem
PPMDV(2,NR,NS) mass concentration (kg/m^3)
PREF default reference pressure (1.03 e+5)
QC(2,NR) net convective heat loss from a zone (Watts)
QF(2,NR) net heat generation rate of a fire into a zone (Watts)
QFIRED(NV) heat release rate for specified fire
QMAX(K),QMIN(K) flow rate at hmax(k) and hmin(k)
QR(2,NR) net radiative loss from a zone (Watts)
QRADRL fraction of heat which leaves a fire as radiation
RA default station ambient (inside) density (kg/m^3)
RAMB(NR) initial (ambient) mass density in a compartment
RELHUM initial relative humidity (default ->0%)
RGAS "universal" gas constant
ROHB(IB) density of gases in branch ib
RR(ID) relative roughness of walls of duct id
RW(MXSLB,NWAL,NR) material density of a boundary slab (kg/m^3)
SA(NR,NR,4) flow field upper to lower (kg/s)
SAL station elevation (m) - default to zero
SAU(NR,NR,4) entrainment rate into the upper layer
SIGM Stefan-Boltzmann constant (5.67×10^{-8} W/m^2/K^4)
SS(NR,NR,4) flow field from upper to upper layer (kg/s)
STIME current simulation time (s) - corresponds to itmstp
SWITCH(NWAL,NR) logical switch for wall conduction - switch...,nr) is used for output
TA station ambient temperature (K)
TAMB(NR) ambient temperature in a compartment (K)
TBR(IB) absolute temperature of gases in branch ib
TE pyrolysis temperature of the fuel
TERRORS(NTHMX) code for errors in the thermal database
TFIRED(NV) time interval specification
TFIRET current time for interpolation
TFMAXT maximum time for the specified fire
TGIGNT ignition temperature for a well stirred gas - limits fires in vents
THDEF(NTHMX) logical for whether thermal name is correctly defined
THRMFILE*20 name of the thermal database
TOXICT(2,NR,NS) conglomeration of stuff for output - see Tech Ref.
TREF default reference temperature

TWE(NWAL,NR)	temperature of the gas external to a compartment boundary
TWJ(NWAL,NR,NN)	temperature profile in the boundaries (ceiling, floor, upper/lower wall)
VOL(IBR)	volume of branch ibr
VR(NR)	volume of a compartment
VVAREA(NR,NR)	area of a vertical vent
WINDC(NR)	wind coefficient for a vent facing the outside
WINDPW	wind power law coefficient
WINDRF	wind reference height (m)
WINDV	wind reference velocity at windrf

PARAMETERS:

MBR	maximum number of branches
MCON	maximum number of connections to a node
MDT	maximum number of ducts
MEXT	maximum number of exterior nodes
MFAN	maximum number of fans
MFCOE	maximum number of fan coefficients
MFT	maximum number of simple fittings
MNODE	maximum number of nodes
MOPT	maximum number of options allowed on the command line
NR	maximum number of compartments
NN	maximum number of nodes in a boundary (walls, ceilings and floor)
NT	maximum number of equations to be solved (4*nr+2*nr*ns)
NTHMX	maximum number of thermal definitions
NV	maximum number of time intervals
NS	maximum number of species to be tracked
NWAL	number of discrete wall surfaces (ceiling, upper wall ...) currently 4
MXSLB	maximum number of different materials in a wall (now 3)
UPPER,LOWER	upper, lower layer pointers (=1,2)

APPENDIX A: SAMPLE INPUT

The first four examples are included in the distribution as demo-fn.dat where n=1->4. The fifth file is simply another example and is the file 3R in FAST_in.

The first example is for a single compartment. This is also the 1R data file referred to in FAST_in. In the latter case the graphics descriptors are not included.

```
VERSN   18 demo #1 a single compartment
TIMES   180  0  0   5   0
TAMB    300.
HI/F    0.
WIDTH   3.3
DEPTH   4.3
HEIGH   2.3
HVENT   1    2    1    1.07  2.0  0.0
CEILI   GYPSUM
FLOOR   WOOD
LFBO    1
LFBT    2
LFMAX   7
CHEMI   0.0  0.0  1.0  18100000 300.
FMASS   .0014 .0014 .025 .045 .050 .0153 .0068 .0041
FAREA   .5    .5    .5    .5    .5    .5    .5 .5
FHIGH   .25    .25    .25    .25    .25    .25    .25 .25
FTIME   20. 20. 50. 50. 100. 100. 400.
OD      02 .02  .02  .02  .02  .02  .02  .02
CO      02 .02  .02  .02  .02  .02  .02  .02
WINDOW      0      0  -100  1280  1024    1100
GRAPH   1  120.  300.    0.  600.  920.   10.  5 TIME  PPM
GRAPH   2  740.  300.    0.  1220. 920.   10.  5 TIME  CELSIUS
LABEL   1  970.  960.    0. 1231. 1005.   10. 15 00:00:00        0.      0.
LABEL   2  690.  960.    0.  987. 1005.   10. 13 TIME_[S]        0.      0.
LABEL   3  200.  050.    0.  520.  125.   10.  2 CO¦D2¦O_CONCENTRATION 0. 0.
CO      0 0 0 0 1    1 U
TEMPERA 0 0 0 0 2    1 U
TEMPERA 0 0 0 0 2    1 L
```

Demonstration #2 is a similar run, but showing other types of displays which are available.

```
VERSN   18 demo #2 a single compartment but plot other stuff
TIMES   180 0  0  5  0
TAMB    300.
HI/F    0.
WIDTH   3.3
DEPTH   4.3
HEIGH   2.3
HVENT   1    2    1    1.07  2.0  0.0
CEILI   KAOWOOL
FLOOR   CONCRETE
```

```
LFBO    1
LFBT    1
LFMAX   7
LFPOS   1
CHEMI   0.0  0.0  6.00  18100000 300.
FMASS   .014 .0014 .025 .045 .050 .0153 .0068 .0041
FAREA   .5   .5   .5   .5   .5   .5   .5 .5
FHIGH   .25   .25   .25   .25   .25   .25   .25 .25
FTIME   20. 20. 50. 50. 100. 100. 400.
WINDOW       0     0  -100  1280  1024   1100
GRAPH   1  150.  300.    0.  620.  920.   10.  3 TIME  PPM
LABEL   1  390.  960.    0.  651. 1005.   10. 15 00:00:00        0.     0.
LABEL   2  110.  960.    0.  407. 1005.   10. 13 TIME_[S]        0.     0.
LABEL   3  200.  050.    0.  520.  125.   10.   14 O¦D2¦O_CONCENTRATION 0. 0.
TABLE   1  700.  300.    0. 1200.  920.   10.
HEAT    0 1 0 0 0   1 U
O2      0 1 0 0 1   1 U
TEMPERA 0 1 0 0 0   1 U
TEMPERA 0 1 0 0 0   1 L
```

This is the data set which produces the NIKE site evaluation scenario.

```
VERSN   18  demo #3 the original nike site evaluation
TIMES  180  0  0   5    0
TAMB   300.
HI/F   0.0  0.0  0.0  0.0  0.0  0.0
WIDTH  3.3  2.4  2.9  2.4  3.3  2.4
DEPTH  4.3 18.8  9.9  9.9  4.3  4.3
HEIGH  2.3  2.3  2.3  2.3  2.3  2.3
HVENT    1    2    1  1.07  2.0  0.0
HVENT    2    3    1  1.07  2.0  0.0
HVENT    3    7    1  0.95  .15  0.0
HVENT    2    4    1  1.07  2.0  0.0
HVENT    4    7    1   .95  .10  0.0
HVENT    2    5    1  1.07  2.0  0.0
HVENT    2    6    1  0.10  2.0  0.0
CEILI    GYPSUM GYPSUM GYPSUM GYPSUM GYPSUM GYPSUM
LFBO     1 ROOM OF FIRE ORIGIN
LFBT     1 TYPE OF FIRE (GAS BURNER)
LFMAX    7 NUMBER OF INTERVALS OF FIRE GROWTH
LFPOS    1 POSITION OF THE FIRE (CENTER)
CHEMI   .0  0.0      1.0     18100000 300.
FMASS   .0014 .0014 .025 .045 .050 .0153 .0068 .0041
FAREA   .5   .5   .5   .5   .5   .5   .5 .5
FHIGH   .25   .25   .25   .25   .25   .25   .25 .25
FTIME   100. 100. 50. 50. 100. 100. 400.
CO      0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05
WINDOW       0     0     0  1280  1024   1100
VIEW   1 300 600 150 1200 900 200 DEMO-F3T.PIC 1 0 0 0 0 1 0 0 0 0 1 0 0 0 0 1
VIEW   2 300 300 150 1200 600 200 DEMO-F3B.PIC 1 0 0 0 0 0 -1 0 0 1 0 0 0 572 572 1
LABEL  1  820.  960.    0. 1081. 1005.   10. 14 ________       0.     0.
LABEL  2   50.   50.    0. 1080.  100.   10. 10 ¦Nike_Site_evaluation 1.57 0
LABEL  3   70.  960.    0.  367. 1005.   10. 03 FIRE_[kW]      0.     0.
LABEL  4  640.  960.    0.  937. 1005.   10. 03 TIME____       0.     0.
LABEL  5  360.  960.    0.  635. 1005.   10. 14 ________       0.     0.
TABLE   1  200.   20.    0.  950.  250.   10.
HEAT    0 0 0 5 0 1 U
TEMPE   0 1 1 0 0 1 U
INTER   0 1 1 0 0 1 U
```

```
CO      0 1 1 0 0 1 U
TEMPE   0 0 2 0 0 1 U
INTER   0 0 2 0 0 1 U
CO      0 0 2 0 0 1 U
```

The fourth demonstration data file is used to generate a dump file for trying FASTplot.

```
VERSN   18  demo # 4 a five compartment calculation with save's
TIMES   180  0  15   5    0
TAMB    300.
HI/F    0.0  0.0  0.0  0.0  0.0
WIDTH   3.3  2.4  2.9  2.4  3.3
DEPTH   4.3 18.8  9.9  9.9  4.3
HEIGH   2.3  2.3  2.3  2.3  2.3
HVENT    1    2  1    1.07  2.0  0.0
HVENT    2    3  1    1.07  2.0  0.0
HVENT    3    6  1    0.95  .15  0.0
HVENT    2    4  1    1.07  2.0  0.0
HVENT    2    5  1    1.07  2.0   0.0
HVENT    4    6  1    0.10  2.0   0.0
CEILING  GYPSUM   GYPSUM   GYPSUM   GYPSUM   GYPSUM
FLOOR    READOAK  READOAK  READOAK  READOAK  READOAK
LFBT     2
LFMAX    7
LFPOS    1
CHEMI    0.0  0.0  6.00  18100000 300.
FMASS   .0014 .0014 .025 .045 .050 .0153 .0068 .0041
FAREA   .5    .5    .5    .5    .5    .5    .5 .5
FHIGH   .25    .25    .25    .25    .25    .25    .25 .25
FTIME   100. 100. 50. 50. 100. 100. 400.
CO      0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05
DUMPR demo-f4.dmp
WINDOW       0      0  -100  1280  1024    1100
GRAPH   1  120.  300.    0.  600.  920.   10.  7 TIME  PPM
GRAPH   2  740.  300.    0.  1220. 920.   10.  7 TIME  CELSIUS
LABEL   1  970.  960.    0. 1231. 1005.   10. 15 00:00:00        0.     0.
LABEL   2  690.  960.    0.  987. 1005.   10. 13 TIME_[S]        0.     0.
LABEL   3  200.  050.    0.  520.  125.   10.   14 CO¦D2¦O_CONCENTRATION 0. 0.
CO      0 0 0 0 1   1 U
CO      0 0 0 0 1   2 U
CO      0 0 0 0 1   3 U
CO      0 0 0 0 1   4 U
CO      0 0 0 0 1   5 U
TEMPERA 0 0 0 0 2   1 U
TEMPERA 0 0 0 0 2   2 U
TEMPERA 0 0 0 0 2   3 U
TEMPERA 0 0 0 0 2   4 U
TEMPERA 0 0 0 0 2   5 U
```

The fifth example is a three compartment scenario, and referenced in the interactive program as 3R. The results obtained by running this data set are shown in Appendix B.

```
VERSN   18  An example of a constrained fire
TIMES   180    10   0    0    0
TAMB    300.  101300.     0.
HI/F    0.00      0.00     0.00
WIDTH   2.34      2.44     2.84
DEPTH   2.34     13.19     2.34
```

```
HEIGH   2.16     2.44     2.44
CEILI   KAOWOOL  GYPSUM   GYPSUM
WALLS   KAOWOOL  GYPSUM   GYPSUM
FLOOR   CONCRETE CONCRETE CONCRETE
HVENT   1  2  1  0.81   1.60   0.00
HVENT   2  3  1  0.79   2.00   0.00
HVENT   2  4  1  1.02   2.00   0.00
CHEMI   0.0 0.0 6.  50026000. 300.
LFBO    1
LFBT    2
LFPOS   1
LFMAX   2
FMASS   0.0000   0.0018     0.0019
FHIGH   0.50     0.50       0.50
FTIME        30.      1000.
```

The corresponding thermal data file for these examples is

```
CONCRETE  1.75    1000.  2200.    .15      .94  CONCRETE,NORMAL WEIGHT
REDOAK     .15    1300.   640.    .016     .9   RED OAK
GYPSUM     .16     900.   800.    .016     .9   GYPSUM BOARD (PLASTERBOARD)
WOOD       .07    1000.   250.    .016     .98  WOOD,CHARRED,DRY
KAOWOOL    .22    1047.   128.    .116     .97  Glass fiber insulation
```

APPENDIX B: SAMPLE OUTPUT

The output of the FAST program consists of two major parts. The first is a summary of the input data and the initial conditions. The second consists of the calculated results at the end of each print interval. A sample of the program output is shown in Appendix B. The particular example comes from the three compartment data file (3R) shown in Appendix A. Due to the effect of the computer's internal precision on the solution of the equations, it is possible that the results from other computers will differ slightly from those found in Appendix B. The output is labeled and most of it is self explanatory. There are however, a number of abbreviations used which are explained in the following sections along with a general description of the output. The output pertaining to each of the compartments is listed across the page beginning with compartment one in the left most column and proceeding to the right to the highest number compartment.

B.1 Summary of Input Data

The summary of input data is divided into three sections. These are geometrical data, thermophysical properties, and the fire specifications. A title precedes these sections and lists the version number and any title which was in the data file.

B.1.1 Title

```
FAST version 18.2 - created May 16, 1988   An example of a constrained fire
```

B.1.2 Geometrical Data

This section lists the run title, the total number of compartments, depth, height, area, and volume for each compartment. It also gives the ceiling and floor height with respect to the reference datum. This is followed by the connections between the compartments. Each compartment is listed vertically down the page and horizontally across the page and the connections between compartments are given at the intersection of the vertical and horizontal lists. The final compartment in the horizontal list is the exterior space. The parenthetical numbers in the vertical compartment list are the number of openings for each compartment. For example, if the maximum number of openings between any two compartments is three, there would be three parts for each compartment in the vertical list. Each part consists of the following:

1) opening width (BW) (m)
2) height of top of opening above floor (HH) (m)
3) height of bottom of opening above floor (HL) (m)
4) height of top of opening above reference datum (HHP) (m)
5) height of bottom of opening above reference datum (HLP) (m)

```
Total compartments =              3

 FLOOR PLAN

          Width      2.3   2.4   2.8
          Depth      2.3  13.2   2.3
          Height     2.2   2.4   2.4
          Area       5.5  32.2   6.6
          Volume    11.8  78.5  16.2
          Ceiling    2.2   2.4   2.4
          Floor      0.0   0.0   0.0

 CONNECTIONS

  1 ( 1)  Width      0.00  0.81  0.00  0.00
          Soffit     0.00  1.60  0.00  0.00
          Sill       0.00  0.00  0.00  0.00
          a.Soffit   0.00  1.60  0.00  0.00
          a.Sill     0.00  0.00  0.00  0.00
  2 ( 1)  Width      0.81  0.00  0.79  1.02
          Soffit     1.60  0.00  2.00  2.00
          Sill       0.00  0.00  0.00  0.00
          a.Soffit   1.60  0.00  2.00  2.00
          a.Sill     0.00  0.00  0.00  0.00
  3 ( 1)  Width      0.00  0.79  0.00  0.00
          Soffit     0.00  2.00  0.00  0.00
          Sill       0.00  0.00  0.00  0.00
          a.Soffit   0.00  2.00  0.00  0.00
          a.Sill     0.00  0.00  0.00  0.00
```

B.1.3 Thermophysical Properties

This section lists the thermophysical properties of the ceiling, floor, upper and lower walls respectively for each compartment. Although the thermophysical properties of the upper and lower walls are the same, they are presented separately to correspond to the temperature of the upper and lower temperature layers of the compartment. The information first shown are the names as given in the data file. Following this is a listing of the conductivity, specific heat, density, thickness and emissivity obtained for each of the thermophysical items which can be found. If the program was unable to find all names, it will quit at this point.

```
 MATERIAL NAMES

  Ceiling:   KAOWOOL   GYPSUM    GYPSUM
  Walls:     KAOWOOL   GYPSUM    GYPSUM
```

```
Floor:      CONCRETE  CONCRETE  CONCRETE

THERMAL DATA BASE USED:        THERMAL.DAT

Name       Conductivity Specific heat   Density       Thickness    Emissi

CONCRETE       1.75        1.000E+03    2.200E+03     0.150         0.940
GYPSUM        0.160         900.         800.         1.600E-02     0.900
KAOWOOL       0.220        1.047E+03     128.         0.116         0.970
```

B.1.4 Fire Specifications

This section consists of three parts. The first part lists the compartment number of the room of fire origin, the time step used in calculating the results, how often output is to be printed, the number of intervals for which the mass loss rate is specified, the total time over which the results will be printed, the fire location within the room of origin, and the fire type.

```
Compartment of origin is                          1
Print interval (seconds)                        900
Number of fire specification intervals is         2
Total time (seconds)                            900
Fire position                                     1
Limiting oxygen index (%) =                     6.0
Initial relative humidity (%) =                 0.0
Fire type is a SPECIFIED (CONSTRAINED)
```

The second part lists the initial fuel temperature, the ambient air temperature, and the ambient sea level reference pressure for the interior and exterior.

```
Pyrolysis  temperature (K) =                300.
Ambient air temperature (K) =               300.
Ambient reference pressure (Pa) =        101300.
Reference elevation (m) =                     0.
External ambient temperature (K) =          300.
External reference pressure (Pa) =       101300.
Reference elevation (m) =                     0.
```

The third part lists for each specified point of the fire, the mass loss rate of the burning fuel, the height of the base of the fire with respect to the floor, the heat of combustion and the fractional production rates of the species. Also listed is the duration of each time interval.

```
Fmass=   0.00      1.80E-03  1.90E-03
Hcomb=   5.00E+07  5.00E+07  5.00E+07
Fqdot=   0.00      9.00E+04  9.50E+04
Fhigh=   0.50      0.50      0.50
C/CO2=   0.00      0.00      0.00
CO/CO2=  0.00      0.00      0.00
H/C=     0.33      0.33      0.33
Ftime=    30.      1.00E+03
```

B.1.5 Initial Conditions

This section shows the conditions in the structure at the beginning. If this is a restart, then the conditions will be at the time step used for the restart.

```
Time =    0.0 seconds.

    Upper temp(K)       300.0      300.0      300.0
    Lower temp(K)       300.0      300.0      300.0      300.0
  Upper vol(m**3)         0.0        0.1        0.0
   Layer depth(m)         0.0        0.0        0.0
  Ceiling temp(K)       300.0      300.0      300.0
  Up wall temp(K)       300.0      300.0      300.0
 Low wall temp(K)       300.0      300.0      300.0
    Floor temp(K)       300.0      300.0      300.0

 Plume flow(kg/s)   0.000E+00  0.000E+00  0.000E+00
 Pyrol rate(kg/s)   0.000E+00  0.000E+00  0.000E+00
     Fire size(W)   0.000E+00  0.000E+00  0.000E+00
                    0.000E+00  0.000E+00  0.000E+00
   Plume in ul(W)   0.000E+00  0.000E+00  0.000E+00
   Plume in ll(W)   0.000E+00  0.000E+00  0.000E+00
     Vent fire(W)   0.000E+00  0.000E+00  0.000E+00  0.000E+00
   Radiant(W/m^2)   0.000E+00  0.000E+00  0.000E+00
                    0.000E+00  0.000E+00  0.000E+00
 On target(W/m^2)   0.000E+00  0.000E+00  0.000E+00
   Convect(W/m^2)   0.000E+00  0.000E+00  0.000E+00
                    0.000E+00  0.000E+00  0.000E+00
                    0.000E+00  0.000E+00  0.000E+00
                    0.000E+00  0.000E+00  0.000E+00
     Pressure(Pa)   0.000E+00  0.000E+00  0.000E+00

                     Upper layer species

       N2    % |  79.3        79.3        79.3
       O2    % |  20.7        20.7        20.7
      CO2    % | 0.000       0.000       0.000
       CO  ppm | 0.000       0.000       0.000
     TUHC    % | 0.000       0.000       0.000
      H2O    % | 0.000       0.000       0.000
       OD  1/m | 0.000       0.000       0.000

                     Lower layer species

       N2    % |  79.3        79.3        79.3
       O2    % |  20.7        20.7        20.7
      CO2    % | 0.000       0.000       0.000
       CO  ppm | 0.000       0.000       0.000
     TUHC    % | 0.000       0.000       0.000
      H2O    % | 0.000       0.000       0.000
       OD  1/m | 0.000       0.000       0.000
```

B.2 Results of Calculations

The final part of the output consists of the calculated results at the end of each print interval. The first line of the output is the simulation time. In this example the results have only been listed for 900 seconds (see the data file in Appendix A). Following the time are the temperatures of the upper and lower layers, the upper layer volume and thickness, and the temperatures of the ceiling, upper (UW.TEMP) (K) and lower walls, and the floor.

```
Time =  900.0 seconds.

   Upper temp(K)        633.5       404.0       338.8
   Lower temp(K)        327.1       307.7       305.8       300.0
 Upper vol(m**3)          5.3        32.0         9.1
  Layer depth(m)          1.0         1.0         1.4
 Ceiling temp(K)        502.8       345.5       315.1
 Up wall temp(K)        466.2       333.4       311.0
Low wall temp(K)        396.3       310.8       303.4
   Floor temp(K)        313.2       301.9       300.2
```

Next is the flow rate of combustion products and entrained air into the upper layer from the plume, the pyrolysis rate of the fuel, the enthalpy release rate of the fire, the total radiant heat transfer to the upper layer, the total convective heat transfer from the surfaces surrounding the layers to the upper and lower layers respectively, and the difference between the current pressure and the initial pressure at the floor.

```
Plume flow(kg/s)   2.202E-01  0.000E+00  0.000E+00
Pyrol rate(kg/s)   1.887E-03  0.000E+00  0.000E+00
    Fire size(W)   9.440E+04  0.000E+00  0.000E+00
                   0.000E+00  0.000E+00  0.000E+00
   Plume in ul(W)  0.000E+00  0.000E+00  0.000E+00
   Plume in ll(W)  9.440E+04  0.000E+00  0.000E+00
    Vent fire(W)   0.000E+00  0.000E+00  0.000E+00  0.000E+00
  Radiant(W/m^2)  -1.886E+02 -5.015E+01 -2.953E+00
                   9.011E+02  1.388E+02  3.524E+01
On target(W/m^2)   6.978E+02  6.610E+00  1.272E-01
  Convect(W/m^2)   1.031E+03  4.779E+02  1.596E+02
                   8.980E+02  3.824E+02  1.225E+02
                  -4.021E+02 -6.817E+00  5.125E+00
                   4.546E+00  1.485E+00  1.445E+00
    Pressure(Pa)  -1.152E+00 -4.932E-01 -4.514E-01
```

The final part of the results consists of the species concentration for each compartment. The total mass of each specie in the upper layer is given for each compartment (kg). Depending on the species, a concentration (ppm) or opacity (m^{-1}) is also given. For CT, the concentration-time product, only the time integrated (from time=0) concentration (mg-min/l) for the upper layer in each compartment is given. The use of this time integrated concentration is discussed in reference [8].

Upper layer species

N2	%	77.4	78.4	78.4
O2	%	16.1	18.5	18.5
CO2	%	2.17	1.06	1.02
CO	ppm	0.000	0.000	0.000
TUHC	%	0.000	0.000	0.000
H2O	%	4.33	2.11	2.05
OD	1/m	0.000	0.000	0.000

Lower layer species

N2	%	79.2	79.2	79.0
O2	%	20.6	20.6	20.1
CO2	%	7.921E-02	7.783E-02	0.302
CO	ppm	0.000	0.000	0.000
TUHC	%	0.000	0.000	0.000
H2O	%	0.158	0.156	0.603
OD	1/m	0.000	0.000	0.000

APPENDIX C: DISTRIBUTION AND INSTALLATION

The installation process which is described applies to the PC version of the model. For mainframe applications, the installation is somewhat more complex, and the authors need to be contacted directly.

For the PC version, the model is distributed on various media, such as 3 1/2 or 5 1/4 disks. All files should be copied to a single directory on a hard disk. Then look at the readme.doc file (if present) for instructions. The following files shown below should be present:

BUILD.EXE		build graphics descriptions
COLORTST.EXE		diagnostic
DATA.DAT		standard data file
DEMO.BAT		run FAST with demonstration data files
DEMO-F1.*	(4)	data files for demonstration (see appendix a)
DEMO-F3B.PIC		graphics data files for demo #3
DEMO-F3T.PIC		" " " "
DEVFONT.*	(2)	data file for stroke (non filled) characters
FAST.EXE		FAST model
FAST_IN.EXE		interactive input program
FASTPLOT.EXE		interactive output program
HLPTXT.V18		help text for FAST_in
INSTALL.EXE		program to set colors, file names and units (FAST_in)
LISTTHRM.EXE		list the contents of the thermal database
RELEASE.DOC		overview and version history
SWU8*.*		another demonstration, showing the stack effect
SYSTEM*.*	(13)	bit mapped font files[7]
TEQUIPT.EXE		diagnostic
TESTGA.EXE		find out what the graphics adaptor is - returns an integer
THERMAL.TPF		default thermal database

The purpose of each program is

BUILD - generate 3D pictorial representations for display by FAST
COLORTST - show the color palette used by FAST (not FAST_in)

[7] These files are to be replaced by a filled stroke (vector) font, at which time there will be only a single file.

FAST - the main model of fire growth and smoke transport
FASTplot - post processing of FAST dump files for tables and graphs
FAST_in - interactive program to generate FAST data files
INSTALL - defined colors, units and default path names for the models
LISTTHRM - list the properties in the thermal database
TEQUIPT - check for available equipment: math coprocessor and display
TESTGA - find out what we think the graphics adaptor is - diagnostic only

The command line arguments for the executable tasks are

BUILD [/Gnnn]
COLORTST - no arguments
FAST [/N] [/L] [/Gnnn] [input or configuration file] [output file]
FASTplot [/N] [/L] [/Gnnn] [script file]
FAST_in [/N] [/L] [/Gnnn] [configuration file]
INSTALL - no arguments
LISTTHRM - no arguments
TEQUIPT - no arguments
TESTGA - no arguments

The options are

/L turn on the log feature - writes to a xxx.log file
/N turn off the header/copyright notice
/Gnnn where nnn is an alternative graphics adaptor

It is necessary to run the installation program before doing anything else. The important settings are the name of the thermal database and the path to the data files. Even if the name is to remain the same, the model(s) will need the configuration file which is generated by running the installation program. The name of the default configuration file is "DEFAULTS.FCG" and must reside in the same directory as the models. To leave the defaults in place, simply exit each section of the program. The colors and units which are set in this program apply only to the interactive interface, FAST_in. It is essential that this file not be modified. All information in the file can be modified by the installation program. The subsequent programs do not check for integrity of this file and if it is not in the correct form they will most likely terminate in an unpredictable way.

The first test should be to run the demonstration files. Enter the command "DEMO" - it should run a sequence of four calculations. If nothing appears then use the two diagnostic programs to check for the presence of the proper equipment. This set of programs requires a minimum of 490K bytes and a graphics adaptor. Note that the 490K is free memory, so generally, 640K of memory (RAM) is required since the operating system takes between 80 and 120K.

Both FAST and FAST_in use a configuration file. They will attempt to find the default file DEFAULTS.FCG unless the configuration file is specified on the command line. FAST also requires a data file. If this is given on the command line, it is used, otherwise the model will look in the configuration file (default or specified) to find the file last edited with FAST_in. There are two conditions which will cause FAST to quit. The first is if it cannot find a data file, and the second is if there are thermophysical properties which are not defined.

The /L option will turn on an error logging feature which describes what each program is doing. It is an ASCII file, so it can be examined. However, it is really only useful if there appears to be a "bug" and help is requested. In this case, we will require a copy of the log file, which was generated when the failure occurred. If a problem arises, rerun the particular program with this feature turned on, duplicate the problem, and send a copy of the appropriate data file(s) together with this log file.

The /G option is used to specify an alternative display adaptor. If the model does not seem to be picking the correct adaptor, then this will be useful. The only case we have found is the Compaq portable which use a high resolution plasma display, but which has the capability for CGA output. When using the CGA output, the option /GC:4 needs to be used to override the default and force the model to use the CGA driver.

APPENDIX D: THERMAL DATABASE

Thermal data is read from a file which is in an ASCII format. The default name used is THERMAL.TPF. Another name can be used by selecting it during installation, or by using the key word THRMF in the FAST datafile. The relationship is by the name used in specifying the boundary. The example shown in section 6.6 was for concrete, brick and redoak. Any name can be used so long as it is in the thermal database. If a name is used which is not in the database, then FAST_in will turn off the conduction calculation, and FAST will stop with an appropriate error message. The form of an entry in the database is

name conductivity specific heat density thickness emissivity

and the units are

name	1 to 8 alphanumeric characters
conductivity	Watts/meter/Kelvin
specific heat	Joules/kilogram/Kelvin
density	kilograms/cubic meter
thickness	meters
emissivity	dimensionless.

The default database that comes with FAST (THERMAL.TPF) is

Name	Conductivity	Specific heat	Density	Thickness	Emissivity
DFIR30	0.1800	900.0	790.0	0.0160	0.9000
PINEWOOD	0.1200	2500.0	540.0	0.0160	0.8000
CONCRETE	1.75	1000.0	2200.0	0.1500	0.9400
REDOAK	0.1500	1300.0	640.0	0.0160	0.9000
FIBER	0.0500	1250.0	240.0	0.0160	0.9000
GYPSUM	0.1600	900.0	800.0	0.0160	0.9000
WOOD	0.0700	1000.0	250.0	0.0160	0.9800
DFIR0	0.1300	1400.0	510.0	0.0127	1.00
DFIR10	0.1500	1500.0	560.0	0.0160	0.9000
GLASS	1.40	760.0	2500.0	0.0160	0.9500
GLASFIBR	0.0360	720.0	32.0	0.0160	0.9000
KAOWOOL	0.2200	1047.0	128.0	0.1160	0.9700
GYP1	0.1200	900.0	800.0	0.0250	0.9000
GYP2	0.1200	900.0	800.0	0.0500	0.9000
BRICK	0.1800	900.0	790.0	0.0160	0.9000

The output listing of FAST, and the thermal data base screen for FAST_in show a table of "codes." The code is an eight character string whose fields are

1-3 number of nodes if it exceeds 'NN' which is currently 48 (36 for the PC version)
4 always blank
5 too many slabs - greater than mxslb (S)
6 inconsistent number of slabs - all properties must have the same number of slabs (I)
7 duplicate names - the first in the list will be used (D)
8 used in the present calculation (U)

APPENDIX C. BEHAVIOR / EVACUATION MODEL

EXITT - A Simulation Model of Occupant Decisions and Actions in Residential Fires

Bernard M. Levin
Center for Fire Research
National Bureau of Standards
Gaithersburg, Maryland 20899, USA

ABSTRACT

EXITT is a discrete event simulation of occupant decisions and actions in a simulated fire. The characteristics of a residence, a fire in that residence, and the occupants of the residence are entered into the computer. Based on a large set of decision rules, the occupants "make" decisions which are a function of the smoke conditions in the building, the characteristics and status of the occupants (including their capabilities), and the available travel routes. The occupants investigate the fire, alert and assist others, and evacuate the building. The simulation ends when all the occupants are either out of the building or are trapped by the smoke.

1. INTRODUCTION

The EXITT model simulates occupant decisions and actions in fire emergencies in small residential buildings. In assigning decisions to an occupant, the computer considers such factors as: age of occupant; sex; whether occupant is asleep; smoke conditions; whether smoke detector is sounding and how loud it sounds; whether occupant needs help in moving; and location, capabilities, condition and status of the occupants. This version of the model does not consider the heat or toxic components of the smoke. The permitted actions include: investigate the fire; alert others; awake others; rescue others; and evacuate. Actions not permitted in the current version include: telephoning fire department from within the building; fighting the fire; and re-entering the building to make a second rescue.

The necessary input data for running the model are: a description of the building, the smoke characteristics of the fire, and the characteristics of the occupants. The user can provide his own input data or select from eight predefined cases.

2. DESCRIPTION OF THE MODEL

2.1 Introduction

The EXITT model simulates occupant decisions and actions during fire emergencies in small residential buildings. Buildings are represented in the model as nodes that represent rooms, exits and secondary locations within rooms; and links or distances between adjacent nodes. The occupants move from node to node at a speed that is a function of their assigned normal travel speed, the smoke conditions, and whether or not they are assisting another occupant.

All the decision rules programmed in the computer model are designed to make the decisions as similar as possible to those that building occupants would make. The decision rules are based on: 1. a limited number of controlled experiments; 2. case studies of occupant actions in residential fires; and 3. the judgment of the author. Whenever the rules are based directly on data in the literature or specific case studies, reference is made to such data. Otherwise, the rules are based on the author's judgment.

Imbedded in the decisions rules are parameters that can be easily changed. Developing improved values for these parameters is a major part of the future development of the model.

2.2. Input Variables and Parameters

2.2.1. Building

The building is represented within the computer by nodes that represent rooms, exits and secondary locations within rooms; and by links or distances between adjacent nodes. The major data used to define a building are: the number of rooms, nodes and exits; the height of each room; the room location of each node; nature of each exit (door or window); and the distances between adjacent nodes. Windows that cannot or would not be used in a fire are not entered into the computer as exits, e.g., those with a window air conditioner installed.

2.2.2. Smoke

The program is designed to use the output of the FAST model for distributing smoke throughout the building over time [Jones, 1984]. EXITT assumes a two layer smoke model. However, it is assumed that a small proportion of the smoke in the upper layer gets into the lower layer so that there is an odor of smoke in the lower layer. EXITT accepts as input the smoke density in the upper layer and the depth or height of the two layers in each room at the beginning of each time period.

The measure of optical density for which the model is being calibrated is the one used by Jin in his studies of human behavior in smoke.

$$OD = \ln (I_0/I)$$

where I_0 is the initial light intensity which reduced to a value of I over a path of 1 meter. This measure is consistent with the well recognized fact that when people perceive a physical stimulus, the perceived intensity tends to vary directly with the log of the physical intensity of the stimulus.

One important factor in making action choices in a residential fire is the properties of the smoke in the occupant's room. A measure of the psychological impact of smoke is determined as follows:

$$S = 2 \times OD \frac{D}{H}$$

where,

S is the psychological impact of the smoke,
OD is the optical density of the smoke in the upper layer,
D is the depth of the upper layer, and
H is the height of the room.

This expression is based on the assumption that the impact varies directly with the optical density (i.e., the log of the amount of smoke in the upper layer) and with the depth of the upper layer relative to the height of the room. The formula is an arbitrary representation of this assumption.

Some of the decision rules and definitions that involve S include:

- Sometimes the response to smoke is largely a function of the height of the lower layer, which can be presumed to be relatively clear. For example, occupants will escape through a room containing any density of smoke provided there is sufficient clear space for crawling, say, 1.2 meters.

- Occupants will not move to a node where $S>0.5$ unless the depth of the lower layer (H-D) is at least 1.2 meters.

- Occupants will not move to a room where $S>0.4$ unless the depth of the lower layer is at least 1.2 meters.

- Occupants will increase their travel speed by 30% after encountering a room where $S>0.1$.

- Occupants will terminate an investigation if they are in a room where $S>0.05$. They will terminate their investigation before entering a room where $S>0.1$.

- Once an occupant is in a room where $S>0.1$, the decision rules are modified, e.g., in the test below these changes are referred to as consequences of believing the fire to be serious.

- When $S>0.4$ there are prohibitions and penalties: these are referred to below as consequences of encountering "bad smoke."

Each of the above mentioned thresholds is an input parameter and can be easily changed as we continually improve the calibration of the model, i.e., modify the model to better correspond to behavior in real fire emergencies. Although the values selected are consistent with a conservative interpretation of Jin's data [1976], these values will be reconsidered as part of the further development of the model.

2.2.3 Noise and Alarm

The background noise level in a room affects the ability of an occupant to hear the alarm, both in real fires and in the model. The minimum level accepted is 35 decibels.

Another input, related to a specific fire scenario, is the loudness of each smoke detector in each room, including the room in which it is located--it is a function of distances and of which doors are open. The impact of the alarm is a function of the difference between the signal intensity of the alarm and the background noise.

2.2.4 Characteristics of the Occupants

The characteristics are: age, sex, normal travel speed, whether or not the occupant needs help in evacuation, whether or not the person is awake, room location, and, if the occupant is asleep, a measure of how difficult it is for the occupant to awaken.

There are a number of additional parameters imbedded in the decision rules which are described below. These include: the age below which a child is considered as a baby, unable to initiate any action; and the times required to perform various actions, such as waking a sleeping adult occupant when the fire does not appear to be serious.

2.3 Decision Rules

2.3.1 Introduction

There are two types of occupants: those who are fully capable when awake and those who need assistance in moving. The decision rules apply only to those who are capable when awake. Those who need assistance moving make no decisions and their movements are determined by their "rescuer."

At the beginning of the simulation, all occupants are unaware of the fire and the potential danger. Actions and decisions are assigned, in part, based on the smoke conditions in each room at the beginning of the appropriate time period.

The following paragraphs describe the sequential steps the computer follows in determining the decisions and actions of one occupant for one time period. The computer goes through these steps for each capable occupant for the first time period and then repeats the process for each subsequent time period, in turn, until all the occupants are either out of the building or trapped by the fire. (For each step, the computer considers all occupants before proceeding to the next step.)

2.3.2 Aware of Fire

The first step in determining the actions of an occupant is to determine if and when an occupant is sufficiently aware of the fire cues (i.e., smoke, sound of alarm and visible flame) to undertake an action. If the occupant became aware of the fire cues in a previous time period, he will remain aware of the fire cues for this and all subsequent time periods. An occupant becomes aware of the fire when the fire cues are sufficiently strong or if the occupant is in the room in which the fire is located. Obviously, stronger cues are needed to awaken and alert a sleeping occupant than to alert an awake occupant. The fire cues are: the sound of the smoke detector; the odor of smoke; and, for awake occupants, visible smoke. If the weighted sum of the intensities of the cues reach a prescribed threshold, the occupant will be flagged as being aware of the fire cues. (If the fire cues are of borderline intensity, the occupant will become awake and aware after an assigned delay.) If the fire cues are not sufficiently strong for the occupant to become aware of the fire during the current time period, the consideration of this occupant for the time period is completed.

The following basic equation, for determining if and when an occupant will start to respond to the fire cues, was suggested by the empirical results of Nober *et. al.* [1981]. While Nober studied only the response of the smoke detector alarm, his results were generalized for the odor of smoke, and the sight of smoke.

```
T = 70 - 4(C-20)          and
C = X1+X2+X3-X4           where,
```

T is the delay time, in seconds, before the occupant will start his first action;

C is the sum of the sensory impacts on the occupant;

A is the sound intensity of the smoke detector as heard by the occupant;

N is the background noise;

X1 = A-N

X2 is impact of an occupant smelling smoke--it is a function of the smoke density and smoke depth and applies to both sleeping and awake occupants. It varies directly with S, the psychological impact of smoke when the smoke remains above 1.2 meters. However, its value dramatically increases when the upper smoke level gets down to the height of a person in a bed;

X3 is impact of an awake occupant seeing smoke--it is a function of the product of the smoke density and smoke depth in the upper layer and also varies directly with S; and

X4 is the sleeping penalty assigned to a sleeping occupant (usually 0) if the (typical) occupant is asleep and X4=15 if the occupant is awake. This reflects the fact that more stimuli are require to awake than to alert an occupant. The value of 15 is based on the data in Nober [Nober et al, 1981]. Occupants who have difficulty waking could be assigned positive values for X4.

Subject to the restrictions:

X1 cannot be less than zero. If N>A then X1 = 0;
If C < 20 then T = infinity (i.e., 99999 in the computer). This restriction is based on Nober's data where occupants usually either responded within 70 seconds or remained asleep for the remainder of the test period;
X3 equals zero if the occupant is asleep.

The model as described above assumes that the response is a function of the sum of the impacts of different sensory cues. This assumes that the relevant aspects of the perceptual processing of olfactory, visual and auditory cues are similar. There does seem to be a surprisingly consistent perceptual observation (Fechner's Law) that the intensity of a perception varies directly with the log of the physical stimulus. (While Fechner's Law has broad applicability, it is not universal and only approximate [Boring, 1950].) Since our measure of the psychological impact of all the cues are based on the log of a physical measure, the impacts to the three types of cues can be assumed to be roughly comparable. The decision to sum the impacts of the three cues is based on the assumption that simple behavioral rules are better than complicated ones when there is no technical reason to select a complicated one. Furthermore, simple summing is consistent with the results of Fletcher and Munson who found that a tone heard binaurally seems twice as loud as the same tone heard monaurally [Licklider, 1951].

The physical measure of each fire cue is measured in different units and they must be converted to a single measure of sensory impact. The cue most easy to quantify, and the one for which we have the most data, is the sound of the smoke alarm which is measured in decibels. It was decided to use "equivalent decibels" as the single measure of sensory impact. The impacts of the other sensory cues are "converted" to equivalent decibels, i.e., the values of X2 and X3 are transformed to the number of decibels that would approximate an equivalent impact in alerting occupants. The transformation factors are input parameters: their values will be the subject of future research and analysis.

While occupants respond more quickly to strong fire cues, there is a minimum duration of time required to awaken or become aware of the fire cues, select an action, and perform preparatory actions. These minimum times range from 1 to 10 s depending on whether the occupant is asleep and the amount of smoke. (See sec. 2.5.5)

For each occupant, a time to start his actions is computed independently at each time period until the occupant starts his first action: that is, a different time to start his actions will be computed each time period. He will start his action at the earliest time among those computed.

2.3.3 Assigning Actions to Occupants Who Are Aware of Fire

If an occupant has been assigned an action in a previous time period, he will be given an opportunity to complete that action before any consideration is made regarding additional actions.

2.3.4 Investigation Top Priority

The normal first action is to investigate the fire cues to determine the nature of the hazard. However, there are a number of exceptions, i.e., situations that would make investigation either a lower priority or an unreasonable choice. [Levin, 1985] If the computer determines that none of these exceptions applies, the computer assigns the room with the most smoke as the GOAL, labels the occupant as investigating, and assigns him the task of going to the room with the most smoke.

One special situation that would cause investigation to be a low priority arises when an adult female occupant is in the same building as a baby--in a case study provided by Keating and Loftus a mother rescued her baby before determining if it was necessary. [Keating and Loftus, 1984]

Investigation is not permitted: if the occupant has already completed an investigation; if the occupant has been in a room with moderate or bad smoke; or if the occupant has been awakened or alerted by an occupant for whom investigation is not permitted.

If the exceptions do apply, the following alternative actions are considered in the order given below.

<ins>Help Occupant in Same Room</ins>. The computer determines if there is another occupant in the same room who needs help. If that occupant is fully capable but asleep, he will be awakened. If he needs assistance moving, he will get that assistance. (If more than one occupant qualifies for help, the sleeping occupant is given priority.)

<ins>Help Occupant in Different Room</ins>. If there is one or more persons in a different room(s) who needs to be alerted, rescued or awakened, the computer will make two assignments: tentatively assign the fully capable occupant a person to alert, rescue or awaken; and assign the capable occupant the action of <ins>going to the room of that person</ins>. (Once he arrives at that room, a new action will be assigned based on the fire situation at that time and the capabilities of the persons in the room. Exception: if he is going to the room of an awake and capable person who needs to be alerted, he will automatically alert that occupant.) The priority order of these tentative assignments for helping persons in different rooms is: alert capable adult; rescue other occupant; wake other occupant; and alert child.

Occasionally an occupant will go to a room for the purpose of assisting a sleeping or disabled occupant: upon arrival at the room he finds an awake, capable adult unaware of the fire, i.e., not responding to the fire cues. In such a situation, the responding occupant will quickly alert the unaware occupant before addressing the needs of the other occupant.

Investigate. If investigation is still a permitted choice, the occupant is assigned the task of investigating. The computer assigns the room with the most smoke as the GOAL, labels the occupant as investigating, and assigns him the task of going to the room with the most smoke.

Egress. If none of the above alternative assignments apply, the occupant is assigned the action of evacuating.

Every capable adult occupant is considered for helping an occupant in the same room before any occupant is considered for helping an occupant in a different room.

In this version of the model, an occupant over the age of 10 functions as an adult, that is, they follow the priority list presented above for adults.

A child who is 8, 9, or 10 will rescue any occupant in the same room and will go to another room to awaken or alert another occupant. However, he will not go to another room for the purpose of rescuing an occupant. Children 7 and younger do not assist others out of the building but will wake or alert other occupants who are older. A child is considered to be a baby if his age is equal to or less than the parameter BABY: babies do not initiate any actions. The tentative value of BABY is 3.

The general rationale for the above priority order is to determine if there is a need for positive action, to assist those known to require help, and then to assist those who might require help. If two people are known to require help, provide help to the one needing more limited help, that is, a sleeping but otherwise capable occupant. The rule that supercedes all others is to help someone in the same room before helping an occupant in different room.

2.4 Travel Within the Building

Occupants move within the building from node to node. The path assigned is determined by finding the shortest path to an exit based on a shortest path algorithm which may assign penalty distances for going through bad smoke or for leaving through windows.

The route to be taken to a designated room, the best exit, or another designated node is determined by Dijkstra's shortest path algorithm [Aho, Hopcroft, and Ullman, 1983]. Normally when the occupant is investigating or going to assist another occupant, no penalties are used to find the shortest path to a destination node.

If the occupant wishes to evacuate the building, or if the occupant had encountered too much smoke when going to assist another occupant, the the shortest path algorithm is used with penalties assigned for bad smoke conditions and for trying to go out windows. A penalty distance of 100 m is assigned for an adult and infinity for a child 10 years or less trying to go out a window (*i.e.*, a child under 10 will not try to go out windows). A penalty of 200 m is assigned an occupant who tries to go through a node in a bad smoke condition. Each meter of travel is assigned one demerit, leaving by a window is assigned 100 demerits, and going to a node through bad smoke is assigned 200 demerits. If the smoke at a node is intolerable, that node cannot be part of a route. If smoke is blocking all routes to the designated node, the occupant will decide to escape. If all escape routes are also blocked, he will be considered trapped. A child 10 years or younger, for whom all doors are blocked is trapped unless a capable adult happens to arrive at the node at which the child is located. In this case, the child will follow the adult.

As an occupant attempts to move, whenever he encounters an intolerable amount of smoke based on the criteria in Section 2.2, he will stop moving and he will redetermine his best route to his destination. If the shortest path algorithm fails to find an acceptable path, the occupant will decide to evacuate the building, and will look for the best route out of the building. If all exit routes are blocked by smoke, the occupant is considered trapped.

2.5 Delays, Pauses, and Action Times

2.5.1 Introduction

The time consuming activities of an occupant can be classified into three categories.
Movement from one node to another. He travels the shortest path at the speed defined below.
Delays and pauses. These activities include time to awaken, time to make decisions, and time to prepare for action.
Assisting actions, i.e., waking another occupant and preparing another occupant for egress.

2.5.2 Speed

The typical travel speed of each occupant is set at:

- 1.3 meters per second for normal conditions;
- 1.69 m/s (30% faster than normal) if an occupant should consider the fire to be serious (e.g., he has been in a room with heavy smoke);
- 0.65 m/s (50% of normal) if the occupant is assisting another occupant, or 0.845 m/s if the occupant also considers the fire to be serious;
- 0.78 m/s (60% of normal) if the smoke is bad (i.e., S>0.4) and if the depth of the lower layer is less than 1.5 meters, i.e. if the occupant has to "crawl" under the smoke. (0.52 m/s if the occupant is also assisting another occupant.)

The normal travel speed and all the modification factors are parameters that can be set by the user. Whenever an occupant moves, his actions are printed on the screen and on the printer, recorded in a data file, and graphically represented on the screen. (Printing on the screen or on the printer can be suppressed.)

2.5.3 Delay Times

The delay time, the decision time, and the time to perform assisting actions (hereafter, collectively called Delay Times) depend on the occupant characteristics, the fire characteristics and the impact of the fire cues on the occupant. The length of these Delay Times are determined by a set of decision rules as described below.

2.5.4 Minimum Response Time

The normal (i.e., smoke is not bad) minimum response (delay) time is 6 s for awake occupants: this includes decision and preparation time. The normal minimum response time for sleeping occupants is 10 s: this also includes decision and response times. These values are based on the work of Nober [Nober et al, 1981]. The status of sleeping occupants is changed to awake status whenever the remaining response time is 6 s or less.

2.5.5 TPAUSE

An occupant is normally assigned a delay time of TPAUSE seconds whenever: he completes his investigation or terminates his movement along a route because of intolerable smoke; or changes his mind about helping another occupant. This delay includes the time required to choose a new action. TPAUSE is tentatively set equal to 3 s.

2.5.6 Decrease in Preparation Time Due to Heavy Smoke

When an occupant is subjected to normal fire stimuli, a 10 second response Delay Time is assigned to a sleeping occupant and six seconds to an awake occupant. (Note the response time will be greater if the fire stimuli are not sufficiently strong for an immediate response.) However, if the occupant believes the fire to be serious, the maximum Delay Time for the occupant becomes 4 s and if the smoke in the room is bad, the maximum Delay Time becomes 1 s.

2.5.7 Hesitation Due to Not Being Alone

Research by Latane and Darley [Latane and Darley, 1968] has shown that when the fire cues are noticed but not immediately compelling, adults will hesitate in their responses if other capable adults are in the same room. A simple explanation is that there is a failure to respond due to a feeling of shared responsibility. The computer program accounts for this by delaying responses by one time period for each time period where: there is no one that needs to be rescued, alerted, or roused; there is a second capable occupant in the room; the smoke detectors are not sounding; and the sum of the psychological impacts of the fire cues is less than 30, i.e., if $C<30$ then $T=99999$, where C and T are defined in Section 2.3. (The threshold for this hesitancy is 30 rather than 20 to reflect that more stimuli or cues than the "minimum for response" are required to prevent the "hesitation due to not being alone.")

2.5.8 Time Required to Alert, Wake or Prepare for Evacuation

Whenever one occupant assists another, time for providing or receiving the service must be assigned. The following times are assigned:

- If Occupant J is alerting a fully capable and awake adult, he moves to the node of the other occupant. Once he arrives at that node, Occupant J starts his next action with no delay or decision time charged. The occupant being alerted is assigned a Delay Time of 5 s or 2.5 s depending on whether the alerting occupant believes the fire to be serious.

- There are two types of assistance that an occupant may be flagged as needing: waking; and help moving. If an occupant is asleep and does not need help moving, the delay is 5 s for the occupant doing the waking. For the occupant who is being awakened the delay is 10 s - 5 s for waking plus 5 s decision and preparation time. However, if the assisting occupant believes the fire to be serious, then his time devoted to waking would be only 2.5 s and the total Delay Time for the previously sleeping occupant would be 5 s.

- If an occupant needs help moving, the Delay Time (at the time the assisting occupant arrives at the location of the other occupant) is usually 10 s if the disabled occupant is awake and 12 s if he is asleep. However. if the disabled occupant is a baby, the Delay Time, in seconds, is the baby's age plus 4. (It does not take long to pick up a baby and wrap him or her in a blanket.) In addition, if the capable occupant believes the fire to be serious, the previously determined Delay Time is halved. For example, if the fire is believed to be serious, the Delay Time for helping a 2-year-old baby would be 3 s ((2+4)/2).

2.6 Smoke Detectors

The building may have from zero to 10 smoke detectors. These smoke detectors are independent and are not interconnected in any way. It is necessary to provide the locations of the smoke detectors and how loud each detector would sound in each room of the building. The time of smoke detector activation can either be determined by EXITT (as the time when the upper layer smoke density is at least 0.015 m^{-1} and the depth of the upper layer is at least 0.15 m in the room in which the detector is located) or preset by the user to a designated time. A smoke detector will sound if the smoke density of the upper layer smoke is at least .015, and the depth of the upper layer is .15 meters or greater.

2.7 Current Limitations and Future Development

The model as described in this paper is a preliminary version of a model under development. The development, improvement and expansion of the model is a continuing activity. The user should be aware of the limitations of the current model. These limitations include:

1. The model is deterministic. Only typical behavior is modeled: aberrant behavior is not permitted.

2. Improved calibration is required to upgrade its validity. Calibration means changing parameter values in the model based on: a. analyses of data in the technical literature; b. judgments of a panel of experts; c. analyses of in depth interviews of survivors of residential fires; and, d. attempts to simulate behavior in

real fire emergencies for which we have information. An intensive effort to improve the calibration of the model, is scheduled for the next year.

3. Some typical actions are not included, especially, fighting the fire, phoning the fire department from within the residence, re-entering the building.

4. Occupants respond to smoke conditions but not to heat conditions.

3. REFERENCES

Aho, A. V., Hopcroft, J. E., and Ullman, J. D. Data structures and algorithms, Addison-Wesley Publishing, 1983, 204-208.

Boring, E. G. A history of experimental psychology, Appleton-Century-Crofts, Inc. New York, 1950, 289.

Kahn, M. J. Human awakening and subsequent identification of fire-related cues, Fire Technology, 20(1); February 1984, pp.20-26.

Nober, E. H., et al, Waking effectiveness of household smoke and fire detection devices, Fire Journal 75(4); July 1981, 86-91,130.

Jin, T. Visibility through fire smoke: Part 5, Allowable smoke density for escape from fire, Report of Fire Research Institute of Japan, No.42, September 1976.

Jones, W. W. A model for the transport of fire, smoke and toxic gases (FAST). Natl. Bur. Stand. (U.S.) NBSIR 84-2934; 1984.

Keating, J. P.; Loftus, E. F. Post fire interviews: Development and field validation of the behavioral sequence interview technique, Natl. Bur. Stand. (U.S.) NBS GCR 84-477; 1984. Interview records provided by the authors in private communication.

Levin, B. M., Design as a function of responses to fire cues, general proceedings of conference research and design 85: Architectural Application of Design and Technology Research held at Los Angeles, CA, March 14-18, 1985, American Institute of Architects Foundation, Washington, DC, 1985, 289-294.

Latane, B., and Darley, J. M., Group inhibition of bystander intervention in emergencies, Journal of Personality Psychology, 10(3): Nov. 1968, 215-221.

Licklider, J. C. R., Basic correlates of the auditory stimulus, in S. S. Stevens, Handbook of Experimental Psychology, John Wiley & Sons, Inc, New York, 1951, 1031.

Nober, E. H., et al. Waking effectiveness of household smoke and fire detection devices, Fire Journal, Vol.75, No.4, July 1981, 86-91,130.

APPENDIX D. DETACT-QS REPORT

Methods to Calculate the Response Time of Heat and Smoke Detectors Installed Below Large Unobstructed Ceilings [1][1]

David D. Evans
David W. Stroup
Center for Fire Research
National Bureau of Standards
Gaithersburg, MD 20899, USA

Abstract

Recently developed methods to calculate the time required for ceiling mounted heat and smoke detectors to respond to growing fires are reviewed. A computer program that calculates activation times for both fixed temperature and rate of rise heat detectors in response to fires that increase in heat release rate proportionally with the square of time from ignition is given. This program produces nearly equivalent results to the tables published in Appendix C, Guide for Automatic Fire Detector Spacing, (NFPA 72E, 1984). A separate method and corresponding program are provided to calculate response time for fires having arbitrary heat release rate histories. This method is based on quasi-steady ceiling layer gas flow assumptions. Assuming a constant proportionality between smoke and heat released from burning materials, a method is described to calculate smoke detector response time, modeling the smoke detector as a low temperature heat detector in either of the two response time models.

1. INTRODUCTION

Studies of the response of heat detectors to fire driven flows under unconfined ceilings have been conducted since the early 1970's [2, 3, 4, 5]. Results of these largely experimental studies have been used to develop correlations of data that are useful under a broad range of fire conditions and building geometries. These correlations have been used to construct engineering methods to determine heat detector spacing, sprinkler response time, and smoke detector alarm times for industrial buildings where large undivided ceilings over storage and manufacturing facilities are common. The method for calculation of heat detector spacing has been adopted by the National Fire Protection

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

Association (NFPA) as an alternate design method published in the standard NFPA 72E, 1984 [6].

Although the NFPA heat detector spacing calculation is a well documented method, it is not in a convenient form for use by the Nuclear Regulatory Commission (NRC) in evaluating the response characteristics of existing systems for two reasons. 1) Currently, the only available form of the information is the tabular form published in the NFPA 72E standard. An analytic form or computer subroutine that produced equivalent answers would be more flexible and or greater use to NRC. 2) The published tables are organized to look-up spacing requirements for a given response time. In the evaluation of existing systems, the opposite problem is of interest - for a given spacing and detector determine the response time.

As part of this study, the basis for the calculation method published in Appendix C of the NFPA 72E standard was determined. Alternative correlations of the same experimental data that are the basis for the tables in Appendix C of the NFPA 72E standard were used to construct a FORTRAN program (DETACT-T2 Code) to evaluate the response time of existing heat detector systems. Using the program, calculated values for response time agree to within 5% of those published in the tables contained in Appendix C of the NFPA 72E standard. Although this calculation method is the most firmly based of those to be discussed in this report, it is restricted to application in which the fire to be detected increases in energy release rate proportionally with the square of time from the ignition.

A separate program (DETACT-QS Code), written in PC BASIC, is capable of evaluating detector response for a fire with an arbitrary energy release rate history. The only restriction is that the energy release rate must be represented as a series of connected straight lines, the end points of which are entered as user input data. Inaccuracies may be introduced in the analysis of rapidly varying fires because this code uses quasi-steady approximation for the fire driven gas flow. This means that changes at the fire source immediately affect the gas flows at all distances from the fire. In reality, time is required for the gases to travel from the fire to remote locations. Generally, fire driven flows have a velocity the order of 1 meter per second. Thus a quasi-steady analysis for locations close to the fire will only be in error by a few seconds, while remote locations can be delayed by tens of seconds. Keeping this approximation in mind, this program represents the most flexible of available methods but has not been tested against experimental data.

Both of the codes discussed above analyze detector response at installation sites under large unconfined ceilings. For smaller compartments, in which confining walls will cause a layer of fire products to accumulate under the ceiling, hence submerging the ceiling-jet flow before the heat detector can respond, different calculations are necessary. The problem of analyzing the response of heat detectors or sprinklers in a two-layer environment (warm fire products over cool air) has been studied [7], but no single code has been produced to facilitate analysis. This class of problem will not be discussed in this report.

Analysis of smoke detector response is currently performed by approximating the smoke detector as a low-temperature zero-lag-time heat detector. Selection of the response temperature corresponding to a given detector sensitivity also depends on the relative proportion of "smoke" and energy released by the burning fuel. Test data of gas temperature rise at the time of smoke detector alarm is presented in this report. An alternative approximate method is given to determine this same temperature rise by using fuel smoke and energy release rate measurements obtained in a laboratory scale apparatus developed by Tewarson [8].

2. DETECTOR RESPONSE TO t^2 - FIRES

Appendix C of the NFPA 72E standard [6], "Guide for Automatic Fire Detector Spacing," contains methods to determine the required heat detector spacing that will provide alarms to growing fires before the fire has grown to a user specified energy release rate. Tables provide information to evaluate different fire growth rates, ceiling heights, ambient temperatures, detector alarm conditions (fixed temperature or rate of rise), and detector thermal time constant. The tables reflect the extensive experimental studies and mathematical fire modeling performed by Heskestad and Delichatsios at Factory Mutual Research Corporation [4, 5].

Beyler [9] uses a different correlation of Heskestad and Delichatsios' data than was used to produce the tables in NFPA 72E Appendix C to obtain an analytical expression for the gas flow temperature and velocity produced under ceilings that can be used to evaluate heat detector response. Beyler's solutions are limited to evaluation of fires that increase in energy release rate proportionally with the square of time from ignition. This class of fire is commonly referred to as a "t-squared-fire." Briefly, the problem of the heat detector response is solved using analytic solutions for the time dependent temperature of the detector sensing element up to the point when it is heated to the specified alarm conditions. The model for the detector sensing element temperature is based on a convective heat detector and sprinkler thermal sensing elements is discussed by Heskestad and Smith [10], and Evans [11]. The first order differential equation that describes the rate of temperature increase of the sensing element is [7]:

$$\frac{dT_s}{dt} = \frac{U^{1/2}}{RTI} \left[T - T_s\right] \qquad (1)$$

The notation for all equations is given in the notation section. The value of RTI (Response Time Index), a measure of the thermal time constant of the detector, is determined by testing [10]. Values of the time-dependent gas temperature and velocity are obtained format the following correlations [9].

$$\Delta T_2^* = 0 \quad \text{for } t_2^* < (t_2^*)_f$$

$$\Delta T_2^* = \{[t_2^* - 0.954(1+r/H)]/[0.188+0.313\ r/H]\}^{4/3} \quad \text{for } t_2^* > (t_2^*)_f$$

$$(t_2^*)_f = 0.954\ [1 + r/H] \tag{2}$$

$$U_2^* = 0.59\ [r/H]^{-.063}\ [\Delta T_2^*]^{1/2}$$

where

$$U_2^* = U/[A\ \alpha\ H]^{1/5}$$

$$\Delta T_2^* = \Delta T/[A^{2/5}(T_\infty/g)\ \alpha^{2/5}\ H^{-3/5}]$$

$$t_2^* = t/[A^{-1/5}\ \alpha^{-1/5}\ H^{4/5}]$$

$$A = g/(c_p T_\infty \rho_\infty)$$

$$\Delta T = T - T_\infty$$

$$\alpha = t^2/Q.$$

The solutions to eq (1) for detector sensing element temperature, T_s, and rate of temperature rise, DT_2/dt, in response to the t^2 - fire with growth rate specified by the value of α are from Beyler [9] as follows:

$$\Delta T_s = (\Delta T/\Delta T_2^*)\ \Delta T_2^*\ [1 - (1 - e^{-Y})/Y] \tag{3}$$

$$\frac{dT_s}{dt} = \frac{(4/3)(\Delta T/\Delta T_2^*)(\Delta T_2^*)^{1/4}}{(t/t_2^*)(0.188 + 0.313\ r/H)}\ (1 - e^{-Y}) \tag{4}$$

where

$$Y = \frac{3}{4}\left(\frac{U}{U_2^*}\right)^{1/2}\left(\frac{U_2^*}{\Delta T_2^*}\right)^{1/2}\frac{\Delta T_2^*}{RTI}\frac{t}{t_2^*}(0.188 + 0.313\ r/H)$$

assuming that $\Delta T_s = 0$ initially. T and U in eq (1) are obtained from the correlations in eq set (2) for ΔT_2 and U_2 respectively. Eq (3) and (4) were programmed into a user interactive FORTRAN code called the DETACT-T2 Code. This code solves for the time required to reach a specified positive value of ΔT_2^* or DT_s^*/dt representing detector alarm. Briefly for a fixed temperature detector, the user enters values for:

Ambient air temperature
Detector response temperature or rate of temperature rise
Detector RTI
Fuel to ceiling distance
Radial distance of detector from the fire plume axis
Fire growth rate constant α (for t^2 fires)

Outputs of the code are the time to detector response and fire energy release rate at that time.

In Appendix A of reference [1], use of the DETACT-T2 Code to calculate the response time of a fixed temperature detector is demonstrated in a worked example using the following program inputs:

Ambient air temperature	21.1°C(70°F)
Detector response temperature	54.44°C (130°F)
Detector RTI	370.34 $m^{1/2}s^{1/2}$ (670.8 ft $^{1/2}s^{1/2}$)
Fuel to ceiling distance	3.66 m (12 ft.)
Radial distance of detector from axis of fire	2.16 m (7.07 ft.)
Fire growth rate constant	11.71 J/s^3 (0.0111 BTU/s^3)

The calculated response time using the DETACT-T2 Code is 298 seconds and corresponding fire energy release rate is 1.04 MW (986 BTU/s). This same fire and detector combination can be seen in the table C-3-2.1.1(e) in Appendix C of NFPA 72E [6], (in the table notation, threshold fire size 1000 BTU/s, fire growth rate, medium; DET TC = 300 Δ s, ΔT = 60°F, ceiling height = 12 Δft, installed spacing in the body of the table 10 ft). All values in table C-3-2.1.2(e) [6] are for detector response times of 300 s.

This is in agreement with the 298 s calculated with the DETACT-T2 Code given in Appendix A of [1].

Eleven other randomly selected combinations of fires and detector were calculated using the DETACT-T2 Code and results compared to table values in Appendix C of NFPA 72E [6]. Of these cases the greatest deviation was 7.5% and least was 0.17%.

Use of the DETACT-T2 Code has two main advantages over the tables in Appendix C of NFPA 72E [6]. One is that the code is specifically designed to evaluate existing facilities. The other is that any t^2 - fire growth rate can be analyzed. The tables in Appendix C of NFPA 72E [6] contain only three different fires. At present, an NBS special publication is being prepared containing tabular results with the same information as those in the NFPA 72E, Appendix C [6], but recast into a form useful for evaluation of existing facilities. This publication "Evaluating Thermal Fire Detection Systems," by Stroup, Evans, and Martin should become available in 1986.

3. DETECTOR RESPONSE TO ARBITRARY FIRES

The DETACT-T2 Code is useful for evaluating the response of specified detectors to t^2 - fire growth rates. In some cases a fire of interest does not follow and energy release rate that is proportional to the square of time from ignition. For these cases use of the DETACT-T2 Code to evaluate the responses of detector systems is inappropriate.

To evaluate detector response to an arbitrary energy release rate history, an assumption of quasi-steady gas flow temperatures and velocities is made. With this assumption, correlation for ceiling-jet temperatures and velocities obtained from experiments using steady fire energy release rate sources can be used to evaluate growing fires. The growing fire is represented in the calculation as a series of steady fires with energy release rate changing in time to correspond to the fire of interest.

Correlations of ceiling-jet temperatures and velocities from experiments using steady fire sources have been published by Alpert [2]. Recast into metric form they are:

$$\begin{aligned}
\Delta T &= 16.9\ Q^{2/3} / H^{5/3} && \text{for } r/H < 0.18 \\
U &= 0.95\ (Q/H)^{1/3} && \text{for } r/H < 0.15 \qquad (5) \\
\Delta T &= 5.38\ (Q/r)^{2/3} / H && \text{for } r/H > 0.18
\end{aligned}$$

$$U = 0.2\ Q^{1/3}\ H^{1/2}\ /\ r^{5/6} \qquad \text{for } r/H > 0.15$$

where the metric units are T[°C], U[m/s], Q[kW], r[m], H[m].

A computer code to perform the integration of eq (1), the differential equation for detector sensor temperature, using the quasi-steady fire driven flow approximation and Alpert's correlations from equation in 5, is listed in Appendix B of [1]. This code, called the DETACT-QS Code, is written in PC BASIC. The code requires user input similar to the DETACT-T2 Code in Appendix A of [1], with the one exception that the fire energy release rate is specified as a series of time, energy release rate data pairs.

The same fire and detector case used as an example of execution for the DETACT-T2 Code was evaluated using the DETACT-QS Code. The example inputs and results are given in Appendix B of [1]. The fire was input as time, energy release rate pairs at intervals of 5 s to match the t^2 - fire with α = 11.7105 W/s^2. Other parameters were maintained the same. The resulting predicted detection time using the DETACT-QS Code was 313 s with the corresponding fire energy release rate at detection of 1147 kW. Remember that with the DETACT-T2 Code the calculated time of detection was 298 s with fire energy release rate at detection of 1040 kW. This example was chosen to demonstrate specifically that there will be differences between the two methods even in the evaluation of the same fire. The quasi-steady fire analysis on which the DETACT-QS Code is based has the advantage that arbitrary fire energy release rates can be input as a data set.

4. SMOKE DETECTOR RESPONSE

Both of the heat detector response models discussed are based on predictions of the temperature and velocity of the fire driven gas flow under the ceiling and models of the heat detector response. The same calculations could be used to predict smoke detector response given a relationship between smoke concentration and temperature rise in the fire driven gas flow and the response characteristics of the smoke detector.

The response characteristics of smoke detectors are not as well understood as thermal detectors. Smoke detector alarm conditions depend on more than smoke concentration. Smoke particle sizes and optical or particle scattering properties can affect the value of smoke concentration necessary to reach alarm conditions. For thermal detectors, measured values of RTI characterize the lag time between gas temperature and sensing element temperature. For smoke detectors there is no analogous method to characterize the lag time between gas flow smoke concentration and the smoke concentration within the sensing chamber. In the absence of understanding of the many processes affecting smoke detector response, a smoke detector will be considered to be a low temperature heat detector with no thermal lag, i.e. RTI = 0. The analogy between smoke obscuration in the gas flow and temperature rise will be developed in order to determine the corresponding temperature rise to use as a model for a smoke detector known to alarm at a given smoke obscuration.

Similarity between temperature rise and smoke concentration will be maintained everywhere within a fire-driven flow if the energy and smoke continuity equations are similar. For the case of constant c_p, k, and D these equations are:

$$\rho c_p \frac{d\Delta T}{dt} - k \nabla^2 \Delta T = \dot{Q}''' \tag{6}$$

$$\rho \frac{dY_s}{dt} - \rho D \nabla^2 Y_s - \dot{m}'''. \tag{7}$$

If the Lewis number $k/\rho c_p D = 1$ then the ratio of temperature rise to smoke concentration can remain constant throughout the fire driven flow, if the ratio $\dot{Q}'''/c_p\dot{m}_s'''$ is maintained constant in all regions where energy is exchanged with the flow. Reactions in the flame over the burning fuel will determine the ratio of temperature rise to smoke concentration throughout the flow. Other energy exchanges in normal fire flows, convection to cool room boundaries, and radiation from smokey gases decrease the ratio of temperature rise to smoke concentration because energy is extracted from the flow without a proportional decrease in smoke concentration. Mixing of hot combustion products with cool smokey gases that may accumulate in an enclosure also decrease the ratio of temperature rise to smoke concentration because smoke mass is added to the flow without proportional increase in energy. For fire driven flows in which the effects that alter the ratio of temperature rise to smoke concentration are not significant, the response of the smoke detector may be calculated as if it were a fixed temperature heat detector. The temperature rise necessary for alarm of this substitute heat detector is calculated from the product of smoke concentration needed to alarm the smoke detector and the ratio of temperature rise to smoke concentration produced by the burning material.

Generally the sensitivity of smoke alarms are given in terms of the amount of obscuration by the smokey flow that is necessary to produce an alarm and not directly in smoke concentration. The more sensitive the smoke detector the smaller the amount of obscuration needed to alarm.

The obscuring ability of a smoke laden gas flow is measured by the attenuation of a light beam. The measure of the attenuation is the optical density per unit beam length, O.D, [4]

$$OD = (\log_{10} \frac{I_o}{I}) / L. \qquad (8)$$

By testing, Seader and Einhorn [12] found that the attenuating abilities of smokes produced from many different materials undergoing flaming combustion were similar. For flaming combustion they found that the optical density per unit length was proportional to the mass concentration of "smoke" in a gas flow as:

$$OD = 3330\ C_s$$

where OD is optical density per meter and C_s is smoke mass concentration in kilograms per cubic meter.

The ratio of temperature rise in fire driven flow to smoke concentration may be recast in terms of optical density using equation 9 as:

$$\frac{\Delta T}{Y_s} = \frac{\rho \Delta T}{C_s} = \frac{3330 \rho \Delta T}{OD}.$$

Under the assumption discussed at the beginning of this section, this ratio will be equal to the ratio $\dot{Q}'''/c_p \dot{m}_s'''$. The last ratio may be approximated by a volume average over the combustion region so that

$$\frac{3330 \rho \Delta T}{OD} = \frac{\dot{Q}}{c_p\ \dot{m}_s}$$

or

$$\frac{OD}{\Delta T} = \frac{3330 \rho c_p \dot{m}_s}{\dot{Q}}.$$

As an example, literature values for oak wood may be used to obtain a representative value. For oak

$\dot{Q}$ = 7600 kJ/kg fuel consumed per unit time [13]
$\dot{m}_s$ = 0.017 kg smoke/kg fuel consumed per unit time [13]
air c_p = 1 kJ/kg°C
air ρ = 1.165 kh/m^3 sy 30°C

From eq (11), $OD/\Delta T = 8.68 \times 10^{-3}\ (m°C)^{-1}$.

Heskestad and Delichatsios [4] have reported representative optical density per meter for smoke detector alarm and corresponding temperature rise in the gas flow. For wood crib (unknown type) fires, the ratio of these values was $OD/\Delta T = 1.2 \times 10^{-3}\ (1/m°C)^{-1}$. This is the same order of magnitude as the number calculated in the analysis given above and may be representative of the expected accuracy given no knowledge of wood type. Heskestad and Delichtsios [4] report that an ionization detector will alarm in response to a wood fire at OD =0.016 l/m.

Using the $OD/\Delta T$ value for wood of $1.2 \times 10^{-3}\ (m°C)^{-1}$ the corresponding change in gas temperature would be 13 °C, ($0.016/1.2 \times 10^{-3}$). For the purpose of response time calculation using the heat detector models, this ionization smoke detector would be represented as a low temperature heat detector alarming to 13 °C above ambient for a wood fire.

Other measurements of the ration $OD/\Delta T$ are obtained for burning materials in a laboratory scale apparatus developed by Tewarson [8]. Values for a large number of plastics an wood under many environmental conditions are given by Tewarson [13].

5. SUMMARY

Two methods have been presented to calculate the response of heat detectors installed under large unobstructed ceilings in response to growing fires. Smoke detector response is calculated using the same thermal calculations by approximating the smoke detector as a low temperature, zero lag time thermal detector.

6. ACKNOWLEDGMENT

The authors are grateful to Mr. Doug Walton for coding DETACT-QS version 1.1 for execution in PC BASIC.

7. REFERENCES

1. Evans, D. D., and Stroup, D. W., Methods to Calculate the Response Time of Heat and Smoke Detectors Installed Below Large Unobstructed Ceilings, NBSIR 85-3167, [U.S.] Nat. Bur. Stand., (1985).

2. Alpert, R.L., Calculation of response time of ceiling-mounted fire detectors. Fire Technology, 8, 1972, p 181.

3. Alpert, R.L., Turbulent ceiling-jet induced by large-scale fires, Combustion Science and Technology, 11, 1975, p 197.

4. Heskestad, G. and Delichatsios, M.A., Environments of fire detectors phase 1; Effects of fire size, ceiling heights and material, Volume II - Analysis. Technical Report Serial No. 22427, RC 77-T-11, Factory Mutual Research Corporation, Norwood Mass. 02062, 1977.

5. Heskestad, 6, and Delichatsios, M.A., The initial convective flow in fire, Seventeenth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, Pennsylvania, 1978, pp 1113-1123.

6. Standard on Automatic Fire Detectors, NFPA 72E-1984, Appendix C, National Fire Protection Association, Batterymarch Park, Quincy, MA, 02269.

7. Evans, D.D., Calculating "Sprinkler Actuation Time in Compartment, to be published in Fire Safety Journal, 1985.

8. Tewarson, A., and Pion, R., "A Laboratory-Scale Test Method for the Measurement of Flammability Parameters, FMRC Serial No. 22524, Factory Mutual Research Corporation, Norwood, Mass. 02062, Oct 1977.

9. Beyler, C.L., A design method for flaming fire detection, Fire Technology, 20, 4, 1984, p 5.

10. Heskestad, G., Smith, H., Investigation of a New Sprinkler Sensitivity Approval Test: The Plunge Test FMRC Technical Report 22485, Factory Mutual Research Corporation, Norwood, Mass. 02062, 1976.

11. Evans, D.D., Madrykowski, D., Characterizing the Thermal Response of Fusible-Link Sprinklers, NBSIR 81-2329, [U.S.] Nat. Bur. Stand. (1981).

12. Seader, J. and Einhorn, I., "Some Physical, Chemical, Toxicological, and Physiological Aspects of Fire Smokes", Sixteenth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, Penn. 1976, pp 1423-1445.

13. Tewarson, ., Physico-Chemical and Combustion/Pyrolysis Properties of Polymeric Materials. FMRC J.I. OEONG.RC, Factory Mutual Research Corporation, Norwood, Mass 02062, Nov. 1980, p 27.

8. NOTATION

A	$g/(c_p T_\infty \rho_\infty)$
c_p	specific heat capacity of ambient air
C_s	smoke mass concentration
D	effective Binary diffusion coefficient
g	acceleration of gravity
H	vertical distance from fuel to ceiling
I	light intensity
I_o	initial light intensity
L	light beam length
$\dot{m}_s'''$	smoke gas mass production rate per unit volume
OD	optical density per unit length [see eq (8)]
$\dot{Q}$	fire energy release rate
$\dot{Q}'''$	energy release rate per unit volume
r	radial distance from fire axis to the detector
RTI	response time index, the product of the detector thermal time constant and the square root of the gas speed used in the test to measure the time constant [9].
t	time
t_2^*	dimensionless time $t/[A^{-1/5}\alpha^{-1/5}H^{-4/5}]$
$(t_2^*)_f$	dimensionless time for time delay for gas front travel
T_∞	ambient temperature
T	gas temperature at detector location
T_s	temperature of detector sensing elements
ΔT	$T - t_\infty$
ΔT_2^*	dimensionless temperature difference $\Delta T/[A^{2/5}(T_f/g)\ \alpha^{2/5}\ H^{-3/5}]$
U	gas speed at the detector location
U_2^*	dimensionless gas speed $U/[A\ \alpha\ H]^{1/5}$
Y_s	local ratio of smoke mass to total mass in flow
α	proportionality constant for t^2- fire growth = Q/t^2
ρ_∞	ambient air density

NBS-114A (REV. 2-80)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET (See instructions)	1. PUBLICATION OR REPORT NO. NIST/HB-146/II	2. Performing Organ. Report No.	3. Publication Date June 1989

4. TITLE AND SUBTITLE

Technical Reference Guide for the HAZARD I Fire Hazard Assessment Method

5. AUTHOR(S)

R. W. Bukowski, R. D. Peacock, W. W. Jones, and C. L. Forney

6. PERFORMING ORGANIZATION (If joint or other than NBS, see instructions)	7. Contract/Grant No.
National Institute of Standards and Technology U.S. Department of Commerce Gaithersburg, MD. 20899	8. Type of Report & Period Covered Final

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (Street, City, State, ZIP)

Same as item 6

10. SUPPLEMENTARY NOTES

Library of Congress Catalog Card Number: 89-600740

☐ 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)

This report describes the first version of a method for predicting the hazards to occupants involved in a building fire. To implement the method, a personal computer software package called HAZARD I is provided. The software consists of modules which can predict the time varying environment within a building resulting from a specified fire; the locations and actions of a specified group of occupants as they interact with the building, the fire, and each other; and the impact of the exposure of each of the occupants to the fire products in terms of whether the occupants successfully escape, are incapacitated, or are killed. The documentation includes the *Software User's Guide*, and a *Reference Guide* consisting of the *Technical Reference Guide* and *Example Cases*.

NIST Handbook 146 is a set consisting of the three volumes described above plus computer software supplied on seven (7) 5¼" and four (4) 3½" disks.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

Computer models; computer programs; evacuation; fire models; hazard assessment; human behavior; toxicity

13. AVAILABILITY	14. NO. OF PRINTED PAGES
[X] Unlimited ☐ For Official Distribution. Do Not Release to NTIS ☐ Order From Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402. [X] Order From National Technical Information Service (NTIS), Springfield, VA. 22161	323 15. Price

USCOMM-DC 6043-P80

NIST Technical Publications

Periodical

Journal of Research of the National Institute of Standards and Technology—Reports NIST research and development in those disciplines of the physical and engineering sciences in which the Institute is active. These include physics, chemistry, engineering, mathematics, and computer sciences. Papers cover a broad range of subjects, with major emphasis on measurement methodology and the basic technology underlying standardization. Also included from time to time are survey articles on topics closely related to the Institute's technical and scientific programs. Issued six times a year.

Nonperiodicals

Monographs—Major contributions to the technical literature on various subjects related to the Institute's scientific and technical activities.

Handbooks—Recommended codes of engineering and industrial practice (including safety codes) developed in cooperation with interested industries, professional organizations, and regulatory bodies.

Special Publications—Include proceedings of conferences sponsored by NIST, NIST annual reports, and other special publications appropriate to this grouping such as wall charts, pocket cards, and bibliographies.

Applied Mathematics Series—Mathematical tables, manuals, and studies of special interest to physicists, engineers, chemists, biologists, mathematicians, computer programmers, and others engaged in scientific and technical work.

National Standard Reference Data Series—Provides quantitative data on the physical and chemical properties of materials, compiled from the world's literature and critically evaluated. Developed under a worldwide program coordinated by NIST under the authority of the National Standard Data Act (Public Law 90-396). NOTE: The Journal of Physical and Chemical Reference Data (JPCRD) is published quarterly for NIST by the American Chemical Society (ACS) and the American Institute of Physics (AIP). Subscriptions, reprints, and supplements are available from ACS, 1155 Sixteenth St., NW., Washington, DC 20056.

Building Science Series—Disseminates technical information developed at the Institute on building materials, components, systems, and whole structures. The series presents research results, test methods, and performance criteria related to the structural and environmental functions and the durability and safety characteristics of building elements and systems.

Technical Notes—Studies or reports which are complete in themselves but restrictive in their treatment of a subject. Analogous to monographs but not so comprehensive in scope or definitive in treatment of the subject area. Often serve as a vehicle for final reports of work performed at NIST under the sponsorship of other government agencies.

Voluntary Product Standards—Developed under procedures published by the Department of Commerce in Part 10, Title 15, of the Code of Federal Regulations. The standards establish nationally recognized requirements for products, and provide all concerned interests with a basis for common understanding of the characteristics of the products. NIST administers this program as a supplement to the activities of the private sector standardizing organizations.

Consumer Information Series—Practical information, based on NIST research and experience, covering areas of interest to the consumer. Easily understandable language and illustrations provide useful background knowledge for shopping in today's technological marketplace.

Order the **above** *NIST publications from: Superintendent of Documents, Government Printing Office, Washington, DC 20402.*

Order the **following** *NIST publications—FIPS and NISTIRs—from the National Technical Information Service, Springfield, VA 22161.*

Federal Information Processing Standards Publications (FIPS PUB)—Publications in this series collectively constitute the Federal Information Processing Standards Register. The Register serves as the official source of information in the Federal Government regarding standards issued by NIST pursuant to the Federal Property and Administrative Services Act of 1949 as amended, Public Law 89-306 (79 Stat. 1127), and as implemented by Executive Order 11717 (38 FR 12315, dated May 11, 1973) and Part 6 of Title 15 CFR (Code of Federal Regulations).

NIST Interagency Reports (NISTIR)—A special series of interim or final reports on work performed by NIST for outside sponsors (both government and non-government). In general, initial distribution is handled by the sponsor; public distribution is by the National Technical Information Service, Springfield, VA 22161, in paper copy or microfiche form.