NIST HANDBOOK 146, Volume II

Technical Reference Guide for the HAZARD I Fire Hazard Assessment Method

Version 1.1

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

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DISCLAIMER

The Department of Commerce makes no warranty, expressed 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. Version 1.1 of 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. J. E. Snell provided the initial concept of HAZARD I and continued support throughout the development of the methodology. A. J. Fowell provided guidance in the overall logic of the hazard assessment 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. W. D. Walton developed the version of DETACT used in HAZARD I. E. Braun wrote FIREDATA and provided the basis for the database portions of the methodology. P. Reneke, N. Breese, C. Arnold, A. B. Fadell, 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.

FAST_in, FAST, FASTplot, EXITT, and TENAB are written in FORTRAN 77 and compiled with Lahey Computer Systems F77L© FORTRAN compiler[1]. The HAZARD I Interface Shell, MLTFUEL, and DETACT are written in Microsoft QuickBasic© with extensions using QuickPak Professional© from Crescent Software. Graphics capabilities in FAST and FASTplot were developed with MetaWindows© from Metagraphics Software Corporation. The METAPRNT utility for printing graphics is copyrighted and provided under license from Metagraphics Software Corporation. METAPRNT is provided to you for the exclusive use with HAZARD I. FIREDATA was written in DBase III© and compiled with the Clipper© DBase compiler. The installation program used to

[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.

install HAZARD I, *INSTALL*, is licensed software provided by Knowledge Dynamics Corporation. *INSTALL* is Copyright© 1987-1989 by Knowledge Dynamics Corporation which reserves all copyright protection worldwide. *INSTALL* is provided to you for the exclusive purpose of installing HAZARD I.

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1 Overview

In June 1989, the Center for Fire Research at the National Institute of Standards and Technology released a method for quantifying the hazards to occupants of buildings from fires, and the relative contribution of specific products (e.g., furniture, wire insulation) to those hazards [1], [2]. The culmination of six years of development this method, called HAZARD I, was the first such comprehensive application of fire modeling in the world. It combined 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 computer software, requires considerable expertise in fire safety practice. The heart of HAZARD I is a sequence of computer software procedures which 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.

The first version can model up to six rooms on multiple floors of a building, but data against which its results have been compared are only available for structures of the general dimensions of single-family homes. The method guides the user to identify the fire problems of concern and then to specify representative fire scenarios. The user then employs a computer software package to predict the outcome of each of the identified scenarios in considerable detail. The software predicts over time, the temperature, smoke, and fire gas concentrations in each room of the building, the behavior and movement of the building occupants as they interact with the fire, the building, and each other, and the impact of exposure of each occupant to the fire-generated environment. The occupant exposures are presented as a prediction of successful escape, physical incapacitation or death along with the time, location, and cause. By accounting for the interactions of a large array of factors on the result of a given fire situation, the method enables the user to analyze the impact of changes in the fire performance of products, building design and arrangement, or the inherent capabilities of occupants on the likely outcome of fires. With such information it should be possible to provide better, more cost-effective strategies for reducing fire losses.

This report marks the first major revision to the original document. In addition to improvements to the documentation, a number of new physical phenomena and features have been added to the software which accompanies the methodology. Constructive feedback from its 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.

There are many highly interactive factors which need to be considered in performing a quantitative fire hazard analysis (see Figure 1). 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 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. It

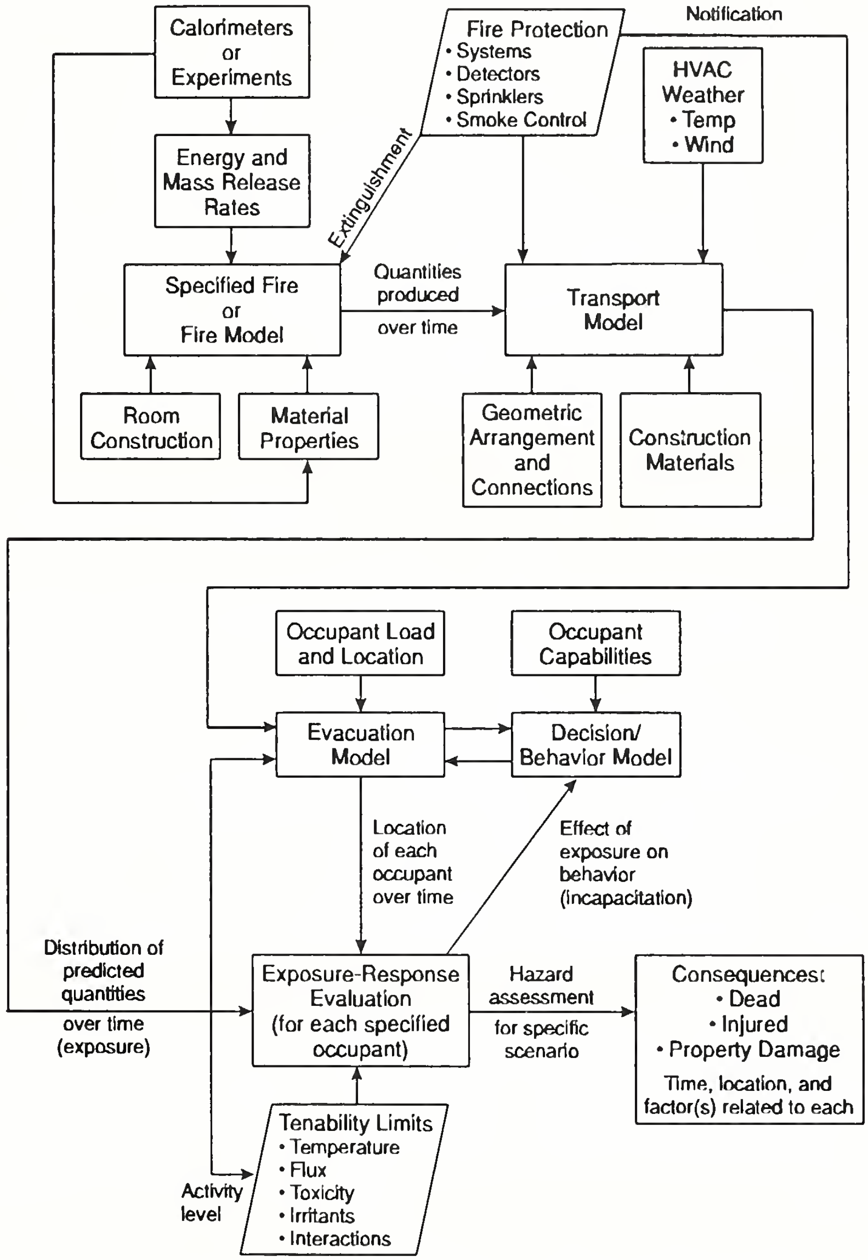

Figure 1. Interrelationships of major components of a fire hazard model.

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 min for safe escape when 10 min are needed results in human disaster. But providing 30 min of protection when 10 are needed can lead to high costs. A hazard analysis method can help prevent both types of problems 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 the 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 (the broad range of applications for a chosen product or products), 2) defining the scenario (the specific cases to be studied), 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 specified buildings and 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 would be more interested in all scenarios involving their products than in scenarios in a specific building. 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, users may find that their questions can be answered simply by estimating or inferring the expected performance of their 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, potential users of HAZARD I may find that their concerns involve 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 users choose to run through a complete set of new calculations for their problem situation. The flow chart, Figure 2, illustrates these three alternatives for the potential user of HAZARD I.

1.3 What's New in HAZARD I

Much of the content of this incremental upgrade to HAZARD is the same as the original release version. Details of the content of the new version is shown below. The following summarizes the changes from the original version of HAZARD I released in August of 1989.

- New in FAST: New physical phenomena were added — forced ventilation (see section 7.3.5.7) and deposition of hydrogen chloride on material surfaces (section 7.3.5.6). A more general chemistry scheme is included which allows for oxygen and chlorine in the fuel (section 7.3.5.5). The limitation on entrainment, applicable to small fires in large spaces, has been changed. Section 7.3.5.3 provides details of the entrainment model used in FAST. There have also been a series of improvements and fixes in the FAST-related software.

- The new documentation is divided into two volumes, a "Technical Reference Guide," (TRG) and a "Software Users Guide" (SUG). To centralize the discussion of examples of using HAZARD, the TRG includes a number of examples of cases in addition to those originally in the Example Cases volume of HAZARD I. The SUG was updated and expanded to describe new phenomena in the model, new operation for the building egress model EXITT, and improvements in the user interface.

- New versions of the sub-models of HAZARD I. Version 18.5 of FAST is the core of the software package. New versions of FAST_in, FASTplot, EXITT, TENAB, and the HAZARD shell are also included, with changes to support the new version of FAST.

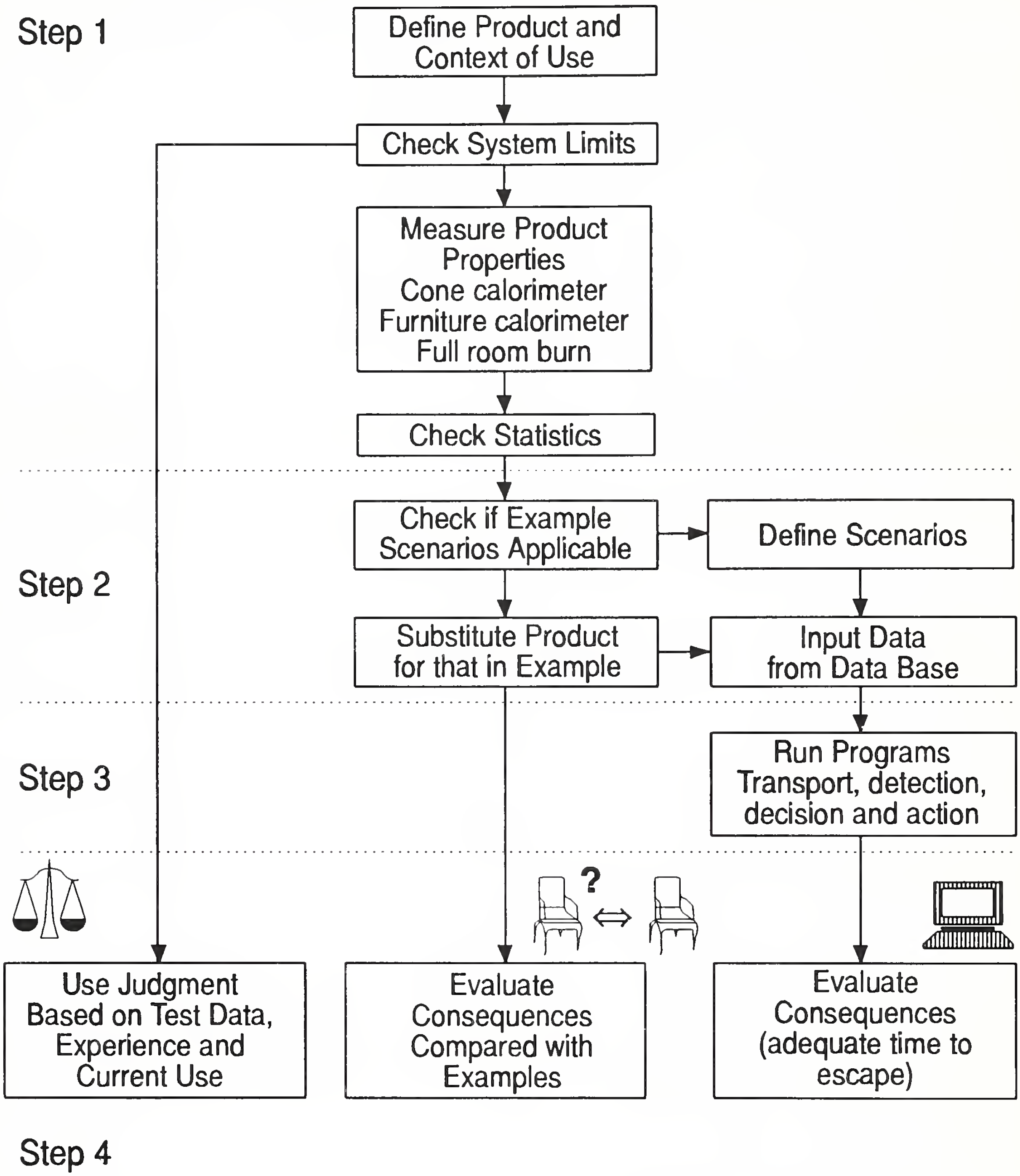

Figure 2. The overall method.

- The EXITT input file is organized for easier data entry — the problem encountered most frequently by those who used the entire hazard prediction was creating EXITT's building files. With a new data structure and a detailed example in the manual, this problem should be significantly reduced.

1.4 A Guide to the Documentation

This section provides an overview of the documentation and a guide to help the user efficiently learn of the capabilities (and limitations) of the methodology and accompanying software.

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 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)
- MS-DOS 3.0 or higher

The organization of the HAZARD I software package is shown in Figure 3. It includes a number of software modules (shown in the figure enclosed in rectangles) which implement the calculations necessary to conduct a hazard analysis:

- 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 18.5) 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

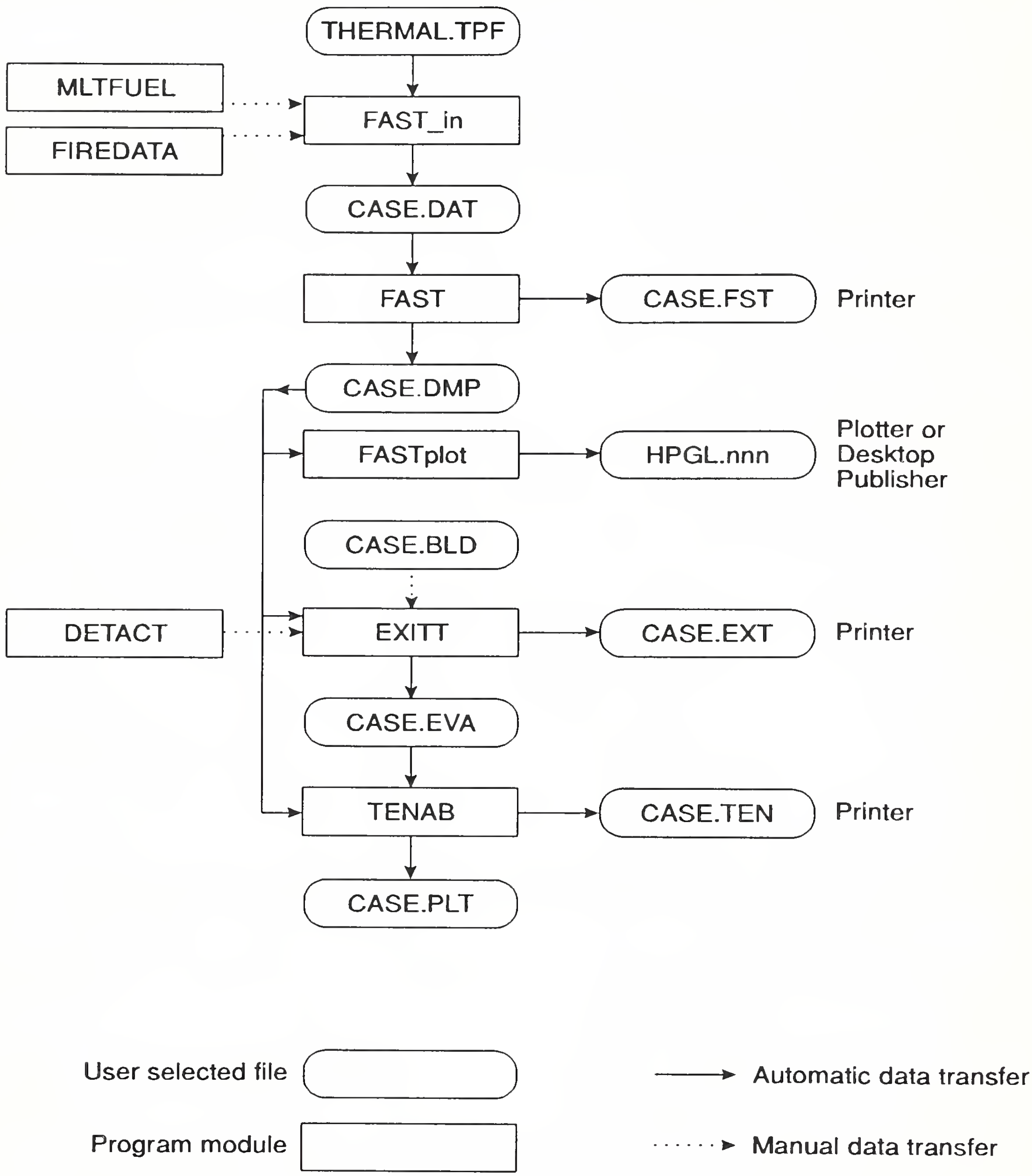

Figure 3. HAZARD I software.

- a tenability model (TENAB) which makes determinations for both incapacitation and lethality from temperature and toxicity, along with potential incapacitation from burns due to flux exposure.

This 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.

A set of 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 one of these cases (input data file listings, program outputs and graphs of selected variables) are provided in section 8.

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.

1.4.1 Technical Reference Guide for HAZARD, Version 1.1

This Technical Reference Guide provides a detailed description of the methodology and its application in HAZARD I.

Overview describes, in very general terms the approach to hazard analysis in HAZARD I. Sections are included to highlight new features and to guide readers through the documentation.

Background provides a historical perspective of fire hazard analysis leading up to HAZARD I. This section has been updated to the present with discussion of the original HAZARD I release and some applications published to date.

Step-by-Step Procedure describes the procedure for hazard analysis using HAZARD I.

Fire Incident Data is a summary of fire statistics which can be used to develop input data for HAZARD I.

Calculational Procedures provides the user with engineering tools which may be used to develop input data for the hazard prediction. Three topics are currently covered: "Determining the rate of heat release," "Adjusting the combustion chemistry," and "Ignition of the second item."

Tenability Limits discusses the background information used to determine appropriate tenability criteria.

Program Modules presents the theory and assumptions inherent in the models and programs of HAZARD I. This section has been greatly expanded by incorporating the theoretical sections of the Appendices B (FAST), C (EXITT), and D (DETACT) of the original HAZARD I release.

Example Cases In addition to the discussions from the original Technical Reference Guide, we have added more examples to illustrate new features (such as mechanical ventilation). The examples from the original Example Cases volume of the original HAZARD I release will be incorporated into this section — but not all in the same level of detail included in the original. Although we have included more examples for the new documentation, only a single example is presented in the full, detailed format included in the original release. For the remaining examples, a scenario description and the model inputs are presented. A single, printed output will be provided for comparison with results calculated on the user's computer.

Concluding Remarks has been enhanced with discussion of some of the experience gained with HAZARD I.

1.4.2 Software User's Guide for HAZARD, Version 1.1

The Software User's Guide provides the user with detailed instruction for the use of the software included as part of HAZARD I. In addition to a detailed reference to all software modules, a learning guide which performs an investigation of a single scenario from initial scenario description to tenability analysis is included.

Overview is identical to the overview in the TRG.

Getting Started provides a keystroke-by-keystroke guide to starting the learning process with the HAZARD I software. We have included new information on installation of the software. We used a commercial package for software installation which should save time and effort in installation.

Learning continues the process of working a single example from start to finish, but without the keystroke-by-keystroke minutia provided in the Getting Started section. It has been expanded to include the development of a building file for EXITT using a worksheet to keep the information organized. Extra worksheets are provided in the back of the manual.

Reference gives complete details of all the inputs and outputs of all the modules. We have updated the EXITT, FAST, and FAST_in sections to reflect the new software.

Error Messages provides an English description of the common error messages encountered with the HAZARD software. This section received only minor updating.

1.5 Learning HAZARD I

Clearly, without some plan of attack, the amount of printed material included as part of HAZARD I is imposing. While some of the material is included mainly for reference purposes, much of the material is required for the effective use the hazard methodology. This section provides one possible strategy to guide one through the documentation.

1. Read this "Overview" section of the Technical Reference Guide. It provides a general description of the hazard methodology and the accompanying software along with a summary of the limitations of the implementation in HAZARD I.

2. Section 3 of the Technical Reference Guide, "Step-by-Step Procedure for Conducting a Hazard Analysis" will introduce the reader to the details of conducting a hazard analysis with HAZARD I.

3. Sections 2 and 3 of the Software User's Guide will allow the user to conduct a complete hazard analysis using HAZARD I for a single scenario.

4. Sections 5 and 6 of the Technical Reference Guide describe details of developing the necessary data for a hazard analysis. The examples in section 8 of the Technical Reference Guide can be used to develop other scenarios of interest to the reader. Section 7 of the Technical Reference Guide provides the detailed theoretical background of the calculations performed by each program modules in the HAZARD I software. Section 4 of the Software User's Guide details all of the inputs for these program modules.

1.6 Assumptions and Limitations

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 (e.g., doors, windows, cracks),

- 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 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 these programs judiciously - including sensitivity analyses for the ranges of values for key parameters - in order to make estimates of these uncertainties. This section provides an overview of these assumptions and limitations. A more detailed discussion is included in section 7.

1.6.1 Scope Limitations

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 future versions of the system. 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.

1.6.2 Programs and Procedures Limitations

Figure 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 all materials that fall within that generic category. 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, or to perform repeatability tests to evaluate experimental error. 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.

1.6.3 Specified Fire Limitations

An important limitation of HAZARD I is the absence of a fire growth model. At the present time, it is 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 (e.g., chair, table, bookcase) 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 [3].

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 [4]. 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 provided data and procedures relate directly only to burning of items initiated by relatively large flaming sources. Little 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 which is currently considered the scenario in the United States where most deaths occur. While the program MLTFUEL allows multiple items burning simultaneously to be converted to a single "equivalent" specified fire, it does not account for the synergy of such mixtures. Thus, for other ignition scenarios, multiple items burning

simultaneously (which exchange energy by radiation and convection), combustible interior finish, and post-flashover conditions, the provided procedures 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 [5] or FIRST [6] which can be used as the source fire.

1.6.4 Transport Limitations

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 assumption is that the estimated error from ignoring the variation of the thermal properties of structural materials with temperature is small. While this information would be fairly simple to add to the computer code, data are scarce over a broad range of temperatures even for the most common materials.

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 Building and Fire Research Laboratory (BFRL). 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. 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., reference [7]) 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 [8] 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 smoke flow along a wall, the associated theory is only now being developed and is not included in the model. This may produce an underestimate of the lower layer concentrations.

5. In the present version of HAZARD I, 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 and 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 gas species produced by the fire are carried through the opening until the upper layer drops to the height of the undercut.

1.6.5 Occupant Behavior and Evacuation Limitations

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 for a monte carlo type of simulation.

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 m/min). 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).

1.6.6 Activation of Thermal Devices Limitations

The activation of smoke detectors, heat detectors, or sprinklers is handled in the program DETACT. The underlying theory and assumptions used are described in the Technical Reference volume in the chapter on Program Modules. 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 [9], [10] done by Factory Mutual Research Corp. for the Fire Detection Institute (FDI) and on which the NFPA 72E [11] 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.

1.6.7 Tenability Criteria Limitations

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 between temperature and toxicity are currently included (e.g., it is assumed but not known whether temperature exposure changes the rate of uptake of toxic species or increases the susceptibility to 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 the 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). 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, the fractional exposure dose (FED), is also introduced. This represents the fraction of the lethal concentration that an individual has been exposed to 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 [12], 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.

2 Background

The Center for Fire Research (former name of the Building and Fire Research Laboratory) project to develop a quantitative hazard assessment method was initiated following the National Bureau of Standards (NBS, former name of the National Institute of Standards and Technology) Workshop on Combustion Product Toxicology held in 1982 [13]. 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 [14]. Later that year, NBS made a commitment to produce a practical hazard assessment method in 3 to 5 years [15]. 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" [16] 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 [17] 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., [18], [19]). 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 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 [20]. 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 [21].

Subsequently, the Toxicity Advisory Committee was asked by the National Electrical Code Committee for assistance in addressing a toxicity hazard question regarding poly-(tetraflouroethylene) (PTFE) plenum cables. In providing that help, a hand calculated analysis was performed [22]. 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.

2.2 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 [23] 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 [24] calculates post-flashover room temperatures. And, very detailed models like the HARVARD 5 code [25] 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 [26] which is similar to the FAST model, and the HARVARD 6 code [27]; 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.

2.3 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.

2.3.1 Cone Calorimeter

The Cone Calorimeter [28] 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 [29]. 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.

2.3.2 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 [30] is then used to extrapolate the test data to the predicted results of a room fire involving that material.

2.3.3 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 [31]. In addition, work on scaling effects on the measured properties have been published [32]. 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 [33]. Time and resource constraints prevented the inclusion of much of this data into the prototype database supplied with this report. Ultimately, all such data needs to be accessible to users of fire models.

2.3.4 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 [34]. 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) [35]. 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.

2.3.5 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 BFRL, 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.

2.3.6 The ASTM room fire test

During the late 1970's and early 1980's a number of laboratories decided on the need for developing a standardized method for measuring heat release rates in rooms, based on oxygen consumption. The concern here was in measuring the burning rate of combustible room linings (i.e., wall, ceiling, or floor coverings), and not furniture or other free-standing combustibles. The original development was at the University of California by Fisher and Williamson [36]. Later, extensive development was also done at the laboratories of the Weyerhaeuser Co., and at NBS [37]. The method, in its simplest form, consisted primarily of adding oxygen consumption measurements into the exhaust system attached to a room very similar to that originally used by Castino and coworkers at Underwriters Laboratories [38], who, however, did not measure heat release rates at all. The room was 2.4 by 3.7 m in size and 2.4 m high, with a single doorway opening in one wall, 0.76 m wide by 2.03 m high (Figure 4). The original studies at the University of California led to ASTM issuing in 1977 a Standard Guide for Room Fire Experiments [39]. The Guide did not contain

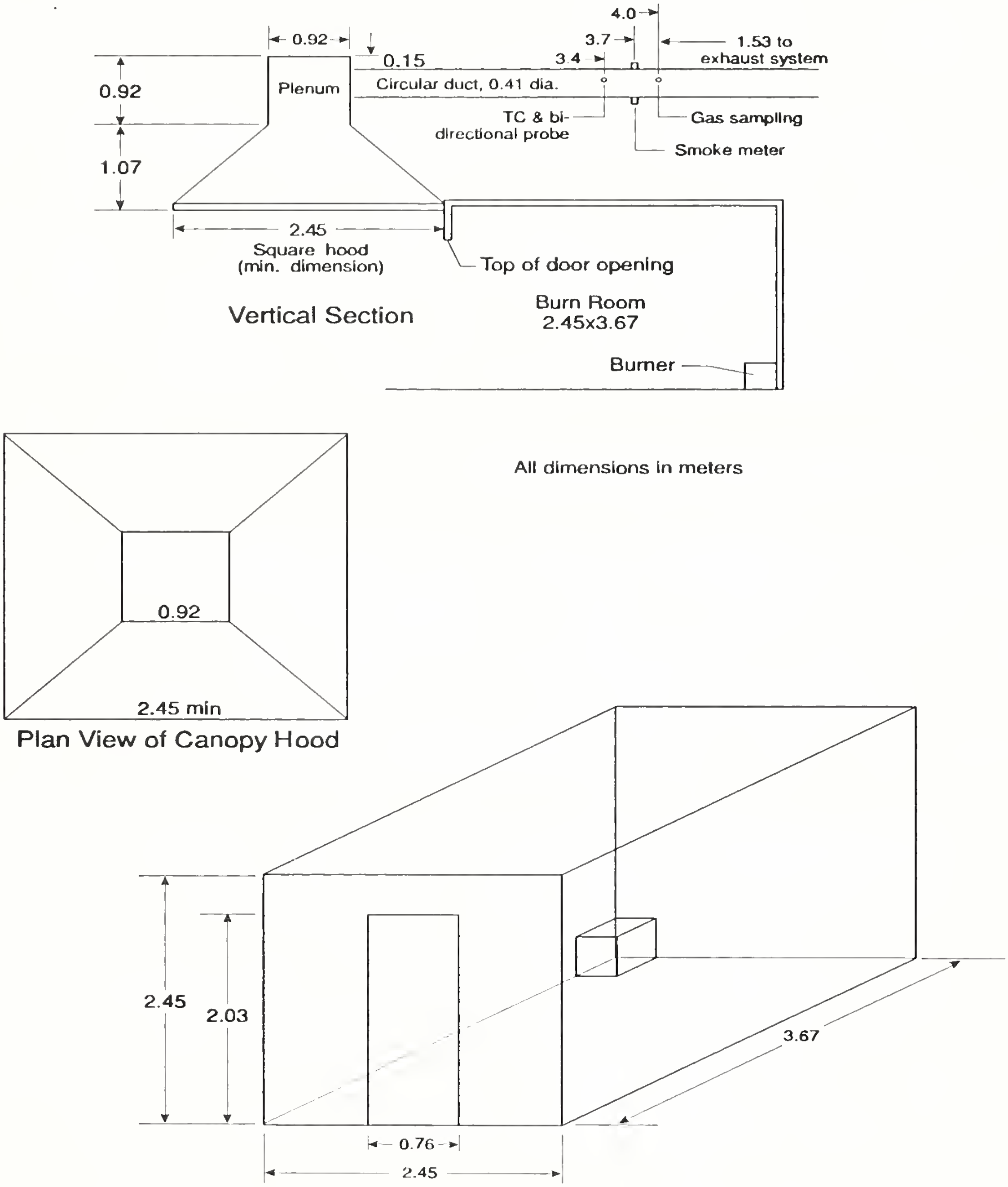

Figure 4. The original (1982) ASTM proposed room fire test.

prescribe details such as room size or ignition source, but was simply a guide to good practice in designing room fire tests of various sorts. The Guide being completed, ASTM then turned to consideration of an actual prescriptive test method. Such a test was published as a 'Proposed method' in 1982 [40]. The 1982 document mandated the above-mentioned room size and also a standard ignition source, which was a gas burner, placed in a rear corner of the room, giving an output of 176 kW. Since the development work at the U. of California with a natural convection exhaust system uncovered problems with it, the actual test specification entailed a requirement to "establish an initial volumetric flow rate of 0.47 m^3/s through the duct if a forced ventilation system is used, and increase the volume flow rate through the duct to 2.36 m^3/s when the oxygen content falls below 14%." This specification required a complex exhaust arrangement, and it is not clear that there were many laboratories prepared to meet it. The proposed method was withdrawn by ASTM; however, variants of this method continue to be used by a number of laboratories. Very recently, an international round robin on this activity has been organized by ASTM [41].

2.3.7 The ISO/NORDTEST room fire test

Following ASTM's disengagement from the development of a standard room fire test, activity was accelerated in the Nordic countries. Development was principally pursued in Sweden, at the Statens Provningsanstalt by Sundström [42] The NORDTEST method [43], [44], as eventually published in 1986, uses a room of essentially the ASTM dimensions, 2.4 by 3.6 m by 2.4 m high, with an 0.8 by 2.0 m doorway opening (Figure 5). The exhaust system flow rate capability was raised to a required value of 4.0 kg/s, with the capability to go down to 0.5 kg/s mandated to be available during the early part of the test in order to increase the resolution.

A special concern in the Nordic countries has been the effect of the igniting burner. A parallel project at the Valtion Teknillinen Tutkimuskeskus (VTT) in Espoo, Finland by Ahonen and co-workers [45] developed data on three burner sizes and three burner outputs. The three burners had top surface sizes of 170 mm by 170 mm, 305 by 305 mm, and 500 by 500 mm. The fuel flow rates were 40, 160, and 300 kW. The results that the VTT reported were on chipboard room linings. They found no significant differences at all between the burner sizes. The burner output did, of course, make a difference; however, the difference between 40 and 160 kW was much larger than between 160 and 300 kW. The VTT conclusion was that either the 160 or the 300 kW level was acceptable. The NORDTEST method itself has taken an ignition source to be at the 100 kW level. If no ignition is achieved in 10 min, the heat output is then raised to 300 kW.

ISO (the International Organization for Standardization) has adopted the NORDTEST room fire test for its use and is in the process of finalizing the standard [46].

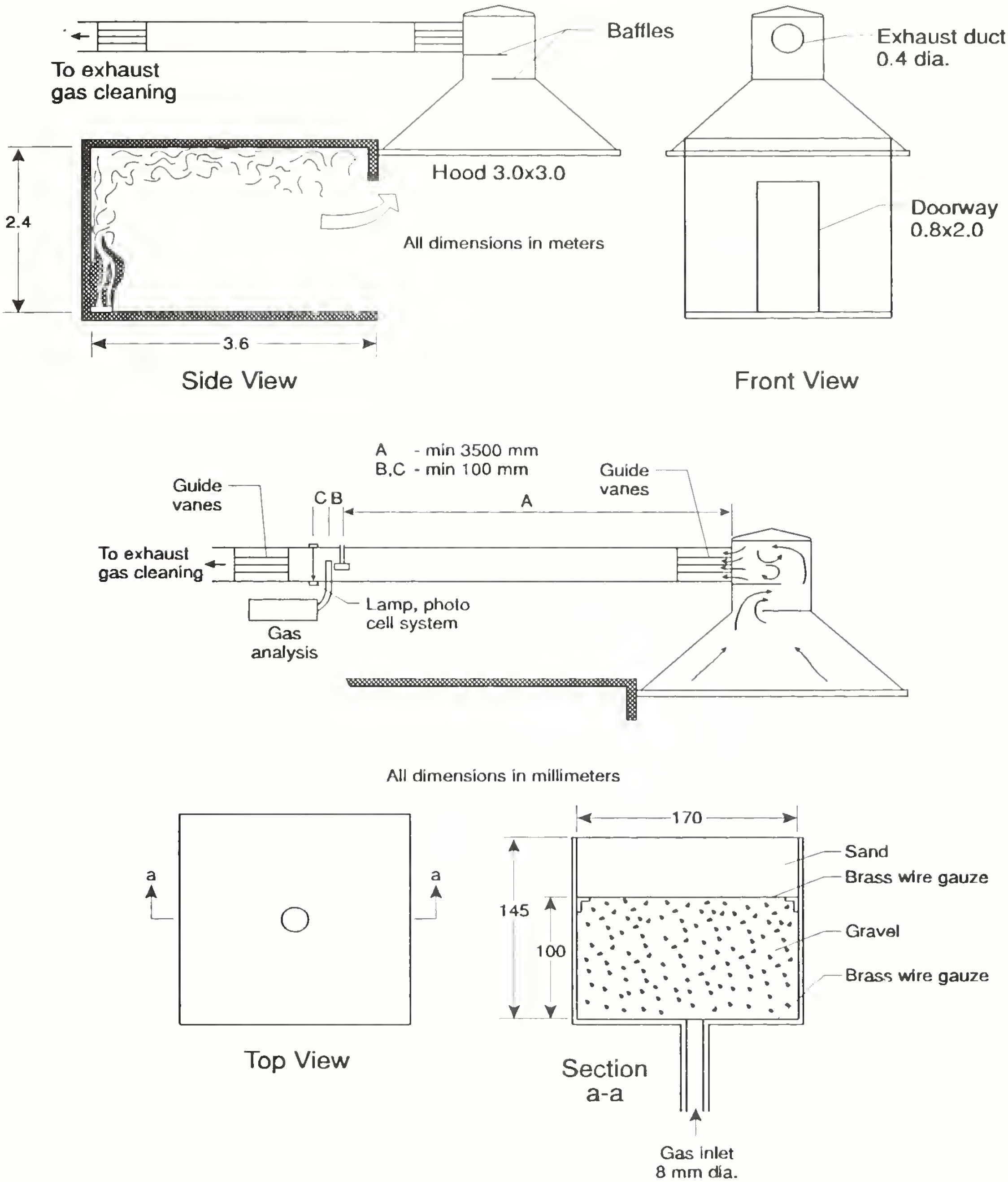

Figure 5. The NORDTEST room fire test.

2.4 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 received from half of these. These comments and suggestions, along with those from our staff, had a substantial influence on the general release version [47].

2.5 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 [48]. 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 [49]. 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 [50]. 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 [51] 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.

2.5.1 Application of Hazard Analysis to Building Codes

Doshi [52] has applied HAZARD I for use with the Canadian Building Code Assessment Framework (BCAF), a system which analyzes code changes in relation to building code objectives and assess economic and social impacts for several building types. The study focused on two main areas: setting up links between HAZARD I and the BCAF and using HAZARD I with Canadian fire data. The study showed the ability of the BCAF to utilize results from external models such as HAZARD I and presented a framework to do it. Although limitations of HAZARD I are noted, its value was seen in assisting experts in formulating responses to code change requests and thereby minimizing the overall effort required in evaluating code changes.

One of the most frequent technical questions asked of a fire code official relates to whether a certain building design or arrangement is equivalent to that prescribed in the code. Such equivalency determinations can only be based on the expert judgement of the official, and often lead to heated discussions among parties who may not agree. Aus [53] used HAZARD I to provide an impartial and technically defensible alternative to such a determination. As a test, an actual case from California was examined using this process. The question involved a small school building which was found in violation of the Uniform Building Code (UBC) with respect to the required separation of alternate exits. The analysis performed examined several alternative approaches to compliance with the intent of the code, with a significant variation in cost. The use of HAZARD I in this analysis offered the opportunity to model the smoke, heat, and toxic gas distribution within the school building as a result of a typical fire. In this way a visual representation of what the building and its occupants could be expected to do under fire conditions was generated. The opportunity to demonstrate aspects of the fire safety codes via fire models potentially increases the acceptance of building requirements during the construction planning process.

Developing scenarios for the HAZARD I analysis involved first addressing the limitations which the school building represented. The two story structure is bordered by a balcony on one side (see Figure 6) limiting exit travel. Providing separate exiting from rooms not bordering the balcony was deemed unacceptable by school officials from the perspective of both cost and the physical security of the building. Options presented for study consisted of either providing additional exiting from rooms one and six with egress to the balcony (the doors toward the ends of the balcony), or separating the building with a two hour separation wall (shown as a dotted line) and associated corridor doors. Such a separation wall would be required to meet the requirements of Section 505 (e) of the Uniform Building Code. Since the costs of constructing a fire rated partition with rated doors is significantly higher than the additional exits, it was felt that a HAZARD I analysis could be used to show the effectiveness of each option in meeting the intent of the code. In this way those making the final decision on the construction design would possess the most accurate and cost effective information in which to meet the fire safety requirements.

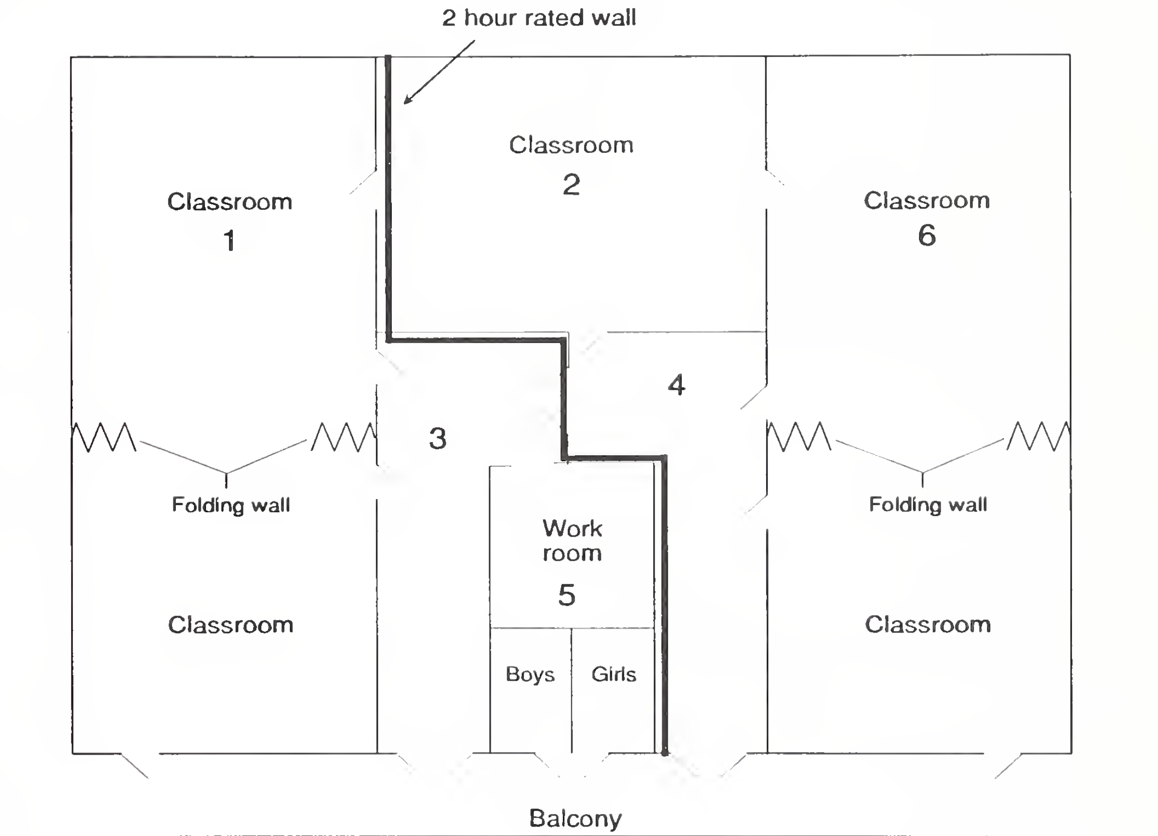

Figure 6. Floor plan of a school building used in a hazard analysis of code alternatives.

Primary concern centered around the existing corridor which is constructed in a horseshoe configuration. All classrooms egress into this corridor. Fire and smoke movement was examined as it effects the exit corridor and thus the occupants' ability to escape. As has been the case in actual school fires, the fire was assumed to begin in the work room (which might also represent a craft room or teachers' lounge) with the door open. A trash can fire spreading to a couch was used as the ignition scenario. Burning rate data for the trash can and couch were selected from the HAZARD I database.

The software was used to predict the travel of smoke and heat, and to present the results in terms of room temperatures and the concentrations of smoke and toxic gases. These are important to the parties concerned in determining exit placement as well as visually demonstrating any rapid loss of egress paths.

Results of both scenarios varied based on assumptions about doors being open or closed. In both cases it was demonstrated that the two hour wall assembly performed according to code requirements presume as long as there is no leakage through it. How much leakage could be allowed without compromising the effectiveness of the barrier could be determined with additional simulations. Thus this wall could be utilized to meet code mandates. In the fire examined, rapid loss of the primary exit from heat and toxic gases necessitates a secondary exit. If classroom doors were kept closed, sufficient safe egress time is provided to allow use of exits through classrooms 1 and 6 to the balcony. Thus, this less costly option could be allowed under this condition.

The results of the analysis present a detailed visual representation of how the building and its occupants could be expected to perform in a fire situation. Such information can be crucial in explaining the complexities of the fire codes to the public as well as in providing a visual plan for architects, building officials, and fire protection specialists. Fire safety depends to a large degree on changing attitudes through facts, assisted by pictorial and diagrammatical representations. From a fire prevention perspective HAZARD I represents one tool with which the fire service may continue to learn from changing technologies while seeking to better educate the public.

2.5.2 Application of Hazard Analysis to Fire Reconstruction

Several researchers have applied fire models and hazard analysis to investigate the growth of fire in important building fires. The work of Emmons [50] on the MGM Grand Hotel fire of 1980, described above, fits in this category. Bukowski [54], [55] has applied HAZARD I to at least two fire reconstructions. In the first [54], the newly-released fire hazard assessment software HAZARD I was successfully employed by BFRL in a litigation against the United States. At the request of the Justice Department, the HAZARD I software was used to recreate the fire. The analysis reproduced many details of the fire including damage patterns to the building, the successful escape of three older children, and three fatalities including the locations of the bodies and the autopsy results.

In the second fire reconstruction [55], an analysis of a multiple fatality fire in a nightclub provided insight into fire growth and potential for cost effective code strategies to prevent similar events from happening. The fire involved a two story building constructed with combustible interior finish materials. The HAZARD I [1] software was used to develop an approximate reconstruction of the fire events and to examine different potential mitigation strategies that could have influenced the outcome of this fire:

- inclusion of a complete automatic sprinkler system,
- installation of a door at the base of the stairs to prevent combustion products from traveling to the second floor,
- provision for a second means of egress from the second floor, and
- upgrading of all interior finish materials to noncombustible materials that would not contribute to the fire.

For each strategy, the ability to mitigate the life loss was evaluated and the retrofit cost estimated. Cost is an important determinate of whether any strategy is realistic since high costs may result in a reluctance by building owners to comply with code mandates. HAZARD I predicted conditions quite similar to those reported for the actual incident, including times to and cause of death for the building occupants consistent with observations. Different levels of effectiveness was noted for the possible design changes.

Duong and Grubits [56] used a number of techniques, including many of the modules of HAZARD I to develop a reconstruction of a six fatality fire in a Sydney, Australia hotel. The hotel was an old, three story building approximately 14 x 20 m in area. The building was constructed of both masonry and timber frame construction. The fire reconstruction was conducted to understand how the fire developed, how the smoke moved from one room to another, and from floor to floor. The analysis was carried out in seven steps:

- DETACT was used to predict the actuation time of a heat detector actuated alarm.
- FAST was used to determined if flashover could be reached.
- HARVARD 6 was used to predict the times for ignition of the timber column support construction.
- Hand calculations predicted the time for flame spread to the building exterior.
- FIRST [57] was used to predict the time for secondary ignition of foam insulation and exterior timber framing.
- Extra, unburned fuel predicted by HARVARD 6 was used to develop a more realistic burning rate curve.
- FAST was used to predict fully-developed fire and smoke movement with this modified burning rate curve.

Based upon this analysis, they discovered a key step in the fire development. The lives of four people (of six total fatalities) would probably have been saved if the stairway was of non-combustible construction or the back doors were not left open. The plywood panelling on the stairway was considered to contribute significantly to the fire spread, not only within the building, but also on the back wall.

Levine and Nelson [58] used a combination of full-scale fire testing and modelling to simulate a fire in a residence. The 1987 fire in a first-floor kitchen resulted in the deaths of three persons in upstairs bedroom, one with a reported blood carboxyhemoglobin content of 91%. Considerable physical evidence remained. The fire was successfully simulated at full scale in a fully-instrumented seven-room two-story test structure. The data collected during the test have been used to evaluate the predictive abilities of two multiroom computer fire models: FAST 18.3 (the version of FAST released with the original version of HAZARD I) and HARVARD 6.3.

A coherent ceiling layer flow occurred during the full-scale test and quickly carried high concentrations of carbon monoxide to remote compartments. Such flow is not directly accounted for in either computer code. However, both codes predicted the carbon monoxide buildup in the room most remote from the fire. Prediction of the pre-flashover temperature rise was also good. Prediction of temperatures after flashover that occurred in the room of fire origin was less good. Other predictions of conditions throughout the seven test rooms varied from good approximations to significant deviations from test data. Some of these deviations are believed to be due to phenomena not considered in any computer models.

2.5.3 Application of Hazard Analysis to Predicting Risk

A methodology which can be employed to predict product fire risk has been developed in a project funded by a broadly based consortium of manufacturers and trade associations through the National Fire Protection Research Foundation (NFPRF) [59]. It builds on recent advances in deterministic fire modeling to provide a physics-based method of estimating the severity of specified fires while retaining the probabilistic framework of traditional risk analysis for estimation of the relative probabilities of various types of fires. This fire risk assessment method is designed to permit the quantitative prediction of the change in expected fire fatalities per year attributable to changes in fire performance properties of combustible products (e.g., building contents and furnishings) in the context of their end use in specific occupancies.

The method is designed to calculate the expected severity (in deaths per fire) and the relative likelihood (as fire probability) of each of a large number of fire scenarios that may involve the product as the first item ignited or as a secondary contributor. Expected severity is estimated through the use of HAZARD I, which requires very specific information on the physical properties of burning items, the thermal properties of rooms in which fire occurs, the sizes and layout of rooms and their associated openings, the locations and conditions of occupants, and the status of built-in detection systems. Relative likelihood is modeled using fire incident data, data from other sources, and many assumptions since such information can be obtained only in terms of *classes* or ranges, e.g., class of burning items, classes of rooms, ranges of occupant ages.

Four case studies were used in the development of this methodology. Upholstered furniture in single family, detached dwellings was selected as the initial case study [60]. The other cases studied were: carpet in offices [61], concealed combustibles in hotels [62], and wall coverings in restaurants [63]. Each of the product/occupancy pairs required the project team to address additional challenges which served to sharpen the methodology, improve the applicability of the hazard modeling, and point out the current limitations imposed by the state of modeling and the availability of data sources.

These initial case studies provided a benchmark against which the prototype risk prediction method's capabilities could be measured against the goals of the project as originally conceived. In some cases, the performance of the method was better than expected for the first application. In others, differences were attributable to shortcomings in the method arising from a lack of technical knowledge of fire phenomenology or a lack of detail in required data. Thus, this effort was beneficial in identifying key needs for improved fire science or data.

Taken as a whole, this series of case studies has demonstrated a significant potential for the risk method to provide highly detailed analyses of the risk (and cost) impact of regulation and of the fire performance of products in our society. The potential benefits to both the provision of public safety and the costs of such safety are enormous. But further investments, particularly in the area of data collection, will be required.

3 Step-by-Step Procedure for Conducting a Hazard Analysis

3.1 The Logic of the Procedure

Table 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 BFRL and by selected groups outside of BFRL, 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 BFRL to enable corrections and improvements to be made.

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.

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 (e.g., form of heat of combustion, equipment involved, material, and area of origin, as well as extent of flame and smoke spread) 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.

Table 1. Hazard analysis procedure

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.

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, or reduce the likelihood of ignition.

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 (e.g., by sensitivity analyses, testing, expert judgment)?

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

The method used in HAZARD I is outlined in Table 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 proposals [64]. 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 Table 2. Detailed discussion of the inputs required is contained in the Software User's Guide. The entire scenario should be developed before data input

Table 2. Scenario description for using the HAZARD I software

BUILDING DESCRIPTION

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

FIRE DESCRIPTION

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

OCCUPANT DESCRIPTION

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. NFIRS 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.**

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. For multi-story buildings, a sectioned elevation drawing should also be prepared to locate the elevation of building elements above some reference 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 BFRL. 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 ignition") 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 section 5 on calculational procedures.

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 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 section 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.

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 discussion of the data inputs will be made later in this section. The four general descriptors as presented in Table 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 terms of the criteria established in step one and applied in step four (e.g., deaths, injuries, or extent of damage). 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 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 section 4 of the Software User's Guide).

A more 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 Fractional Exposure Dose (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 section 6.) 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)"[2] nor an "unusual toxicological response (UTR)"[3]. 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." It is based on the work of B. C. Levin and coworkers [65] with rats. The equations used by TENAB to make this evaluation are discussed in section 7 of the Technical Reference Guide. When the computed value for FED reaches about 1, lethality is assumed to occur; at a value of about 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 section 7.5 of this Technical Reference volume.

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[2] 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.

[3] 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, HCN, and reduced O_2.

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 exposure 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 exposure dose for each room is computed. The total exposure is the sum of the exposure doses accumulated in each room until the occupant exits the building. The same technique is used for the FED data.

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.

4 Fire Incident Data

4.1 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. Table 2 on page 38 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) [66]. 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.

4.2 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. Since the most recent data was used for each purpose, multiple data sources were used. Thus, different points will highlight different year's data.

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 3 shows the distribution of fires, civilian deaths and injuries by occupancy for 1989 [67]. As Table 3 indicates, residential fires in 1989 only represented about 24% of the total fires but contributed to over 80% of the civilian

Table 3. Estimates of reported fires, civilian deaths and injuries by occupancy, 1989

Occupancy	Fires		Civilian Deaths		Civilian Injuries	
	Estimate	Percent of All Fires	Estimate	Percent of All Civilian Deaths	Estimate	Percent of All Civil-ian Injuries
Residential (total)	513,500	24	4,435	82	20,750	74
One- and two-family dwellings	402,500	19	3,545	66	15,225	54
Apartments	96,000	5	790	15	5,040	18
Hotels and motels	6,500	0	35	1	300	1
Other residential	8,500	0	65	1	175	1
Nonresidential structures	174,500	8	220	4	3,275	12
Highway vehicles	415,500	20	560	10	2,750	10
Other vehicles	20,000	1	125	2	275	1
All others (includes fires outside of structures with value in-volved and fires in brush and rubbish with no loss involved)	991,500	47	70	1	1,200	4
TOTAL	2,115,000		5,410		28,250	

Source: NFPA Survey of Fire Departments [67]

deaths. In 1989, the bulk of civilian fire deaths (82%) and injuries (74%) occur in residences, although residences account for only 24% of the total fires. One- and two-family dwelling fires alone accounted for over 65% of the deaths. This proportion has remained fairly constant over the past several years [68].

The National Fire Incident Reporting System (NFIRS) developed by the U. S. Fire Administration provides 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, and time of day.

Table 4 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 5% of the fires,

Table 4. Cause analysis, one- and two-family dwellings (mobile homes not included)

	Fires (%)	Fatalities (%)	Injuries (%)
Incendiary / Suspicious	11	13	8
Children Playing	4	10	11
Smoking	5	26	12
Heating	28	16	14
Cooking	16	7	23
Electrical Distribution	8	11	8
Appliance	6	2	5
Open Flame	6	5	7
Other Heat	1	1	2
Other Equipment	9	7	9
Natural	2	0.4	1
Exposure	3	0.4	1

Source: 1987 NFIRS adjusted to distribute fires of unknown cause like the fires for which the cause is known.

causes 26% of the deaths; whereas heating which has contributed to nearly one-third of the total fires has a proportionately lower death rate, but still is attributed with a very significant 16% of the deaths in one- and two-family dwellings.

4.3 Who Dies in Fires?

Clearly the fire risk is not equally divided among all persons. An analysis of the 1987 NFIRS data shown in Figure 7, indicates the very young (5 and under) and the elderly (70 and over) have death rates of about two to three times, respectively, greater than the 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 [68]. From the standpoint of the fire victim, Table 5 and Table 6 differentiate the location at ignition and the physical conditions expected for victims of different age groups [69]. Such information is of direct use in locating the occupants relative to the fire and establishing their capabilities for escape and rescue.

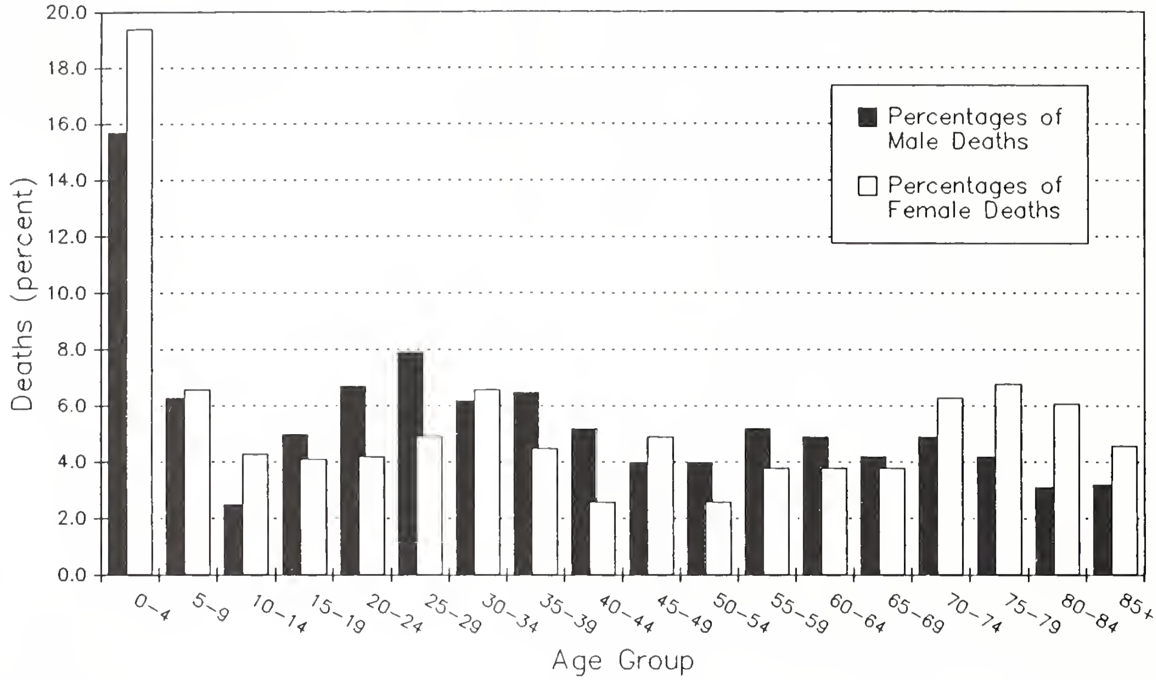


Figure 7. Fatality rate by age and sex in residences (1987 NFIRS).

A study which analyzed the leading causes for fire fatalities among the young and elderly summarized the important ignition factors based upon the 1987 NFIRS [68]. For children under 5 in fatal fires, the leading cause of fire deaths by far is “children playing.” It accounts for 39% of their fire deaths with known cause. That is one reason why they have such a high death rate. For children, the second leading cause is heating, and third is arson. Careless smoking, the leading cause for adults, accounts for only 5%. For adults over 70, the leading cause of fire deaths is careless smoking. It accounts for 32% of the fire deaths among the elderly. Both elderly men (27%) and women (22%) have careless smoking as the leading cause, but it is a somewhat greater problem among elderly men. The second leading cause of fire deaths is heating.

Table 5. Civilian fire deaths in residences by condition before injury and age of victim, 1983-1987

	All Ages	1-5	6-9	10-19	20-29	30-49	50-64	65-74	75-84	85+
Asleep	55	51	78	79	65	57	53	46	40	31
Bedridden, other physical handicap	6	0	0	1	0	3	9	16	20	21
Impaired by drugs or alcohol	9		0	2	18	21	19	12	4	1
Too young to act	9	36	7	2						
Too old to act	3						1	4	11	27
Senile, mentally handicapped	2	0	1	1	1	2	2	3	3	2
Awake, unimpaired	14	12	12	12	14	15	15	17	18	14
Other	2	1	1	3	14	2	1	2	4	4
Estimated annual number of fire deaths percentages were based on	4,570	916	251	347	536	804	586	469	450	212

Source: 1983-87 NFIRS and NFPA Survey

An analysis of the data from [69] on 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	57	41
Unable to act because of age or bed ridden	30	30
Awake, but unable to escape	13	29

Table 6. Civilian fire deaths in residences by location and age of victim, 1983-1987

	All Ages	1-5	6-9	10-19	20-29	30-49	50-64	65-74	75-84	85+
Intimately involved with ignition	18	10	6	9	12	18	25	26	28	35
Room of fire origin	22	26	16	15	18	20	22	24	26	19
Floor of fire origin	31	35	31	29	40	32	27	27	25	27
Building of fire origin	28	28	47	46	28	28	23	22	19	19
Other	1	1	0	1	2	2	3	1	2	0
Estimated annual number of fire deaths percentages were based on	4,570	916	251	347	536	804	586	469	450	212

Source: 1983-87 NFIRS and NFPA Survey

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 [68], [70], [71].

An analysis of civilian injuries indicates that unlike fatalities, adults aged 20-39 have the highest risk of injury from fire in residences. The recent 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 [68].

The distribution of fatalities for one- and two-family dwellings (Table 7) 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% of the multiple death fires reported in 1985 occurred in residential properties resulting in 80% of the total multiple deaths [72].

Table 7. 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	8
10*	0	0

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

4.4 Smoke Detector Performance

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 [73]. As Figure 8 shows, of the fires reported to NFIRS in 1988 where detector status was known, nearly 70% of the fires occurred in residences without detectors [68]. Also, when households do have detectors and the fire is not small, they do not work in over one-third of the cases (9% "present and did not operate" out of 24% total present). In addition, it is disturbing to note that in about 18% of the fire deaths, smoke detectors were present in the home. In some of these cases, the detector may have gone off too late to help the victim, the victim may have been unable to react, or the fire may have been too close to the victim.

4.5 Flame and Smoke Spread

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. Table 8 through Table 11 provide an analysis of the 1982 NFIRS data [74]. Flame and smoke spread relate directly to the physics of fire development in buildings which are directly usable in the fire models.

Table 8. Extent of flame and smoke damage at extinguishment

Extent of damage	Flame damage		Smoke damage	
	Fires (%)	Deaths (%)	Fires (%)	Deaths (%)
Confined to object	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 [74]

Table 9. Extent of flame versus detector status

Extent of flame	Percentage of Fires		Deaths per 100 fires	
	With Detectors	Without Detectors	With Detectors	Without 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 [74]

4.6 Scenario Development

4.6.1 Cause of Fire

A study in 1976 by Clarke and Ottoson looked at fire death scenarios defined by occupancy, ignition agent and ignition source [75]. Their analysis indicated that about two-thirds of the fatalities

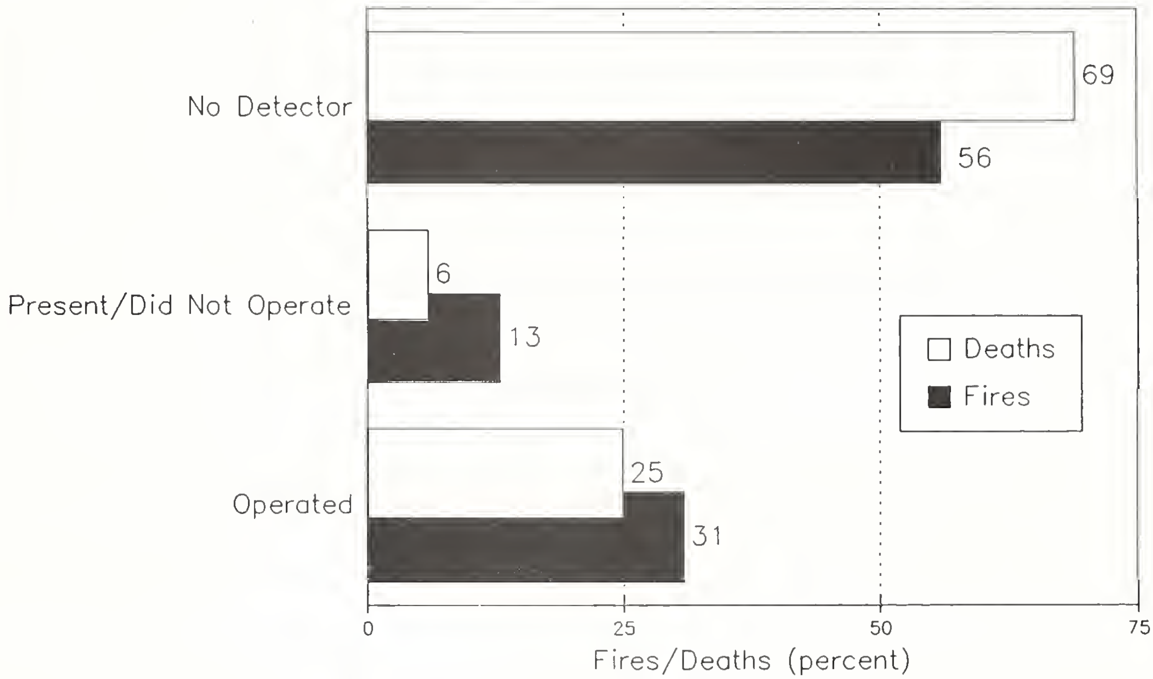


Figure 8. Smoke detector performance in residential fires, 1988.

could be accounted for by 14 general scenarios. Fire involving residential furnishings accounted for 36% of the deaths for all scenarios.

The 1987 NFIRS data, can be used with a similar approach to examine the leading ignition scenarios in residential structure fires [68]. Because of the potential influence of climatic and construction differences an analysis was performed for the northeast, central, southern and western regions of the United States (see Figure 9 to Figure 12). The three leading causes of fires in 1987 — heating, cooking, and incendiary/suspicious — were the same as in 1983, and the top two were the same for all four regions of the country. However, the difference between the top two causes grew smaller over time in every region. Heating fires showed a dramatic drop in all regions from 1983 to 1987 [68].

Smoking dominated all four regions as the leading cause for civilian fire deaths (25 to 29%) for a small portion of the fires (6 to 8%). Although the percentage of careless smoking deaths decreased in every region but the South, a more recent study [76] indicates a 12% increase in these deaths in 1988. Heating, with a range of from 13 to 22%, was the second leading cause of fire deaths in

Table 10. Percentage of deaths for extent of flame versus victim condition and activity

Extent of flame	All cases	Awake	Asleep	Handi-capped	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 compart-ment or floor	14	14	12	19	13	12	14
Extended beyond floor	69	59	76	55	78	65	70

Source: 1982 NFIRS [74]

Table 11. Extent of flame versus time of day

Extent of flame	Day (7 a.m. to 5 p.m.)		Evening (5 p.m. to 1 a.m.)		Night (1 a.m. to 7 a.m.)	
	Percent of fires	Deaths per 100 fires	Percent of fires	Deaths per 100 fires	Percent of fires	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 [74]

all but the Central region [68]. Miller [75] notes that the 1988 death toll in home fires caused by smoking materials was more than twice the death toll for the next leading cause of civilian deaths in structures: heating fires.

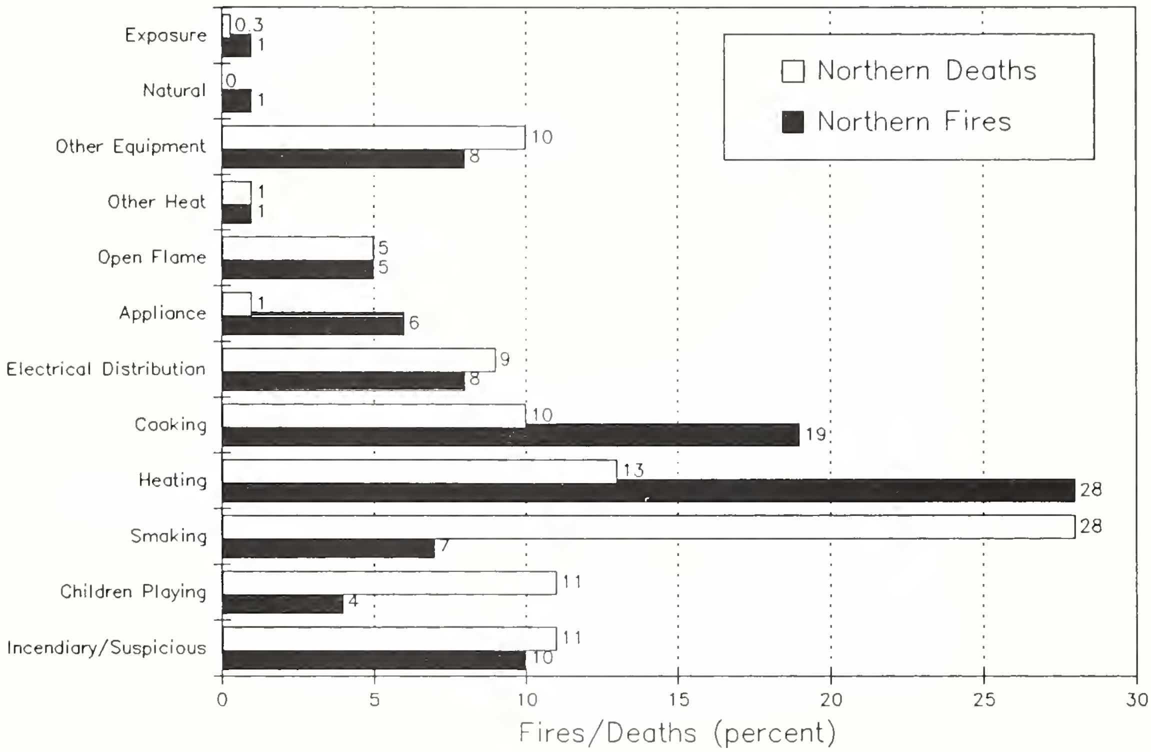


Figure 9. Causes of fires and deaths in residential structure fires in the Northeast, 1987.

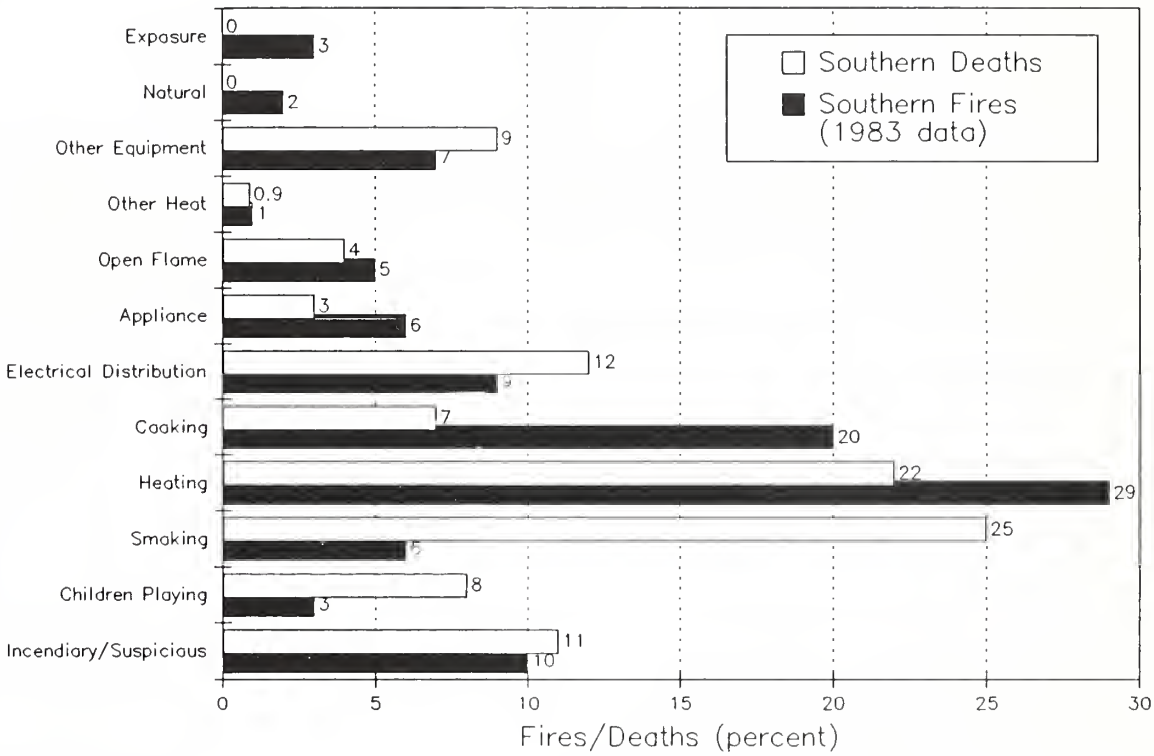


Figure 10. Causes of fires and deaths in residential structure fires in the South, 1987.

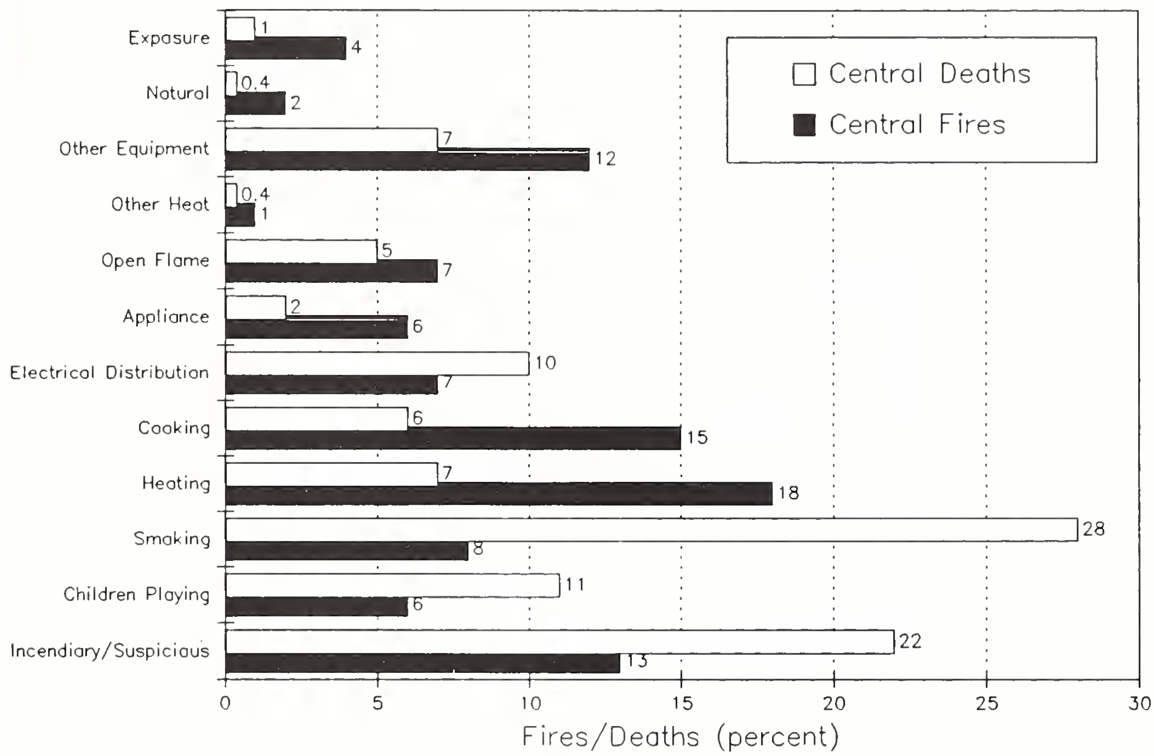


Figure 11. Causes of fires and deaths in residential structure fires in the central states, 1987.

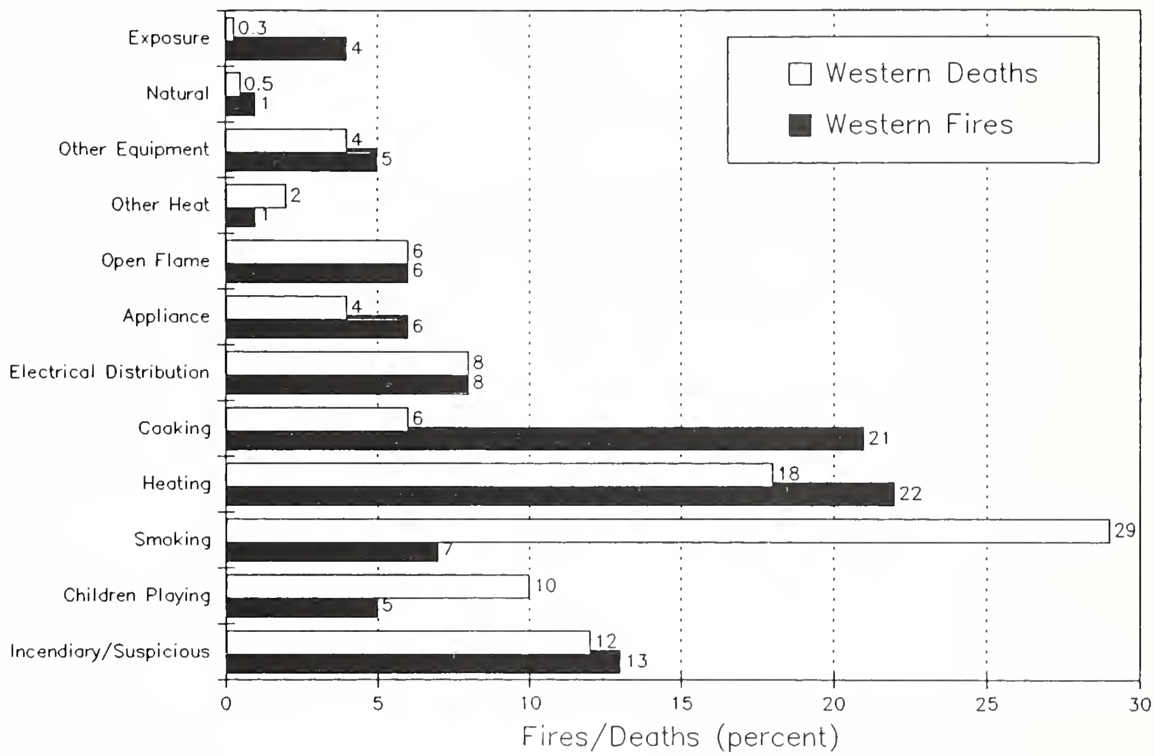


Figure 12. Causes of fires and deaths in residential structure fires in the west, 1987.

4.6.2 Area of Fire Origin

Figure 13 shows the leading rooms or areas of origin for fires and deaths in 1987 [68]. The most common area to have fires is the kitchen, most obviously those associated with cooking. The second most common area is the chimney; not surprising since chimney fires are a leading cause of heating fires. The leading room of fire origin in one- and two-family homes for deaths is the lounge area.

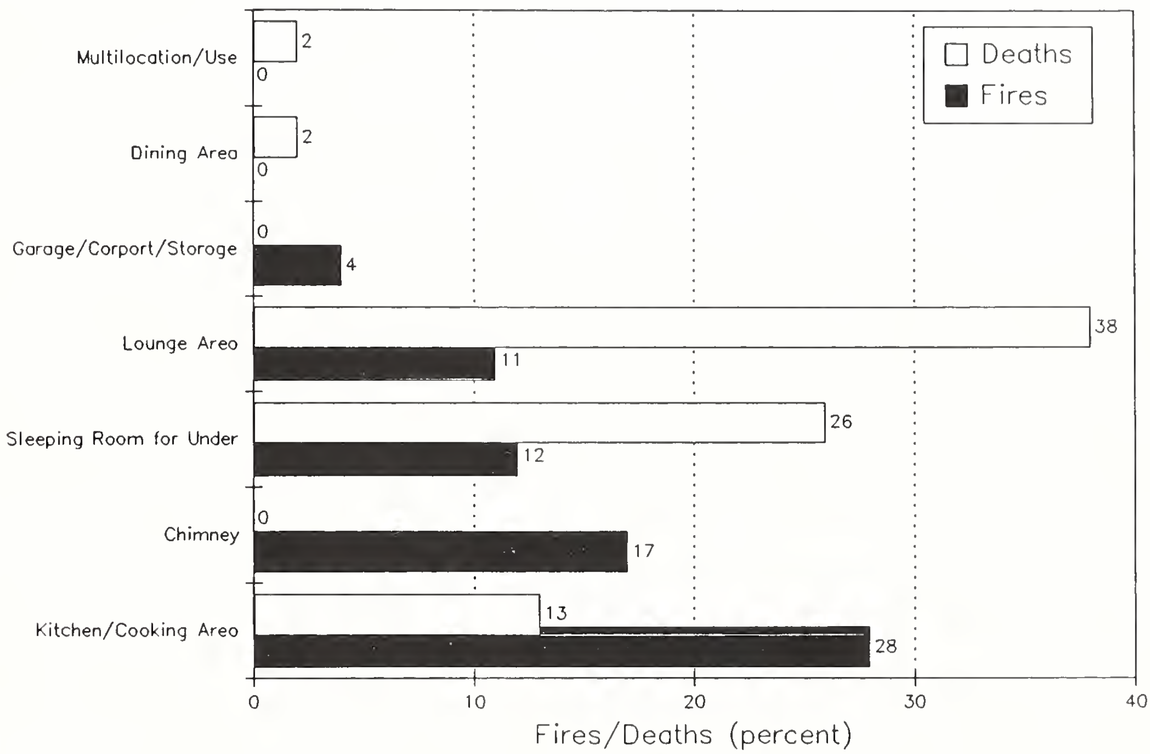


Figure 13. Leading rooms or areas of origin for fires and deaths in one- and two-family dwellings in 1987.

4.7 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. Although this is limited to the cases where the product is either the first material ignited or the product is equipment involved in ignition, it still provides insight into product involvement in fires.

Table 12 through Table 14 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 [77]. 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 these tables 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: ignition source (the NFIRS "form of heat of ignition"), equipment involved, and area of fire origin.

Table 12. Upholstered furniture fires in one- and two-family dwellings with unknowns distributed

Upholstered Furniture Fires	Percentage of Incidents	Percentage of Deaths	Percentage of Injuries	Percentage of Loss
Ignition Source				
Smoking Materials	60%	82%	66%	65%
(Cigarettes)	(55)	(70)	(57)	(60)
Open Flames	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-Fired 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: 1980-1982 NFIRS.

Table 13. Mattress and pillow fire in one and two-family dwellings with unknowns distributed

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

Numbers in () are percent of the total for a subclass. Totals may not add to 100% due to rounding errors.

Source: 1980-1982 NFIRS.

Table 14. Bedding fires in one- and two-family dwellings with unknowns distributed

Bedding Fires	Percentage of Incidents	Percentage of Deaths	Percentage of Injuries	Percentage of Loss
Ignition Source				
Smoking Materials	26%	61%	31%	25%
(Cigarettes)	(24)	(54)	(29)	(23)
Open Flames	33	21	33	32
(Matches and Lighters)	(27)	(16)	(28)	(25)
Electrical Equipment Arcing	19	3	16	20
Hot Objects	18	12	14	19
Fuel-Fired Objects	3	1	3	2
Other Known	2	0	3	2
Equipment Involved				
None	57	84	65	60
Heating Systems	9	9	11	9
Electrical Distribution Equipment	11	2	7	10
Appliances	21	2	15	20
Other Known	2	2	2	1
Area of Origin				
Living Room	4	10	6	3
Bedroom	85	88	90	86
Storage Areas	3	0	1	3
Other Known	8	2	3	6

Numbers in () are percent of the total for a subclass. Totals may not add to 100% due to rounding errors.

Source: 1980-1982 NFIRS.

Table 15. Curtain and drapery fires in one-and two-family dwellings with unknowns distributed

Curtain and Drapery Fires	Percentage of Incidents	Percentage of Deaths	Percentage of Injuries	Percentage of Loss
Ignition Source				
Smoking Materials	6%	9	4%	5%
(Cigarettes)	(4)	(9)	(2)	(4)
Open Flames	39	41	50	28
(Matches and Lighters)	(24)	(5)	(25)	(17)
Electrical Equipment Arcing	24	32	21	34
Hot Objects	17	9	15	15
Fuel-Fired Objects	9	9	9	13
Other Known	7	0	2	4
Equipment Involved				
None	50	50	50	39
Heating Systems	9	14	7	16
Electrical Distribution Equipment	17	8	17	22
Appliances	8	14	9	12
Cooking Equipment	13	14	14	7
Other Known	3	0	2	5
Area of Origin				
Living Room	26	48	38	40
Bedroom	33	24	30	31
Kitchen	20	15	21	11
Bathroom	5	0	3	5
Dining Room	4	5	1	3
Structural Area	3	0	1	3
Other Known	8	2	3	6

Numbers in () are percent of the total for a subclass. Totals may not add to 100% due to rounding errors.

Source: 1980-1982 NFIRS.

5 Calculational Procedures

5.1 Determining the Rate of Heat Release

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., [78], [79]. 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 [80], 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 [81] was developed at NIST, and a device on similar principles for industrial commodities was constructed at the Factory Mutual Research Corporation [82]. Several other units have recently been installed at laboratories in the United States and in Europe.

5.1.1 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 [83]. 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 [83] 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 [84] 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.

5.1.2 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 [83], and more details have been published by Lee [85]. 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.

5.1.2.1 Estimating Method for Upholstered Furniture

A method for determining the full-scale heat release rates of upholstered furniture has been developed [86], [87]. 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 (Figure 14). 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 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 [88], [89].

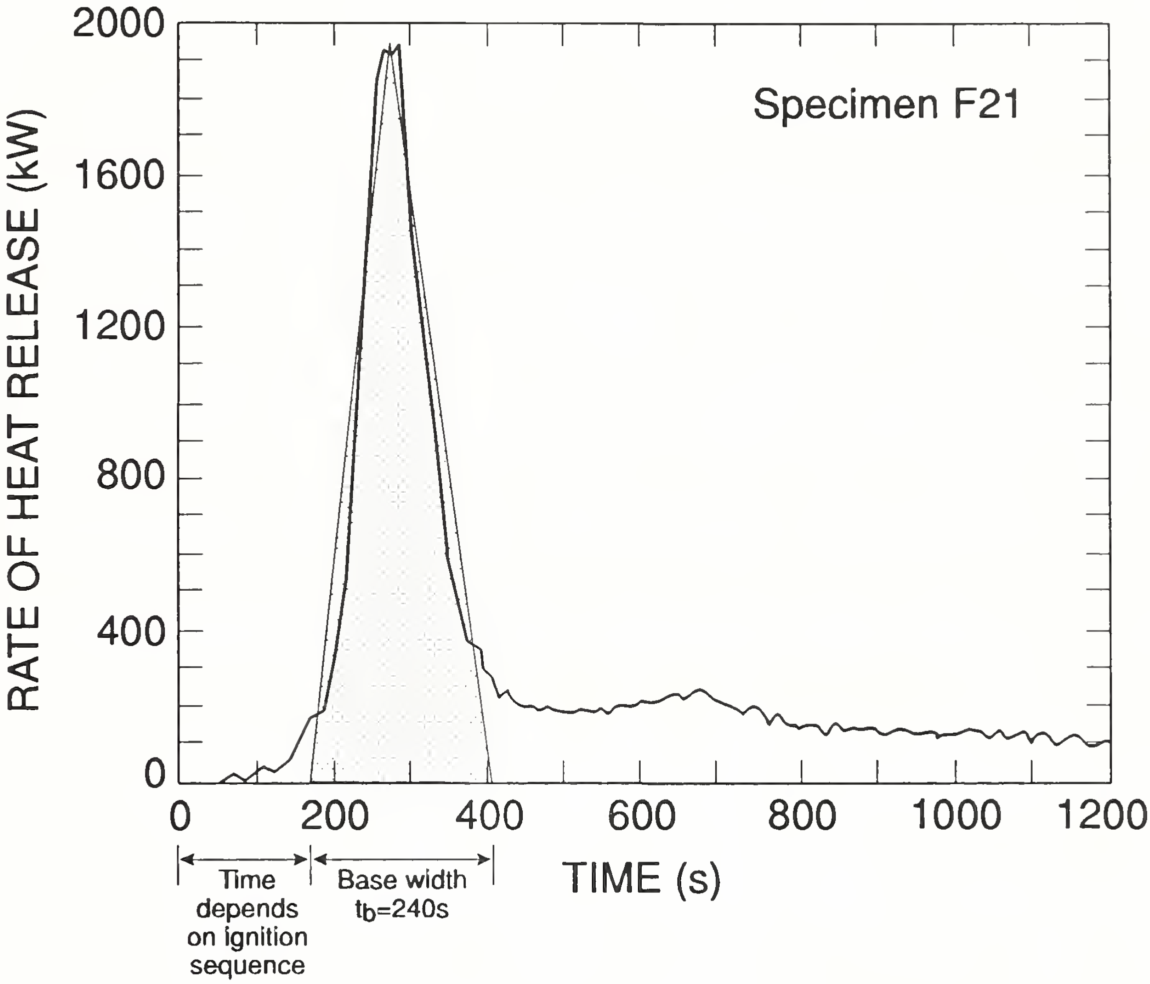


Figure 14. Approximation of the rate of heat release for an upholstered chair by a triangular shape.

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:

$$\dot{q}_{fs} = 0.63 \left(\dot{q}''_{bs}\right) \text{(mass factor) (frame factor) (style factor)} \qquad (1)$$

where $\dot{q}''_{bs}$ is the rate of heat release (kW/m^2) in the bench scale test; (mass factor) is the combustible mass (kg); (frame factor) is 1.66 for non-combustible, 0.58 for melting plastic, 0.30 for wood, and 0.18 for charring plastic; and (style factor) is 1.0 for plain, primarily rectilinear construction, 1.5 for ornate, convolute shapes, and intermediate values for intermediate shapes. Table 16 summarizes the design factors. The constant 0.63 has units m^2/kg. The bench-scale data are obtained from the Cone Calorimeter with radiant heating at 25 kW/m^2 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 [87].

Table 16. Design constants for estimating full-scale heat release rate for upholstered furniture

	(mass factor)	(frame factor)	(style factor)	(fabric factor)	(padding factor)
non-combustible melting plastic wood charring plastic	combustible mass in kg	1.66 0.58 0.30 0.18			
plain ornate			1.0 1.5		
thermoplastics cellulosics PVC				1.0 0.4 0.25	
polyurethane cotton mixed materials neoprene					1.0 0.4 1.0 0.4

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

$$\dot{q}_{fs} = 210 \text{ (fabric factor) (padding factor) (mass factor) (frame factor) (style factor)} \qquad (2)$$

where (fabric factor) is 1.0 for thermoplastic fabrics (fabrics such as polyolefin, which melt prior to burning), 0.4 for cellulosic fabrics (e.g., cotton, rayon), 0.25 for PVC or polyurethane film type coverings; and (padding factor) is 1.0 for polyurethane foam or latex foam, 0.4 for cotton batting, 1.0 for mixed materials (i.e., both polyurethane or latex foam and cotton batting), and 0.4 for neoprene foam. Table 16 summarizes the design factors. The constant 210 has units kW/kg.

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

$$t_b = \frac{C_e m \Delta h_c}{\dot{q}_{fs}} \tag{3}$$

where C_e is 1.3 for wood frames and 1.8 for metal frames and plastic frames, m is the combustible mass of item (kg), Δh_c is the 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 [87].

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 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 [87] 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_e 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.

5.1.2.2 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 [87] and are shown in Figure 15. 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_e = 1.8, since a wood frame is not involved in mattress construction.

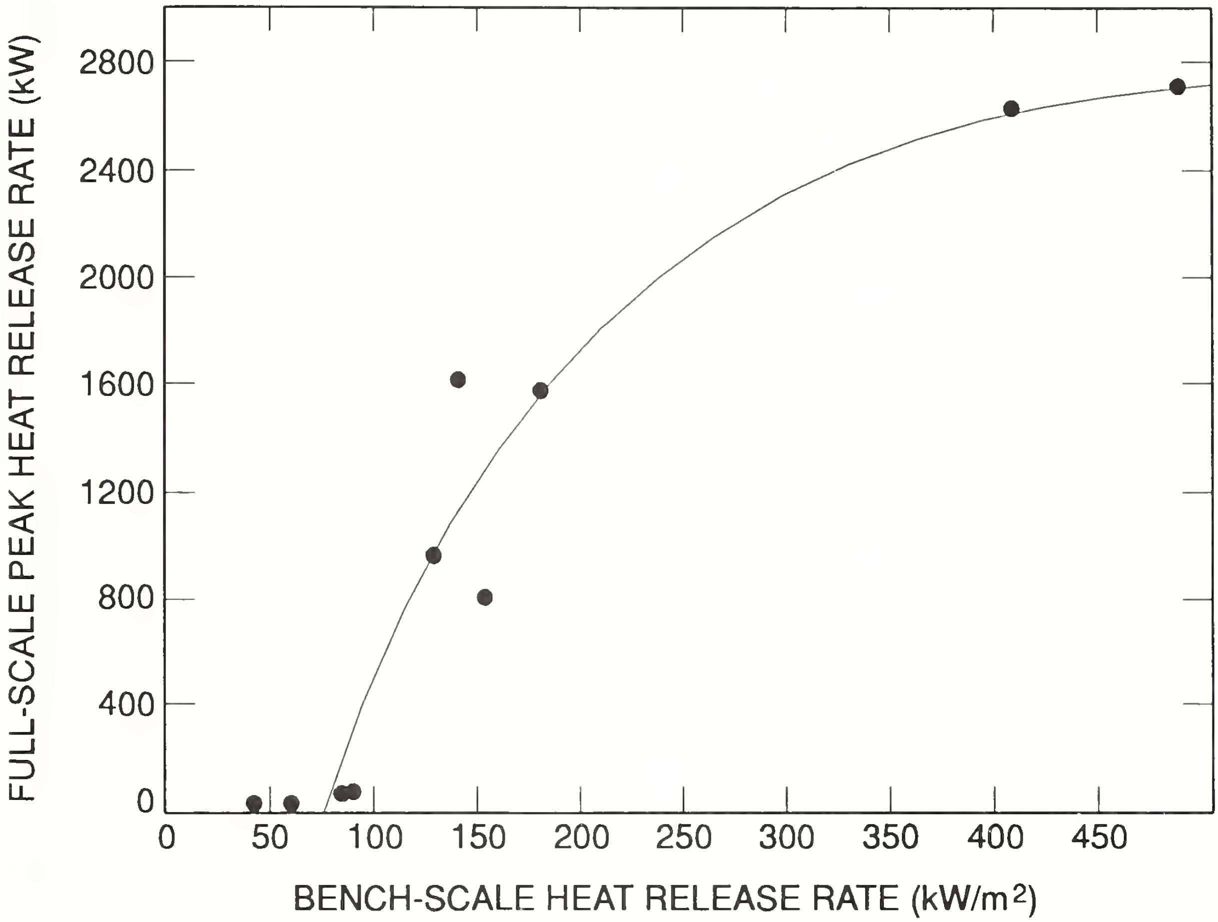


Figure 15. Correlation between bench-scale rate of heat release measurements for mattresses and peak full-scale rates of heat release.

5.1.2.3 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 [90]. 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 $\dot{q}_{fs}$ after flashover. 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

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

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

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

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 [91] 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.

5.1.2.4 Estimating Method for General Combustibles

For most combustibles, neither estimating rules, such as developed above, nor detailed full-scale test results [83] 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:

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

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 [90] 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 [92]. 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 [92] were seen to be correlated as

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

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:

$$\dot{q}_{fs} = C_e \, \dot{q}''_{bs} \, A_t \tag{8}$$

where C_e is 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 is 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.

5.2 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 10 (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 [93], [94], and [95] 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:

$$\frac{dm_i}{dt} + \sum_i Y_{i,j}\,\dot{m}_j = f_i\,\dot{m}_{fuel\ generated} \tag{9}$$

$$\begin{pmatrix} \text{Rate of mass} \\ \text{of species } i \\ \text{changing in} \\ \text{a volume} \end{pmatrix} + \begin{pmatrix} \text{Net rate of} \\ \text{flow of species } i \\ \text{out of the volume} \end{pmatrix} = \begin{pmatrix} \text{Rate of} \\ \text{species } i \\ \text{produced in} \\ \text{a fire} \end{pmatrix}$$

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), and $Y_{i,j}$ 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

$$\phi = \frac{\dot{m}_{fuelgenerated} / \dot{m}_{O_2supplied}}{1/r_{ox}} \quad (10)$$

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 [96], [97] and Beyler [98].

5.3 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 [99] 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 16. 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

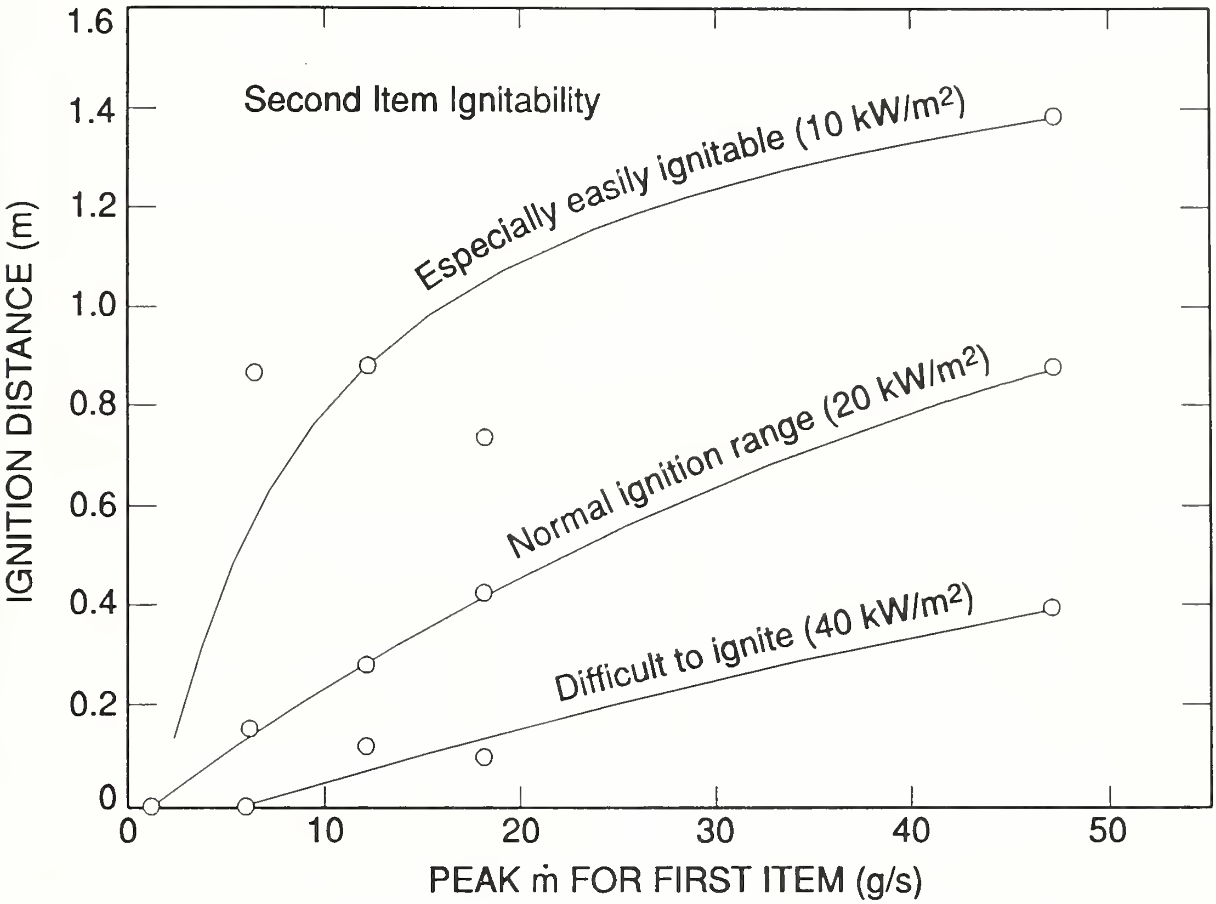


Figure 16. Relationship between peak mass loss rate and ignition distance for various ignitability levels.

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 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 predicted total flux (TARGET plus the flux from the flame estimated from Figure 16) 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 16 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 [100]. For materials tested in this apparatus, the parameters $\dot{q}_{o,ig}$, t_m, and b are tabulated for use in the following relation:

$$\frac{\dot{q}''_{o,ig}}{\dot{q}''_e} = \begin{cases} b\sqrt{t}, & t \le t_m \\ 1, & t > t_m \end{cases} \tag{11}$$

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, and 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 TARGET (note that 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 [101], 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:

$$\dot{q}''_{r,f} = \Pi\ E \tag{12}$$

$$E = \frac{\xi \dot{q} \ell D}{2} \tag{13}$$

$$\ell = 0.23\ \dot{q}^{2/5} - 1.02\ D \tag{14}$$

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

Combining eqs (12) and (13), 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:

$$\dot{q}''_{rf} = \frac{0.3\ \dot{q}\ell d}{4\pi\left(d^2+\frac{\ell^2}{2}\right)^2} \tag{15}$$

Rearranging eq (11) (for $t \leq t_m$), we obtain an expression for the ignition time of the target item:

$$t = \left(\frac{\dot{q}''_{o,ig}}{b\left(\frac{\text{TARGET}}{10}+\dot{q}''_{rf}\right)}\right)^2 \tag{16}$$

The target object will not ignite when:

$$\dot{q}''_{o,ig} < \frac{\text{TARGET}}{10}+\dot{q}''_{rf} \tag{17}$$

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 TARGET and $\dot{q}''_{rf}$ vary over time. As a rough estimate, eq (11) 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 [100], 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 may be 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 Tenability Limits

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. Section 6.6 provides a brief discussion of the accuracy of the tenability limits.

6.1 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 [102], [103], [104]; 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 [105], [106]; the filling of almost the entire room volume with flames [107]; and the dropping of oxygen levels to low values, typically 5% or less [108]. All of these phenomena occur at roughly the same time. 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.

6.2 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 h, exposures. The older literature, as it relates to fire, has been reviewed by Simms and Hinkley [109], 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 [110], [111]. 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 [112]. These experimental values seem high. To place them in context, Zapp [113] 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 [114] has recommended that for healthy, clothed, adult males, collapse due to elevated temperatures will occur when the exposure time, t, exceeds the following value:

$$t = \frac{2.46 \times 10^{10}}{T^{3.61}} \tag{18}$$

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 additional factors such as the relative humidity and the interactions of heat toxic gases. 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 [115]. Similar concurring studies are available for 85-90 °C exposures for 20 min [116]. 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" [117].

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., [118]). 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 [119] to 100 °C [120].

Purser [121] 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.

6.3 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 [122] 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 $\Omega \geq 1$.

$$\Omega = 3.1\times10^{98} \int_0^t e^{\left(\frac{-75,000}{T}\right)} \tag{19}$$

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

Hendler [123], 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 values for the thermal properties. Stoll [124], however, concluded that the thermal properties of human skin vary according to irradiance. She also determined that a more complex expression than Henriques' Ω value may be more realistic.

Stoll and coworkers [124], [125], [126] and Derksen and coworkers [127] have over the years collected a large amount of experimental data, some of which are summarized in Table 17. Table 17 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 [126] also gives data for pain thresholds, and shows that both pain and blistering can be very well represented as power laws:

$$t_{\text{Pain}} = 85(\dot{q}'')^{-1.35} \tag{20}$$

Table 17. Time required to blister or burn blackened skin

Stoll/Greene [124]		Stoll/Chianta [126]			Derkson/Monahan/DeLhery [127]		
Time (s)	Flux (kW/m²)	Time (s)	Flux (kW/m²)	Total Heat (kJ/m²)	Time (s)	Flux (kW/m²)	Total Heat (kJ/m²)
					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	13.4	66.9
		5.6	16.7	93.7			
		7.8	12.6	97.9			
8.6	12.6						
					10.0	9.2	92.0
		13.4	8.37	112.			
					20.0	6.06	121.
		20.8	6.28	131.			
24.4	6.28						
		33.8	4.18	141.			
37.2	4.18						
					50.0	3.10	155.
					100.	2.13	213.

$$t_{Burn} = 223(\dot{q}'')^{-1.35} \qquad (21)$$

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

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:

$$H_{\text{Pain}} = 26.8\ t^{0.26} \tag{22}$$

$$H_{\text{Burn}} = 54.7\ t^{0.26} \tag{23}$$

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 [128], [129], [130], [131]. By comparison, some 1943 Japanese data reported by Hasemi [132] 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 [105], [120], 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 [133] have employed a direct comparison of the time-integrated flux exposure of exposed skin to the relation in eq (23). The time at which the time-integrated flux exposure curve intersects the curve from eq (23) 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.

6.4 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 [134]. The most significant body of work in this area has been accomplished by Jin [135],

[136], 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:

$$kV = 2 \tag{24}$$

where k is the smoke extinction coefficient (m^{-1}), and V is the 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 [120], [137].

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 section 7.4 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).

6.5 Toxic Gases

Assuming 50% COHb is sufficient to kill individuals, studies on the causes of fire deaths have typically indicated that CO poisoning accounts for roughly one-half of total fatalities [138], [139]. The remaining requires additional factors (e.g., 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. However, if the COHb level is less than 50% and smoke inhalation is the cause of death, then other gases for factors are likely to be involved. 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 additioıal combustion products whose presence is suggested by the decomposition chemistry, although not ıecessarily confirmed by medical evidence. Table 18 lists, in order of increasing estimated toxicity, hose primary gases which have been suggested by various investigators as being potentially ignificant in fire situations [140-155]. Human data are in most cases unavailable, and even ›rimate data are rare. The tabulated values represent the estimated LC_{50}'s (in ppm), i.e., those :oncentrations which would be lethal to 50% of the exposed subjects for the specified time. Animal lata on the combined effects are, beginning to be evaluate, but are insufficient for a general abulation [141], [142], [143], [144], [145], [146].

Table 18. Preliminary list of primary toxic gases

Gas		Assumed LC_{50} (for humans)		Ref. No.	Reference data (species, exposure time in min)
		5 min (ppm)	30 min (ppm)		
CO_2	carbon dioxide	>150-,000	>150-,000	[140]	$LC_{50}(r^a,30)=470,000$
C_2H_4O	acetaldehyde		20,000	[147] [148]	$LC^b(m,240)=1500$ $LC_0(r,240)=4000$ LC(ham,240)=17,000 LC(r,30)=20,000 LC(r,240)=16,000
$C_2H_4O_2$	acetic acid		11,000	[147]	LC(m,60)=5620
NH_3	ammonia	20,000	9,000	[149] [150]	EC(m,5)=20,000 EC(m,30)=4400 EC(r,5)=10,000 EC(r,30)=4000
HCl	hydrogen chloride	16,000	3,700	[151] [152]	r,p LC(r,5)=40,989
CO	carbon monoxide		3,000	[140] [153]	LC(r,30)=4600 LC(h,30)=3000
HBr	hydrogen bromide		3,000	[147]	LC(m,60)=814 LC(r,60)=2858
NO	nitric oxide	10,000	2,500	[148]	1/5 as toxic as NO_2 LC(h,1)=15,000
COS	carbonyl sulfide		2,000	[147]	LC_0(var.,35-90)=1000-1400
H_2S	hydrogen sulfide		2,000	[147] [153]	LC(m,60)=673 $LC_0(h,30)=600$ $LC_0(mam,5)=800$ LC(h,30)=2000

Table 18. Preliminary list of primary toxic gases

Gas		Assumed LC_{50} (for humans) 5 min (ppm)	Assumed LC_{50} (for humans) 30 min (ppm)	Ref. No.	Reference data (species, exposure time in min)
HF	hydrogen fluoride	10,000	2,000	[147] [152] [153]	LC(gpg,15)=4327 LC(p,60)=1774 LC_0(h,30)=50 LC(m,60)=456 LC(r,60)=1276 LC(r,5)=18,200 LC(gpg,2)=300 LC(m,5)=6247 LC(r,5)=18,200
C_3H_4N	acrylonitrile		2,000	[147]	LC(gpg,240)=576 LC(r,240)=500
COF_2	carbonyl fluoride		750	[148]	LC(r,60)=360
NO_2	nitrogen dioxide	5,000	500	[149] [150] [152]	EC(m,5)=2500 EC(m,30)=700 EC(r,5)=5000 EC(r,30)=300 LC(m,5)=831 LC(r,5)=1880
C_3H_5O	acrolein	750	300	[147] [154]	LC(m,360)=66 LC_0(p,10)=153 LC(p,5)=505 to 1025
CH_2O	formaldehyde		250	[147] [153] [148]	LC_0(r,240)=250 LC(r,30)=250 LC(r,240)=830 LC(cat,480)=700 LC(m,120)=700
SO_2	sulfur dioxide	500		[147] [153]	rodents poor; LC_0(m,300)=6000 LC(var.,5) 600 to 800
HCN	hydrogen cyanide	280	135	[65] [152] [153]	LC(r,5)=570 LC(r,30)=110 LC(r,5)=503 LC(m,5)=323 LC(h,30)=135 LC(h,5)=280
$C_9H_6O_2N_2$	toluene diisocyanate		≈ 100	[147] [153]	LC(gpg,240)=13 LC(rbt,180)=1500 LC(r,360)=600 LC(m,240)=10 LC(m,r,rbt,gpg,240)=9.7 to 13.9
$COCl_2$	phosgene	50	90	[147] [155]	rec. 50 ppm short exp. LC(h,30)=90
C_4F_8	perfluoroisobutylene	28	6	[147]	LC(r,10)=17 LC(r,5)=28

a h=human, r=rat, m=mouse, p=primate, gpg=guinea pig, rbt=rabbit, mam=mammal

b LC=concentration in ppm causing 50% of animals to die for given exposure time. Deaths could occur following exposure. EC=concentration for effect, LC_0=concentration below which no lethal effects are observed

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% [153]. 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 [154], [156]. 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 sparse and limited to the study of a few specific polymers - poly(vinyl chloride) [157], and fluoropolymers [158], [159], [160].

6.5.1 Fractional Exposure Dose (FED)

Researchers at BFRL [154], [161], Huntingdon Research Centre (UK) [121], and at the Southwest Research Institute (SwRI) [162] 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 the combined effect 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 and combined 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 and combined gas studies of Levin et al. [161]. It includes the gases CO, CO_2, and HCN, along with reduced oxygen, combining their effect in a parameter called Fractional Exposure 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. [154], and by Hartzell et al. [162] for these two gases. Simply stated then, FED is the sum of the effects of each of the gases toward the total effect on the exposed person. More recent work indicates that additivity may be too simple and synergistic and antagonistic effects also occur [141], [156].

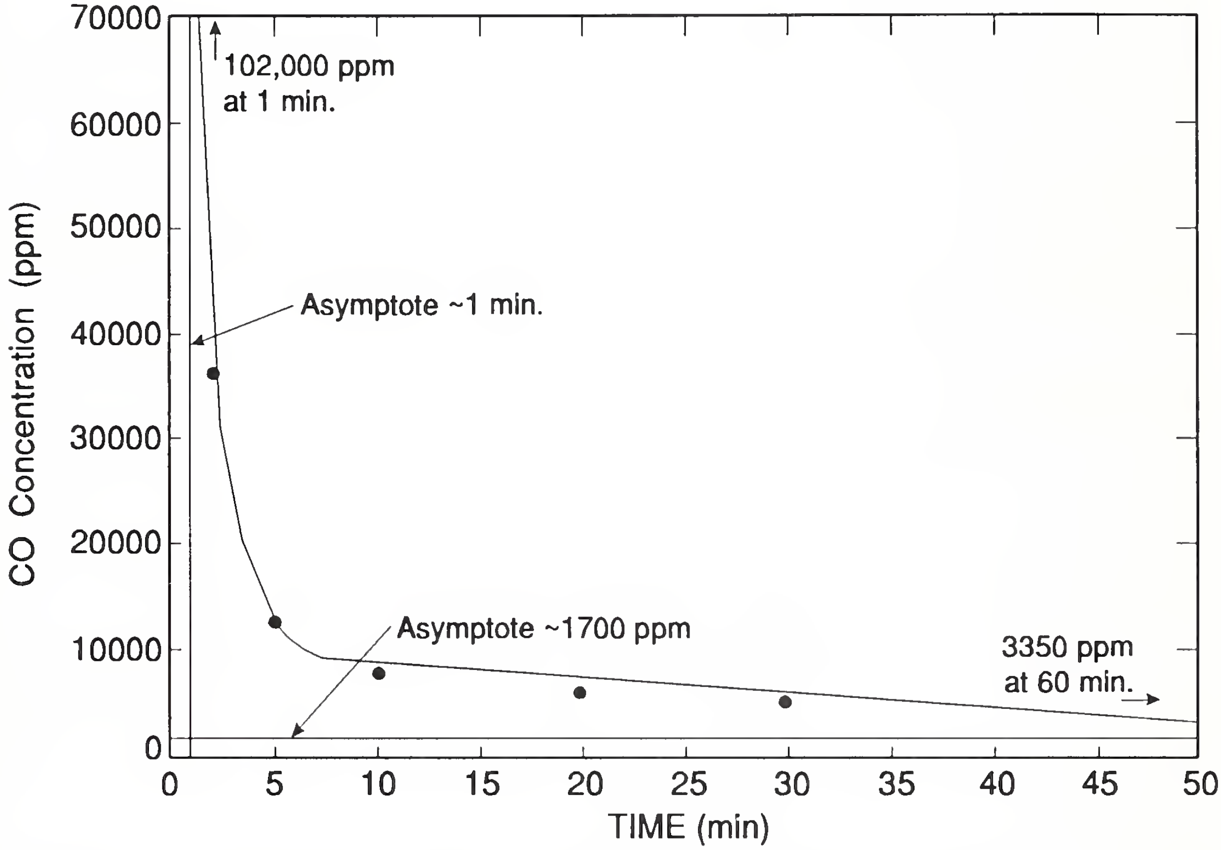


Figure 17. Carbon monoxide concentration versus time to lethality of 50% of exposed rats.

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 [141], [154]. 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 (Figure 17), 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 animals to respond to the toxic insult. 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 [154].

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:

$$\left(C_{CO}-1700\right) = 80{,}000 \qquad (25)$$

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 17, the critical dose is not constant, but rather varies with concentration. Thus, eq (25) is used within the FED calculation to determine the critical dose at the particular incremental concentration (see Figure 18).

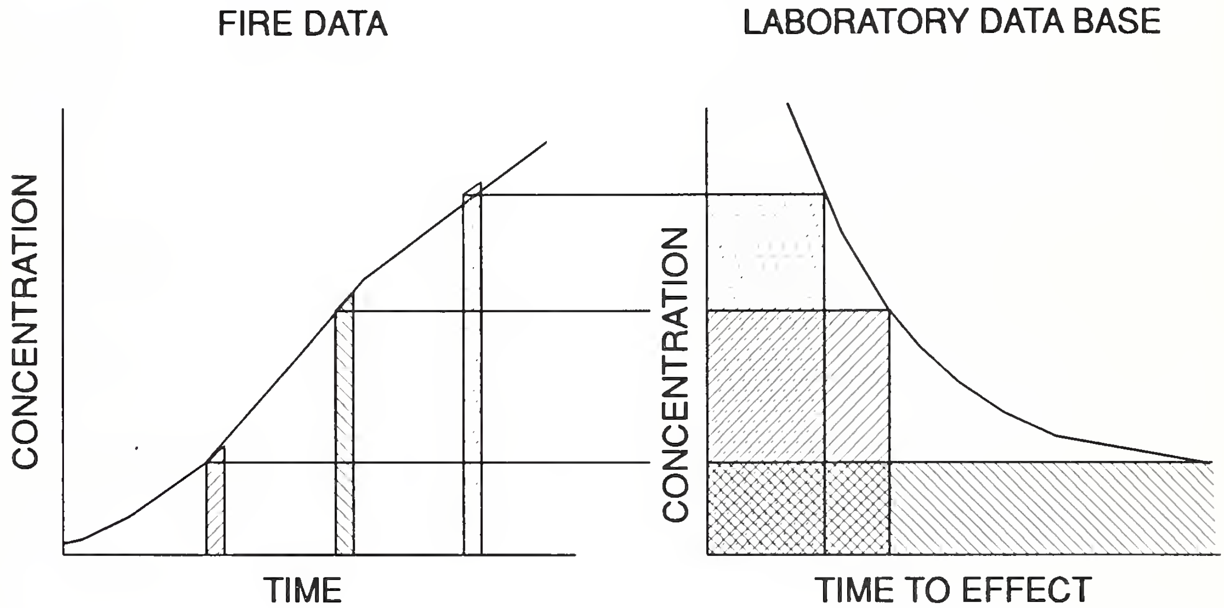
Following the work with CO, the effect of CO_2 on the observed CO toxicity was studied. The result of this work (shown in Figure 19 [140]) was the observation that the "effective toxicity" of CO increases linearly with increasing CO_2 concentration, up to a level of 5% (50000 ppm). The physiological effects of the CO_2 are to increase the respiration rate and reduce the blood pH, producing a respiratory 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:

$$\frac{100{,}000-C_{CO_2}}{100{,}000} \qquad (26)$$

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. that the effect holds for all times.

HCN and the combination of CO and HCN were similarly studied. The data on HCN [163] showed that the lethal exposure dose (time-integral of concentration) was relatively constant at a value of 3100 ppm-min for exposure times from 1 to 30 min (note that some deaths occurred in the 24 h period following exposure). Thus, this value is used in the HCN term of the FED calculation.



$$\sum \frac{\bar{C} \times \Delta T}{(Ct)_c} = \text{Fractional Dose to Produce Effect}$$

Effect Occurs at Time t When Σ Fractional Doses = 1

Figure 18. Fractional effective dose.

The data on CO and HCN combinations showed that the effects are directly additive [154]. This is not surprising since they both act to reduce the utilization of the oxygen by 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.

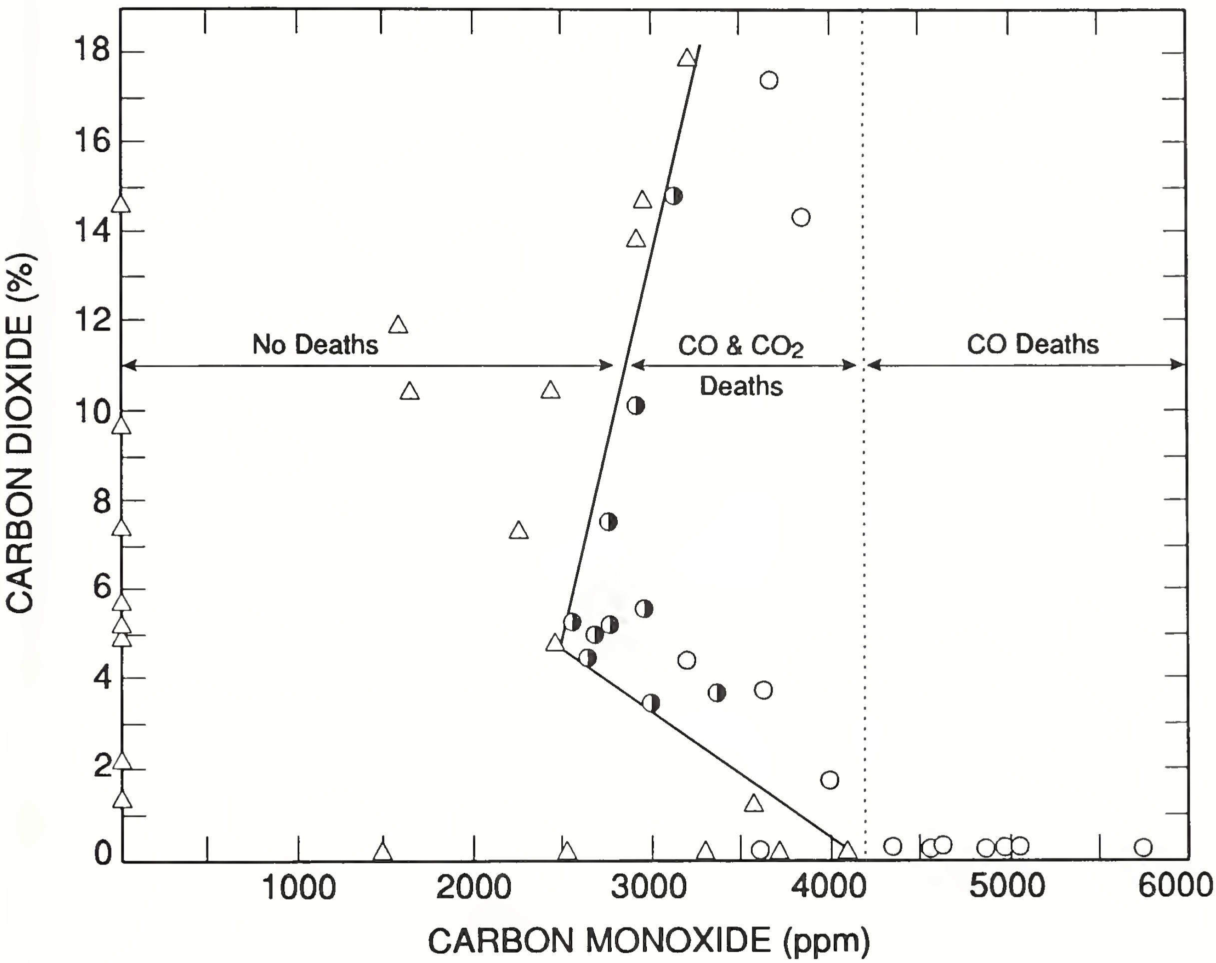


Figure 19. Combination of carbon monoxide and carbon dioxide which is lethal to 50% of exposed rats.

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

$$FED = \sum \left(\frac{\overline{C_{CO}}\Delta t}{\left(\frac{\overline{C_{CO}}\ 80{,}000}{\overline{C_{CO}}-1{,}700}\right)\left(\frac{100{,}000-\overline{C_{CO_2}}}{100{,}000}\right)} + \frac{\overline{C_{HCN}}\Delta t}{3{,}100} + \frac{9.2-\overline{C_{O_2}}\Delta t}{15.4} \right) \tag{27}$$

where $\overline{C_{CO}}$, $\overline{C_{CO_2}}$, $\overline{C_{O_2}}$, 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 (27) is implemented such that negative values of any term do not result in a negative FED.

The predictive capability of eq (27) was tested against the material toxicity data included in the cup furnace toxicity screening protocol report [164]. It should be noted that the oxygen term was not tested since the test protocol is designed to maintain the oxygen at close to its ambient value. First, the average gas concentration data provided in the report was used - a time weighted average value. 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 of pure and mixed gases [154], which successfully predicts the results of the same 16 materials plus flaming red oak. The reason for eq (27) falling 30% short on red oak is currently unclear.

Next, the exposure time-independent nature of eq (27) was tested against the data reported by Hartzell et al., for two ramped exposures to CO only [165]. 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.

Since the gas data reported in the NBS report were time-weighted averages over the 30 min exposure time while, in fact, they increased asymptotically 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 Table 19 to Table 21. It should be noted that in the original work [154], the uncertainty in the FED values range from no deaths observed at FED values below 0.9 to death of all animals exposed at FED values greater than 1.3.

Thus, a correct prediction of deaths is assumed if the FED value is greater than 0.9 and deaths were observed in the experiment.

Table 19. Predictions for average gas concentrations

Material	Mode	Observed Deaths	Predicted FED at 30 min		Predicted Results Correctly	
			Levin	Bukowski	Levin	Bukowski
Acrylonitrile butadiene styrene (ABS)	F NF	W P	1.21 1.62	1.3 1.3	Y Y	Y Y
Douglas fir (DFIR)	F NF	W W,P	1.19 0.67	1.0 0.4	Y N	Y N
Flexible polyurethane (FPU)	F NF	W P	0.53 0.29	--[b] --	N N	N N
Fire retandant flexible polyurethane (FPU/FR)	F NF	W,P none	0.95,1.17[a] 0.1	0.9 --	Y/Y Y	Y Y
Modacrylic (MOD)	F NF	W,P W	1.22,1.73 1.67	1.4 2.1	Y Y	Y Y
Poly(phenyl-sulfone) (PPS)	F NF	W,P W	1.04 1.10	0.9 1.1	Y Y	Y Y
Polystyrene (PSTY)	F NF	W none	0.37 0.02	-- --	N Y	N Y
Poly(vinyl chloride) (PVC)	F NF	P P	0.28 0.15	-- --	N N	N N
Poly(vinyl chloride) with zinc ferrocyanide (PVCZ)	F NF	W,P P	1.26,1.57 1.66	1.4 1.4	Y Y	Y Y
Red oak (REDO)	F NF	W P	1.03 0.61	0.7 0.3	Y N	N N
Rigid polyurethane (RPV)	F NF	W none	1.27 0.72,0.84	1.4 0.6	Y Y	Y Y
Wool	F NF	W,P W,P	1.03,1.04 1.73,2.42	1.0 2.1	Y Y	Y Y

a left value is for within-exposure deaths only and right value includes post-exposure deaths.
b cannot be predicted since the average CO concentration is below threshold values in eq (27).

Table 20. Prediction of ramped CO exposure

Linear ramp	Observed Lethality Time (min)	Predicted Lethality Time (min)
to 9,500 ppm in 10 min	22.8 ± 3.5	16.5
to 7500 ppm in 30 min	43.9 ± 13.9	33.3

Table 21. Prediction from time-varying gas concentrations

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

6.5.2 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 g-min/m^3. A value of 900 g-min/m^3 has been proposed as a reference value for the lethality of smoke from most common building materials [164]. 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 [166]. The concept of *Ct* evolved from the NBS Toxicity Screening Protocol [164] 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:

$$Ct \equiv \int_0^t Y\rho dt \qquad (28)$$

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 [167].

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 (Figure 20 [168]). 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).

6.5.3 Incapacitation

The work of Purser [121] 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 2/3 of the lethal values of FED and Ct be used as incapacitation indicators [169] 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.

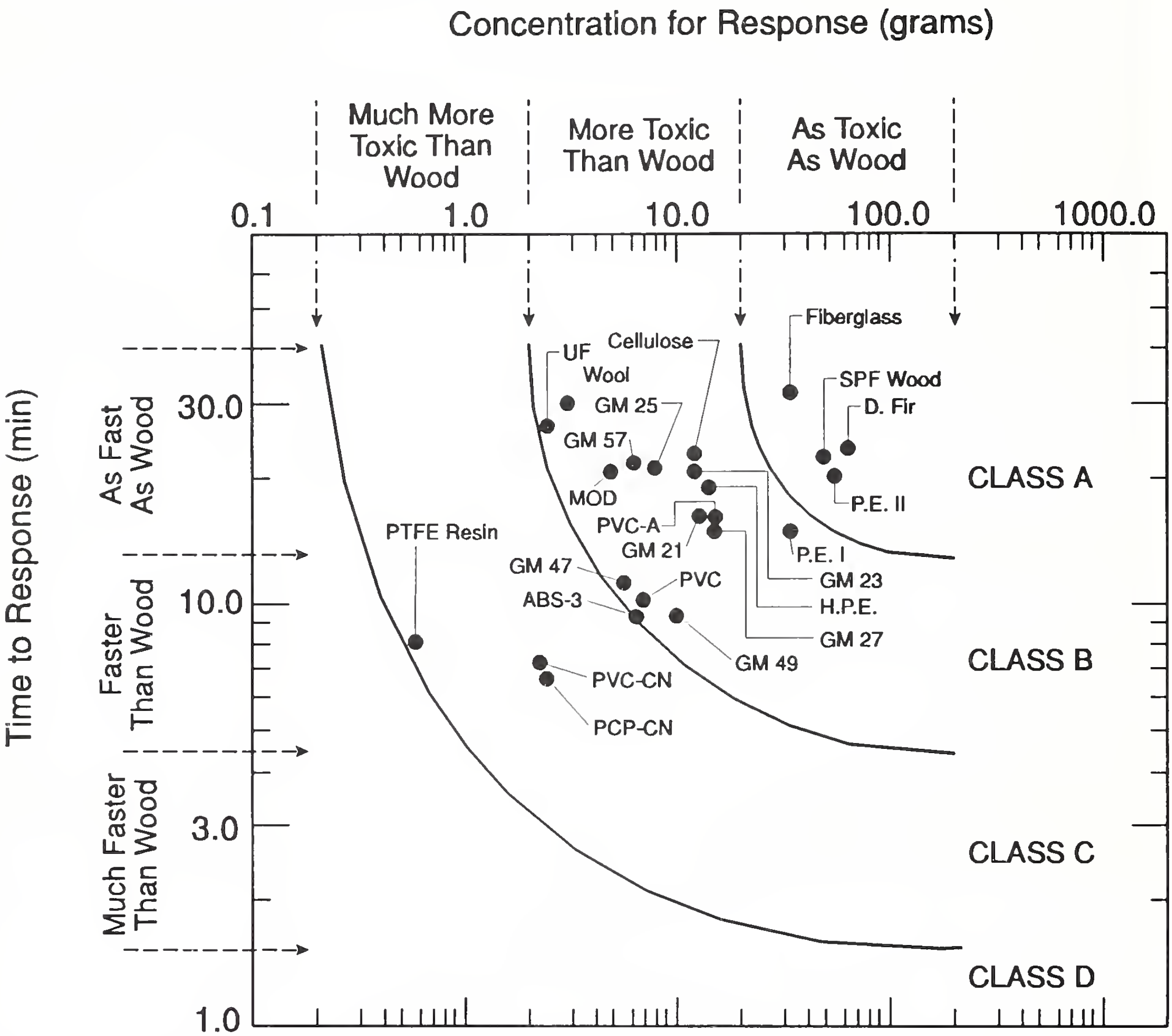


Figure 20. Example of a toxicity grading scheme by order of magnitude of observed effect.

6.6 Tenability Limits Used in HAZARD I

This section has provided a background of the development of tenability limits for HAZARD I. Although there certainly are no rigid rules for appropriate limits in all cases, the following table presents tenability criteria used as defaults in the TENAB module of HAZARDI. Of course, these can be modified as appropriate for specific cases.

These limits should be considered approximate. In a study comparing bench-scale test results to real-scale fires, several methods were compared to real-scale tests for similarity of gas yields, of primary gases, and on types of death [170]. As a result of these studies, a factor-of-3 agreement between bench-scale and real-scale results was established as both useful and practical. In another study [59], changing the relative toxicity of materials by an order of magnitude had minimal impact on the predicted hazard for some cases. For predicting hazard, the relative toxicity of a material may play a smaller role than the rate of heat release [171].

Table 22. Summary of default tenability criteria used in HAZARD I

Tenability Criteria	Incapacitation	Death
Temperature	65°C	100°C
	1.0 (Purser convective heat [121])	
Heat Flux	Equation (22)	Equation (23)
Fractional exposure Dose	Equation (27), FED=0.5	Equation (27), FED=1.0
	1.0 (Purser, FED due to gases [121])	
	1.0 (Purser, FED due to CO_2 [121])	
Species Ct	450 ppm-min	900 ppm-min

7 Program Modules

This chapter presents 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.

7.1 MLTFUEL

7.1.1 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.

7.1.2 Theory

The calculations performed by the program are based on conservation of energy and mass. That is, the energy, or the mass of any species, 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 species), 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 [172], [173], Beyler [174], and Morehart, Zukowski, and Kubota [175].

7.1.3 Limitations

The program assumes that the burning characteristics of multiple items burning together are equal to the combination of 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 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 a correspondingly low estimate of species concentrations).

7.2 DETACT

7.2.1 Purpose

DETACT is a program to predict the response of thermal detectors to fires of arbitrary heat release rate [176]. 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 NFPA 72E should have no problem with this program, as the procedures are similar.

7.2.2 Theory

Studies of the response of heat detectors to fire driven flows under unconfined ceilings have been conducted since the early 1970's [177], [178], [179], [180]. 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 Association (NFPA) as an alternate design method in the standard NFPA 72E, 1984 [181].

Although the NFPA heat detector spacing calculation is a well documented method, it is not in a convenient form for use 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.

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 applications 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 heat release rate history. The only restriction is that the heat 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 m/s. 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 has been studied [182], 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 [183].

7.2.2.1 Detector Response to t^2 Fires

Appendix C of the NFPA 72E standard [181], "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 specified heat 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 [179], [180].

Beyler [184] 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 heat release rate proportionally with the square of time from ignition. This class of fire is commonly referred to as a "t^2-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, which is based on a convective heat detector and sprinkler thermal sensing elements, is discussed by Heskestad and Smith [185], and Evans [186]. The first order differential equation that describes the rate of temperature increase of the sensing element is [182]:

$$\frac{DT_s}{dt} = \frac{\sqrt{U}}{RTI}(T-T_s) \tag{29}$$

The notation for all equations is given in the notation section. The value of RTI (Response Time Index), a measure of the thermal response of the detector, is determined by testing [184]. Values of the time-dependent gas temperature and velocity are obtained from the following correlations [184].

$$\Delta T_2^* = 0 \qquad t_2^* \le (t_2^*)_f$$

$$\Delta T_2^* = \left(\frac{t_2^* - 0.954\left(1+\frac{r}{H}\right)}{0.188+0.313\frac{r}{H}} \right)^{4/3} \qquad t_2^* > (t_2^*)_f \tag{30}$$

$$(t_2^*)_f = 0.954\left(1+\frac{r}{H}\right)$$

$$U_2^* = 0.59\left(\frac{r}{H}\right)^{-0.063}\sqrt{\Delta T_2^*}$$

where

$$
\begin{aligned}
U_2^* &= \frac{U}{(A\alpha H)^{1/5}} \\
\Delta T_2^* &= \frac{\Delta T}{A^{2/5}\frac{T_\infty}{g}\alpha^{2/5}H^{-3/5}} \\
t_2^* &= \frac{t}{A^{-1/5}\alpha^{-1/5}H^{4/5}} \\
A &= \frac{g}{c_{pt_\infty}\rho_\infty} \\
\Delta T &= T - T_\infty \\
\alpha &= \frac{t^2}{Q}
\end{aligned}
\tag{31}
$$

The solutions to eq (29) 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 [184] as follows:

$$
\Delta T_s = \frac{\Delta T}{\Delta T_2^*}\Delta T_2^*\left(1 - \frac{1-e^{-Y}}{Y}\right) \tag{32}
$$

$$
\frac{dT_s}{dt} = \frac{4}{3}\frac{\frac{\Delta T}{\Delta T_2^*}(\Delta T_2^*)^{1/4}}{\frac{t}{t_2^*}\left(0.188 + 0.313\frac{r}{H}\right)} \tag{33}
$$

where

$$T = \frac{3}{4}\sqrt{\frac{U}{U_2^*}\sqrt{\frac{U_2^*}{\Delta T_2^*}\frac{\Delta T_2^*}{RTI}\frac{t}{t_2^*}\left(0.188+0.313\frac{r}{H}\right)}} \tag{34}$$

assuming that $\Delta T_s = 0$ initially. T and U in eq (29) are obtained from the correlations in eq (30) for ΔT_2 and U_2 respectively. Equations (32) and (33) 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 heat release rate at that time.

The response time of 11 randomly selected combinations of fires and detectors were calculated using the DETACT-T2 Code and results compared to table values in Appendix C of NFPA 72E [181]. Of these cases the greatest deviation from experimentally determined values was 7.5% and the least was 0.17%.

7.2.2.2 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 an heat 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 [177]. Recast into metric form they are:

$$\begin{aligned} \Delta T &= 16.9\frac{Q^{2/3}}{H^{5/3}} & \frac{r}{H} &< 0.18 \\ U &= 0.95\left(\frac{Q}{H}\right)^{1/3} & \frac{r}{H} &< 0.15 \\ \Delta T &= 5.38\frac{(Q/r)^{2/3}}{H} & \frac{r}{H} &> 0.18 \\ U &= 0.2\frac{Q^{1/3}H^{1/2}}{r^{5/6}} & \frac{r}{H} &> 0.15 \end{aligned} \qquad (35)$$

where the metric units are T(°C), U(m/s), Q(kW), r(m), H(m).

7.2.2.3 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:

$$\rho c_p \frac{d\Delta T}{dt} - k\nabla^2 \Delta T = \dot{Q}''' \tag{36}$$

$$\rho \frac{dY_s}{Dt} - \rho D \nabla^2 Y_s = \dot{m}''' \tag{37}$$

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, *OD*, [179]

$$OD = \frac{\log \frac{I_o}{I}}{L} \tag{38}$$

By testing, Seader and Einhorn [187] 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:

$$OD = 3330\ C_s \tag{39}$$

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 eq (39) as:

$$\frac{\Delta T}{Y_s} = \frac{\rho \Delta T}{C_s} = \frac{3330 \rho \Delta T}{OD} \tag{40}$$

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

$$\frac{3330 \rho \Delta T}{OD} = \frac{\dot{Q}}{c_p \dot{m}_s} \tag{41}$$

or

$$\frac{OD}{\Delta T} = \frac{3330 \rho c_p \dot{m}_s}{\dot{Q}} \tag{42}$$

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 [188]
$\dot{m}_s$ = 0.017 kg smoke/kg fuel consumed per unit time [188]
air c_p = 1 kJ/kg°C
air ρ = 1.165 kh/m^3 at 30 °C

From eq (42), $OD/\Delta T = 8.68 \times 10^{-3}$ (m°C)$^{-1}$.

Heskestad and Delichatsios [179] have reported representative optical density per meter for smoke detector alarm and corresponding temperature rise in the gas flow. For wood crib fires, the ratio of these values was $OD/\Delta T = 1.2 \times 10^{-3}$ (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 [179] report that an ionization detector will alarm in response to a wood fire at OD =0.016 1/m.

Using the $OD/\Delta T$ value for wood of 1.2×10^{-3} (m°C)$^{-1}$ the corresponding change in gas temperature would be 13 °C, (0.016/1.2 x 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 ratio $OD/\Delta T$ are obtained for burning materials in a laboratory scale apparatus developed by Tewarson [183]. Values for a large number of plastics and wood under many environmental conditions are given in ref [183].

7.2.2.4 Nomenclature used in DETACT

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 (38)]
$\dot{Q}$	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

7.2.3 Limitations

A 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 be used for smoldering. Other limitations are discussed in reference [176].

7.3 FAST

7.3.1 Purpose

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. FAST [189] is such a program used 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. This section provides an overview of the assumptions and limitations of FAST as well as an in-depth presentation of the fundamental equations and the way in which they are implemented in the module. Values of internal constants and coefficients, and references to the literature sources from which these all come are included.

The physical basis of zone models, their limitations, and development of the predictive equations are described elsewhere [190] and are only summarized here. The intent of this section is to provide a complete description of the way the model is structured. In particular the relationship between the equations and the numerical implementation of the equations is laid out.

7.3.2 Theoretical Overview

FAST is a member of a class of models referred to as zone or control volume models. This means that each room is divided into a small number 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. In FAST, each room is divided into two layers. Since these layers represent the upper and lower parts of the room, 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 enthalpy and mass over small increments of time. These equations are derived from the conservation equations for enthalpy, mass, and momentum, and the ideal gas law. 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 error will be highlighted in the following discussion.

7.3.2.1 The Fire

The fire is a source of fuel which is released at a rate specified by the user. This fuel is converted into enthalpy (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 fire, or for a constrained 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, 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 is consumed or gets to the outside.

This version of FAST does not predict fire growth. Rather, the user must input a pyrolysis rate to define the fire history. The similarity of that input to the real fire problem of interest will determine the accuracy of the resulting calculation. The user must account for any interactions between the fire and the pyrolysis rate.

7.3.2.2 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 enthalpy and mass 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 to determine the amount of mass moved between layers by the plume.

Two sources exist for moving energy and mass between the layers within and between rooms. Within the room, the fire plume provides one source. 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 flow 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.

While experiments show that there is very little mixing between the layers at their 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 phenomena which are not included because the theories are still under development. 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 the door. Such effects are not included in the model.

7.3.2.3 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 upper layer 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. 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 enthalpy between the layers.

7.3.2.4 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 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. These effects are not modeled.

Radiative transfer occurs between the fire and the gas 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 from unity. 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.

7.3.2.5 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 compute each species concentration with an independent yield fraction, FAST maintains a carbon-hydrogen-oxygen 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. The second is the portion in the upper layer, also in the room of origin. The third is in the vent flow which entrains air from a lower layer into an upper layer in an adjacent compartment.

7.3.3 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 and pressure 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 or air conditioning ducts. 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 (typically called the "upper layer" and the "lower layer"). 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 [191]. The general layout of the zones and the form of the conservation equations is discussed elsewhere [190] 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.

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.

7.3.4 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 shown in 7.3.5.9, the predictive equations can be written [190]:

$$\frac{dP}{dt} = \frac{\dot{s}}{(\beta-1)V} \tag{43}$$

$$\frac{dT_u}{dt} = \frac{1}{\beta}\left(\frac{T_u}{PV_u}\right)\left(\dot{E}_u + \frac{V_u}{(\beta-1)V}\dot{s}\right) \tag{44}$$

$$\frac{dT_l}{dt} = \frac{1}{\beta}\left(\frac{T_l}{PV_l}\right)\left(\dot{E}_l + \frac{V_l}{(\beta-1)V}\dot{s}\right) \tag{45}$$

$$\frac{dV_u}{dt} = \frac{1}{P\beta}\left(c_p\dot{m}_u T_u + \dot{E}_u - \frac{V_u}{V}\dot{s}\right) \tag{46}$$

where

$$\dot{s} = c_p\dot{m}_u T_u + c_p\dot{m}_l T_l + \dot{E}_u + \dot{E}_l \tag{47}$$

and

$$\beta = \frac{c_p}{R} = \frac{\gamma}{\gamma - 1} \tag{48}$$

with the assumption for the pressure

$$P_R = P_u = P_l = \rho_u R T_u = \rho_l R T_l \tag{49}$$

and the constraint that the total volume of a compartment is fixed

$$V = V_u + V_l \ .$$

There is a set of these equations for each compartment.

7.3.5 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.

7.3.5.1 Source Terms: Radiation

Objects such as walls, gases and fires radiate as well as absorb radiation. Each object has its own properties, such as temperature, emissivity. 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 [192]. 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. 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 choosing 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^{2}K^4
α = Absorption coefficient of the upper gas layer, m^{-1}
$\epsilon_{u/l}$ = Emissivity of the upper/lower walls
ϵ_g = Emissivity of the upper gas layer

Using the formalism of Siegal and Howell [192] we have

$$D = \left[1-(1-\epsilon u)(1-\epsilon_g)F_{uu}\right]\left[1-(1-\epsilon_l)F_{ll}\right] - \left[(1-\epsilon_u)(1-\epsilon_l)(1-\epsilon_g)^2 F_{ul}F_{lu}\right] \qquad (51)$$

$$\begin{aligned} \Pi_u = {} & \left[1-(1-\epsilon g)F_{uu}\right]\left[1-(1-\epsilon_l)F_{ll}\right]\left[(1-\epsilon_l)(1-\epsilon_g)^2 F_{ul}F_{lu}\right]\sigma T_{uw}^4 \\ & - (1-\epsilon_g)F_{ul}\epsilon_l \sigma T_{lw}^4 \\ & - (1+(1-\epsilon_l)[\,(1-\epsilon_g)F_{ul}F_{lu}-F_{ll}]\,)\epsilon_g \sigma T_g^4 \end{aligned} \qquad (52)$$

$$\Pi_l = \Big(\big[1-(1-\epsilon_u)(1-\epsilon g)F_{uu}\big](1-F_{ll})-(1-\epsilon_u)(1-\epsilon_g)^2 F_{ul}F_{lu}\Big)\sigma T_{lw}^4 \\ -(1-\epsilon_g)F_{lu}\epsilon_u\sigma T_{uw}^4 \\ -\Big(\big[1-(1-\epsilon_u)(1-\epsilon_g)F_{uu}\big]F_{lu}+(1-\epsilon_u)(1-\epsilon_g)F_{lu}\Big)\epsilon_g\sigma T_g^4 \tag{53}$$

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

$$\dot{Q}_{(upper)} = \frac{A_u \epsilon_u \Pi_u}{D} \tag{54}$$

$$\dot{Q}_{(lower)} = \frac{A_l \epsilon_l \Pi_l}{D} \ . \tag{55}$$

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 $\varepsilon_u = \varepsilon_l = 1$ we have a simple expression for the energy absorbed by the gas layer, namely

$$\dot{Q}_g = -\sigma\Big(\epsilon_g T_u^4 + (1-\epsilon_g)T_{uw}^4(A_u + A_{uv}) - T_{uw}^4 A_u - \epsilon_{gT_u^4}A_d - T_l^4 A_{uv}\Big) + F_{fQ_f} \tag{56}$$

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 = $A_u + A_d$.

Note that although radiation can exit a vent, we assume no heating of a wall or object in adjacent compartments. Further, there is no attempt to account 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 overestimate the amount of radiative transfer. All of these phenomena require a much more complex radiation model.

7.3.5.2 Source Terms: Convective Heating

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 [193]. We can write the heat flux term as

$$\dot{Q}_c = h_c(T_g - T_w)A_w \tag{57}$$

where the transfer coefficient can be written as

$$h_c = \frac{\kappa}{l} C_o (Gr\ Pr)^{1/3}$$
$$Gr = \frac{g l^3 |T_g - T_w|}{\upsilon^2 T_g}$$
$$\kappa = 2.72\times10^{-4}\left(\frac{T_g+T_w}{2}\right)^{4/5} \tag{58}$$
$$\upsilon = 7.18\times10^{-10}\left(\frac{T_g+T_w}{2}\right)^{7/4}$$

and T_g and T_w are the temperatures of the gas layer and the wall respectively, A_w is the area of surfaces in contact with the zone, Pr is the Prandtl number (0.72), l is a characteristic length scale $\approx (A_w)^{1/2}$, and C_o is a coefficient which depends on orientation [193].

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, 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_o]	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. 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.

7.3.5.3 Source Terms: Plumes

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 net 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 [194] 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. [195] 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.

$$\begin{aligned}
&\text{flaming:} && \frac{\dot{m}_e}{\dot{Q}} = 0.011\left(\frac{Z}{\dot{Q}^{2/5}}\right)^{0.566} && 0.00 \le \left(\frac{Z}{\dot{Q}^{2/5}}\right) < 0.08 \\
&\text{intermittent:} && \frac{\dot{m}_e}{\dot{Q}} = 0.026\left(\frac{Z}{\dot{Q}^{2/5}}\right)^{0.909} && 0.08 \le \left(\frac{Z}{\dot{Q}^{2/5}}\right) < 0.20 \qquad (59) \\
&\text{plume:} && \frac{\dot{m}_e}{\dot{Q}} = 0.124\left(\frac{Z}{\dot{Q}^{2/5}}\right)^{1.895} && 0.20 \le \left(\frac{Z}{\dot{Q}^{2/5}}\right)
\end{aligned}$$

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.

In FAST, there is a constraint on the quantity of gas which can be entrained by a plume arising from a fire. The constraint arises from the physical fact that a plume can rise only so high for a given size of a heat source. In the earlier versions of this model (version 17 and earlier), the plume was not treated as a separate zone. Rather we assumed that the upper layer was connected immediately to the fire by the plume. The implication is that the plume is formed instantaneously and stretches from the fire to the upper layer or ceiling. Consequently, early in a fire, when the energy flux was very small and the plume length very long, the entrainment was over predicted. This resulted in the interface falling more rapidly than was seen in experiments. Also the initial temperature was too low and the rate of rise too fast, whereas the asymptotic temperature was correct. The latter occurred when these early effects were no longer important.

The correct sequence of events is for a small fire to generate a plume which does not reach the ceiling or upper layer initially. The fire entrains enough cool gas to decrease the buoyancy to the point where the plume no longer rises. When there is sufficient energy present in the plume, it will penetrate the upper layer. The effect is two-fold: first, the interface will take longer to fall and second, the rate of rise of the upper layer temperature will not be as great. To this end the following prescription has been incorporated: for a given size fire, a limit is placed on the amount of mass which can be entrained, such that no more is entrained than would allow the plume to reach the layer interface. The result is that the interface falls at about the correct rate, although it starts a little too soon, and the upper layer temperature is slightly over predicted but after the initial phase, follows the experimental data very well.

In version 18.3 (Hazard 1.0) this constraint was based on the concept following Chen and Rodi [196] that the final energy of a parcel of gas must be greater than some value in order for the gas to penetrate the inversion layer formed by the upper zone in a compartment. The form of this constraint is

$$\dot{m}_e = \min(\dot{m}_e(\text{predicted}), \frac{\dot{Q}}{(T_a+T_L)R}) \tag{60}$$

This constraint is based on large plumes in the atmosphere and assumes a certain lapse rate and inversion scenario. From recent experiments it appears to have been too conservative for the compartment scenarios with which we deal and we have incorporated the following into version 18.5, which is the model in Hazard 1.1, and later.

For a section (segment) of the plume to penetrate the inversion formed by a hot layer at T_u over a cool layer T_ℓ, the density of the gas in the plume at the point of intersection must be less than the density of the gas in the upper layer, that is $\rho_p < \rho_u$. The subscript "v"is the point at which mass is coming off the fire, "q" the state at which this same mass would be were there no cooling from the entrained gases and "p" the plume at the point at which it intersects the upper layer. The "ℓ" refers to the lower layer, and the "u" to the upper layer. The temperature rise in the plume is given by

$$(T_q - T_v)\, C_p \dot{m}_v = \dot{Q}. \tag{61}$$

From conservation of mass we have

$$\dot{m}_p = \dot{m}_e + \dot{m}_q. \tag{62}$$

And from conservation of energy we have

$$\dot{m}_p T_p = \dot{m}_e T_l + \dot{m}_v T_v. \tag{63}$$

The criterion that the density in the plume region must be lower than the upper layer implies

$$T_u < T_p. \tag{64}$$

By substituting the equation for temperature rise, eq (61), and the conservation of mass, eq (62), into the energy equation, eq (63), we find

$$\dot{M}_e < \frac{\dot{Q}}{C_p(T_u - T_l)} - \left(\frac{T_u - T_v}{T_u - T_l}\right)\dot{m}_v. \tag{65}$$

The right most term is negligible in the cases under consideration so we will ignore it. It the case where it is of the same order as the first term, there are other constraints on the entrainment. Thus we are left with the maximum for $\dot{m}_v$ of

$$\dot{m}_e < \frac{\dot{Q}}{C_p(T_u - T_l)} \tag{66}$$

which is incorporated into the solver (DSOURC).

7.3.5.4 Source Terms: Vent Flow

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.

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 [197]. 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

$$V = CS\sqrt{2\rho|P_i - P_o|} \tag{67}$$

where C is an orifice coefficient ($\simeq$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

$$\text{flow} = \int_{width} \int_{height} \rho V dz db \rightarrow width \int_{z_1}^{z_2} \rho V dz \tag{68}$$

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. 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. Assuming two zones in each room, it is possible to have up to three neutral planes [198] at openings between the rooms. We have for the internal pressure on each side of the opening as shown in Figure 21:

$$P_i(z) = P_i(0) - \min(z, Z_i)\rho_2 g - \max(z - Z_i, 0)\rho_1 g \tag{69}$$

$$P_o(z) = P_o(0) - \min(z, Z_0)\rho_4 g - \max(z - Z_o, 0)\rho_3 g \tag{70}$$

where $P(0)$ represents the 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 five possibilities as shown below.

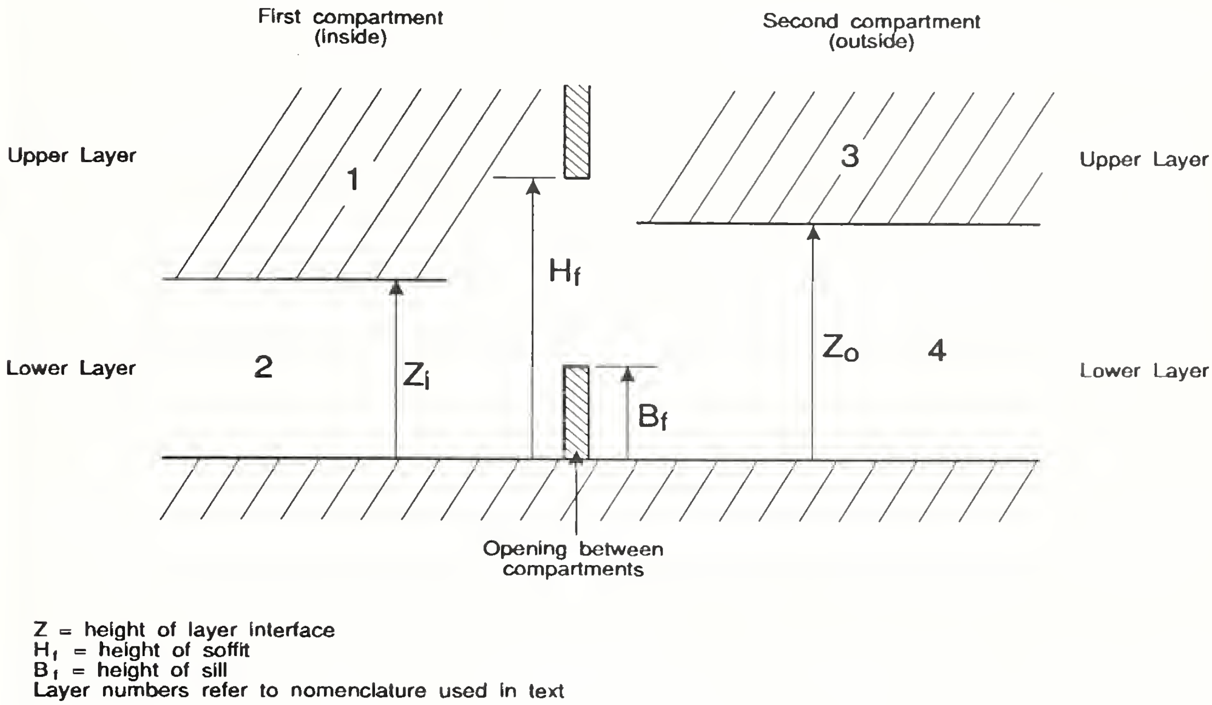


Figure 21. Notation conventions for two-layer model in two rooms with a connecting vent.

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. For example, the first of the restrictions above 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

$$\dot{m}_{i\to o} = \frac{2}{3}CS\sqrt{2\rho}(z_2-z_1)\frac{1}{P_2-P_1}\left(P_2^{2/3}-P_1^{2/3}\right) \tag{71}$$

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 $P_1 \to 0$, whence the expression becomes

$$\dot{m}_{i\to o} = \frac{2}{3}CS(z_2-z_1)\sqrt{2\rho P_2}\ . \tag{72}$$

The latter expression is much faster to evaluate than the former. We can partially ameliorate the difference in computation speed by rewriting eq (71) in a better form, using a continued fraction, as

$$\begin{aligned} x &\equiv \min\left(\sqrt{P_2},\sqrt{P_1}\right) \\ y &\equiv \max\left(\sqrt{P_2},\sqrt{P_1}\right) \\ \dot{m}_{i\to o} &= \frac{2}{3}CS\sqrt{2\rho}(z_2-z_1)\left(x+\frac{y}{1+x/y}\right) \end{aligned} \tag{73}$$

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 (72) or (73) 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 22. 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. [195]. 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

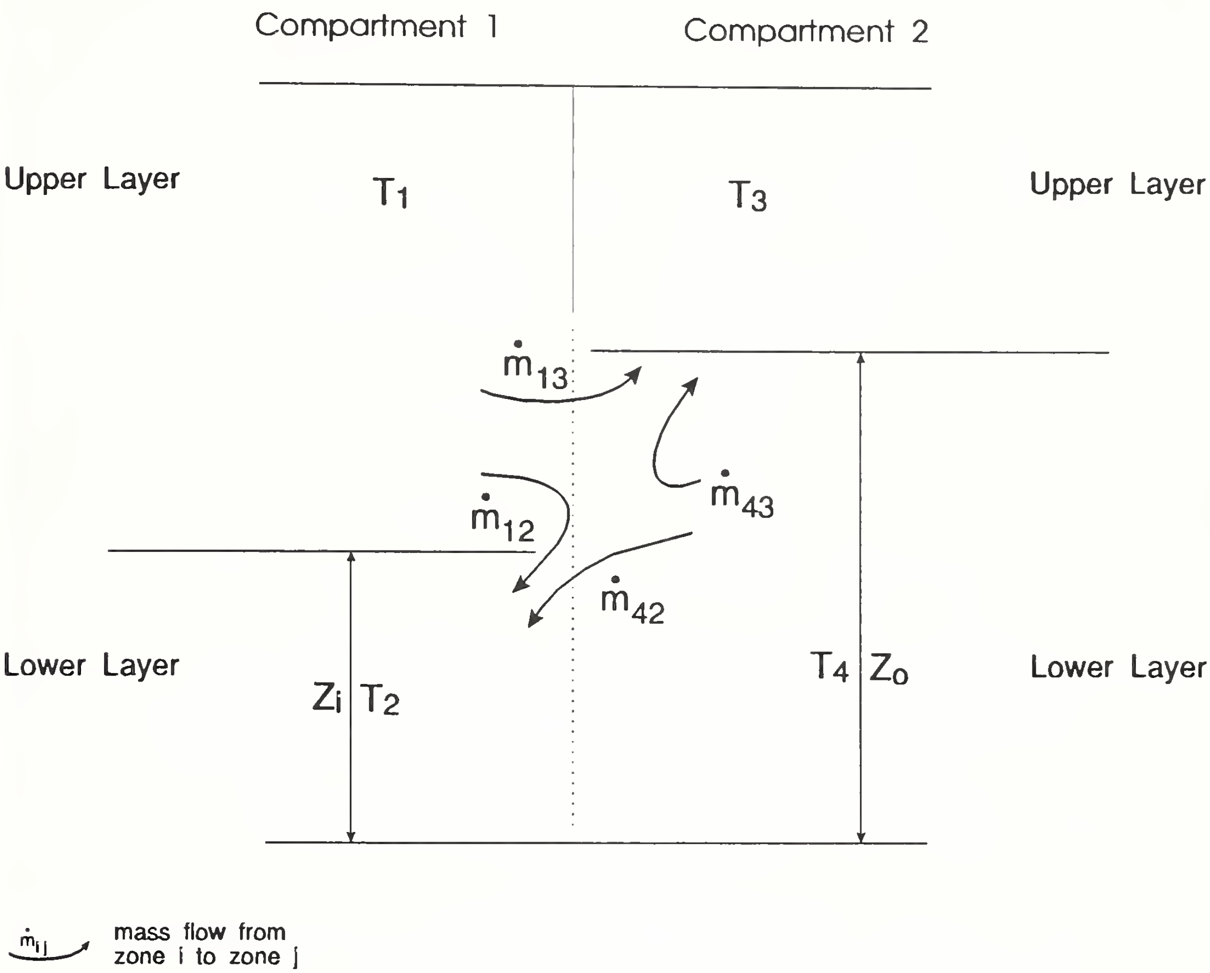


Figure 22. Example of a possible flow pattern and layer numbering convention.

$$\dot{Q}_{eq} = c_p(T_1 - T_4)\dot{m}_{13} \tag{74}$$

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, z_p, of the plume is

$$z_p = \frac{z_{13}}{\dot{Q}_{eq}^{2/5}} + v_p \qquad (75)$$

where v_p, the virtual source point, is defined by inverting the entrainment process to yield

$$v_p = \left(\frac{90.9\dot{m}}{\dot{Q}_{eq}}\right)^{1.76} \qquad \text{if } 0.00<v_p\leq 0.08$$

$$v_p = \left(\frac{38.5\dot{m}}{\dot{Q}_{eq}}\right)^{1.001} \qquad \text{if } 0.08<v_p\leq 0.20 \qquad (76)$$

$$v_p = \left(\frac{8.10\dot{m}}{\dot{Q}_{eq}}\right)^{0.528} \qquad \text{if } 0.20<v_p$$

The units of this height, z_p and of v_p, are not length, but rather the reduced notation of McCaffrey [194]. 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. [199] 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.

7.3.5.5 Source Terms: Fire

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 the data file structure. 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

$$\dot{Q}_f = h_c \dot{m}_b - c_p (T_u - T_v) \dot{m}_b \tag{77}$$

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 [200]. 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 enthalpy which is released goes into radiation and convection

$$\begin{aligned} \dot{Q}_r(fire) &= \chi_R \dot{Q}_f \\ \dot{Q}_c(fire) &= (1-\chi_r)\dot{Q}_f \end{aligned} \tag{78}$$

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

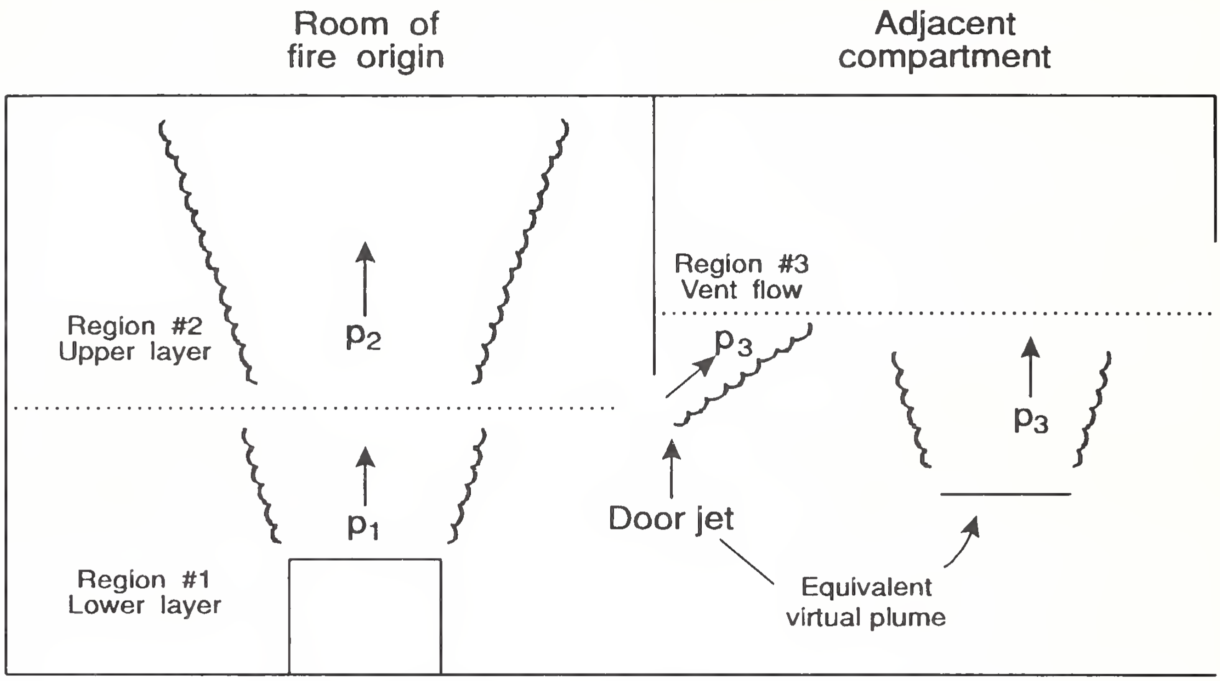


Figure 23. Schematic of entrainment and burning regions.

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 simplest form of enthalpy release is made by specifying a heat release rate, together with a consistent mass eflux. This would simulate the fire that occurs in an unconfined area. This is the form that all zone models have used until now. As soon as one is constrained by the confines of a compartment, then the nature of the fire changes. In particular, the available oxygen may not be sufficient to allow complete combustion. It is not consistent to try to account for the oxygen alone, however. All pertinent species must be followed. Several models [201] have attempted to impose such constraints based solely on the available oxygen. In general they do not work well simply because the chemistry is more complex. A consistent prescription for the kinetics is required. The way we use the term kinetics is not quite the meaning used by chemists. In this case we are merely calculating the branching ratio of species to carbon dioxide, the primary product of combustion. Indeed, we assume infinite rate kinetics. Further, we do not calculate backwards reactions. More proper terminology would be that used in high energy physics, the branching ratio, for indeed we calculate the ratio of species such as carbon monoxide to carbon dioxide, etc.

The essence of the change in the chemistry scheme which we now utilize is to allow for a more realistic fuel composition, i.e., include oxygen, carbon, hydrogen and chlorine as part of the fuel. Then carbon monoxide, carbon dioxide, soot, water, hydrogen cyanide and hydrogen chloride are the products of combustion.

The fuel burning rate in terms of the carbon production is

$$\Delta m_f = \{-\} \times \Delta m_C \tag{79}$$

where {—} is the multiplier in the fuel production

$$\{-\} = \left(1 + \frac{H}{C} + \frac{HCl}{C} + \frac{HCN}{C} + \frac{O}{C}\right) \equiv fIC. \tag{80}$$

The following definitions are for the heat release rate as a function of the fuel burning rate, and the heat release rate based on oxygen consumption. H/C, HCl/C, HCN/C and O/C are the ratio of mass of that species to carbon in the fuel. Thus H/C is for the mass of hydrogen to the mass of carbon produced in **pyrolysis**. This is a very useful way to characterize the fuel. This is in terms of the elemental composition of the fuel, and not elemental molecules, such as H_2. These are the ratios for the fuel, and the material which comes from it. For the products of the combustion process, we have CO_2/C, CO/C, H_2O/C and S/C. These ratios are in terms of free molecules, generally gaseous. Note that the subscript "S" is used to designate soot, and we assume it consists primarily of carbon.

The first step is to limit the actual burning which takes place in the combustion zone. In each combustion zone, there is a quantity of fuel available. At the source this results from the pyrolysis of the material. In other situations such as a plume or door jet, it is the net unburned fuel available. At the source we refer to Δm_p, but in the other regions we use a catchall, Δm_{TUHC}. In each case, the fuel which is available but not burned is then deposited into this category. This provides a consistent notation. In the discussion below, we will speak of the Δm_f as the amount burned. The understanding is that in the iterative scheme discussed, this value is initialized to the available fuel, and then possible reduced by the algorithm discussed. Subsequently, the available fuel, m_{TUHC}, is reduced by the final value of m_f. Thus we have a consistent description in each burning region, with an algorithm that can be invoked independent of the region being analyzed.

$$\Delta Q = \Delta m_f \times h_c \tag{81}$$

$$\Delta m_O = \frac{\Delta Q}{1.32\times10^7} \tag{82}$$

$$\Delta m_O(\text{needed}) = \Delta m_O - \Delta m_O(\text{in the fuel}) \tag{83}$$

$$\Delta m_O = \Delta m_f \times \frac{h_c}{1.32\times10^7}, \text{ and} \tag{84}$$

$$\Delta m_O(\text{actual}) \leftarrow \text{minimum of } \left\{ \Delta m_O(\text{available}), \Delta m_O(\text{needed}) \right\}, \tag{85}$$

$$\Delta m_f(\text{actual}) = \Delta m_O(\text{actual}) \times \frac{1.32\, x\, 10^7}{h_c} \tag{86}$$

Essentially, we limit the amount of fuel that is burned, as opposed to the amount that is pyrolyzed, to the lesser of the amount pyrolyzed and that required to consume the *available* oxygen. The Δm_O(actual) and Δm_f(actual) are the quantities used below. By way of explanation, eq (81) tells us how much energy would be released by the available fuel if there were no constraint (free burn). Equation (82) then tells us the mass of oxygen required to achieve this energy release rate. The relationship is based on the work in reference [202]. Equation (83) yields the amount needed based on the required amount less the oxygen available in the fuel. Rocket fuel would yield a value of zero at this point. Equation (85) limits the amount used and eq (86) then yields the amount of fuel actually burned, as opposed to the amount pyrolyzed.

We begin with the mass balance equation. The mass consumed as pyrolyzate plus oxygen must reappear as product.

$$\Delta m_f + \Delta m_O = \Delta m_f + \Delta m_f \times \frac{h_c}{1.32\times10^7} - \frac{\Delta m_f}{\{-\}} \times \left(\frac{O}{C}\right) \tag{87}$$
$$= \Delta m_{CO_2} + \Delta m_{CO} + \Delta m_S + \Delta m_{H_2O} + \Delta m_{HCl} + \Delta m_{HCN}$$

We then substitute the following definitions of mass produced of each species based on the amount of carbon (ala. fuel) consumed as

$$\Delta m_{HCl} = \left(\frac{HCl}{C}\right) \times \Delta m_C \rightarrow \left(\frac{HCl}{f}\right) \times \Delta m_f \tag{88}$$

$$\Delta m_{HCN} = \left(\frac{HCN}{C}\right) \times \Delta m_C \rightarrow \left(\frac{HCN}{f}\right) \times \Delta m_f \tag{89}$$

$$\Delta m_{H_2O} = \frac{1}{2}\left(\frac{H_2O}{H}\right)\times\left(\frac{H}{C}\right)\times\Delta m_C = 9 \times \left(\frac{H}{C}\right) \times \Delta m_C \rightarrow 9 \times \left(\frac{H}{C}\right) \times \frac{\Delta m_f}{\{-\}} \tag{90}$$

$$\Delta m_{CO_2} = \left(\frac{CO_2}{C}\right) \times \Delta m_C \tag{91}$$

$$\Delta m_S = \left(\frac{S}{C}\right) \times \Delta m_C = \left(\frac{CO_2}{C}\right) \times \left(\frac{S}{CO_2}\right) \times \Delta m_C \rightarrow \left(\frac{S}{CO_2}\right) \times \Delta m_{CO_2} \tag{92}$$

$$\Delta m_{CO} = \left(\frac{CO}{C}\right) \times \Delta m_C = \left(\frac{CO_2}{C}\right) \times \left(\frac{CO}{CO_2}\right) \times \Delta m_C \rightarrow \left(\frac{CO}{CO_2}\right) \times \Delta m_{CO_2} \tag{93}$$

Substituting the above definitions into the mass balance equation yields:

$$\left(\frac{CO_2}{C}\right) = \frac{\{-\} \times \left(1 + \dfrac{h_c}{1.32\times10^7} - \dfrac{O/C}{\{-\}}\right) - \left(\dfrac{HCl}{C} + \dfrac{HCN}{C} + \dfrac{H}{C}\right)}{\left(1 + \dfrac{S}{CO_2} + \dfrac{CO}{CO_2}\right)} \tag{94}$$

With this definition, we can substitute back into the equation for carbon dioxide production, which yields

$$\Delta m_{CO_2} = \Delta m_f \times \frac{\left(1 + \frac{h_c}{1.32\times10^7} - \frac{O/C}{\{-\}}\right) - \left(\frac{HCl}{C} + \frac{HCN}{C} + \frac{H}{C}\right)/\{-\}}{\left(1 + \frac{S}{CO_2} + \frac{CO}{CO_2}\right)}. \quad (95)$$

The form in which we cast these equations evolves naturally from the properties of combustion. Hydrogen, carbon and bound oxygen are properties of the fuel. They can be measured experimentally independent of the combustion process. Thus we use these ratios as the basis of the scheme. In a similar sense, hydrogen chloride and hydrogen cyanide are properties of the pyrolysis process. So hydrogen chlorine and hydrogen cyanide production are specified with respect to the fuel pyrolysis. Normally this is how they are measured, for example with the cone calorimeter, so we can use the measured quantities directly. Other than the cyanide, chloride and water production, hydrogen does not play a role. In general, hydrogen has much more of an affinity for oxygen than carbon, so almost all of the hydrogen will be utilized. This dictates our next choice, which is that soot is essentially all carbon. On a mass basis this is certainly true. On a molecular basis, however, it may not be so simple. Carbon dioxide is a direct product of combustion, and the assumption is that most carbon will end up here. Carbon monoxide and soot are functions of incomplete combustion. Thus they depend on the environment in which the burning takes place. They are in no case a function of the pyrolysis process itself. Thus the production of these products are specified with respect to the carbon dioxide. At present, we must rely on measured ratios, but this is beginning to change as we gain a better understanding of the combustion process. So, in the present model, carbon goes to one of three final species, carbon dioxide, carbon monoxide or soot (carbon), with the particular branching ratio depending on the chemistry active at the time.

Equations (90) through (95) are used in terms of the carbon production. We now need to recast HCl and HCN in terms of fuel production rather than carbon production, since that is how they are measured. Since HCl and HCN are similar, we will just make the argument for one, and then assume that the derivation is the same. One simplification will be possible for the HCN though, and that is that its production rate is *always* much less than the pyrolysis rate.

Since {—} is just f/C,

$$\left(\frac{HCl}{C}\right) = \left(\frac{HCl}{f}\right) \times \left(1 + \frac{H}{C} + \frac{HCl}{C} + \frac{HCN}{C} + \frac{O}{C}\right). \quad (96)$$

Therefore

$$\left(\frac{HCl}{C}\right) = \left(\frac{HCl}{f}\right) \times \left(\frac{1 + \frac{H}{C} + \frac{O}{C}}{1 - \left(\frac{HCl}{f}\right)}\right), \tag{97}$$

and for hydrogen cyanide we have

$$\left(\frac{HCN}{C}\right) = \left(\frac{HCN}{f}\right) \times \left(1 + \frac{H}{C} + \frac{HCl}{C} + \frac{O}{C}\right). \tag{98}$$

In this latter case, we assume that the cyanide ratio (HCN/C) is small compared to unity. It is the HCl/C and HCN/C ratios which are used by the model.

As stated, the burning rate simply decreases as the oxygen level decreases. We know that there is an oxygen concentration below which combustion does not self-sustain. The "rich limit" is where, for a given ratio of O_2 to N_2 (generally the ratio in air), there is too much fuel for combustion. At the other end, there is "lean flammability" limit. In the present context we refer to this point as the limiting oxygen index. At present, we have incorporated only the rich flammability limit. Since this is essentially an Arrhenius dependence on the species, a temperature effect should also be included. At present, we do not have sufficient theoretical underpinnings, nor sufficient experimental data to include such effects. The way we incorporate the limiting oxygen index is through an exponential decrease near the limit (Figure 24). The oxygen concentration varies from 0% to 21%. The limiting oxygen index varies from 0% to 17%. Any cross section of this graph will be just like the curve discussed in the Technical Reference Guide [189]. Noteworthy, however, is the fact that as the two rates approach the high limit (21%), the curve steepens. This is an artifact of the approximation to the cutoff, and is not necessarily reflected in the reality of the chemistry being approximated. In the lean flammability limit, we use only an ignition temperature criterion below which we assume no burning takes place.

In summary, we can predict the formation of some of the products of combustion, carbon dioxide, carbon monoxide, soot, water, hydrogen cyanide, and hydrogen chloride given the branching ratios CO/CO_2, $S(soot)/CO_2$, the composition of the fuel, H/C, O/C, HCl/f and HCN/f and the flammability limit. The In principle, the flammability limit comes from theory. At present, in practice we use experimental values, such as those from Morehart et al. [203]. The composition of the fuel is a measurable quantity, although it is complicated somewhat by physical

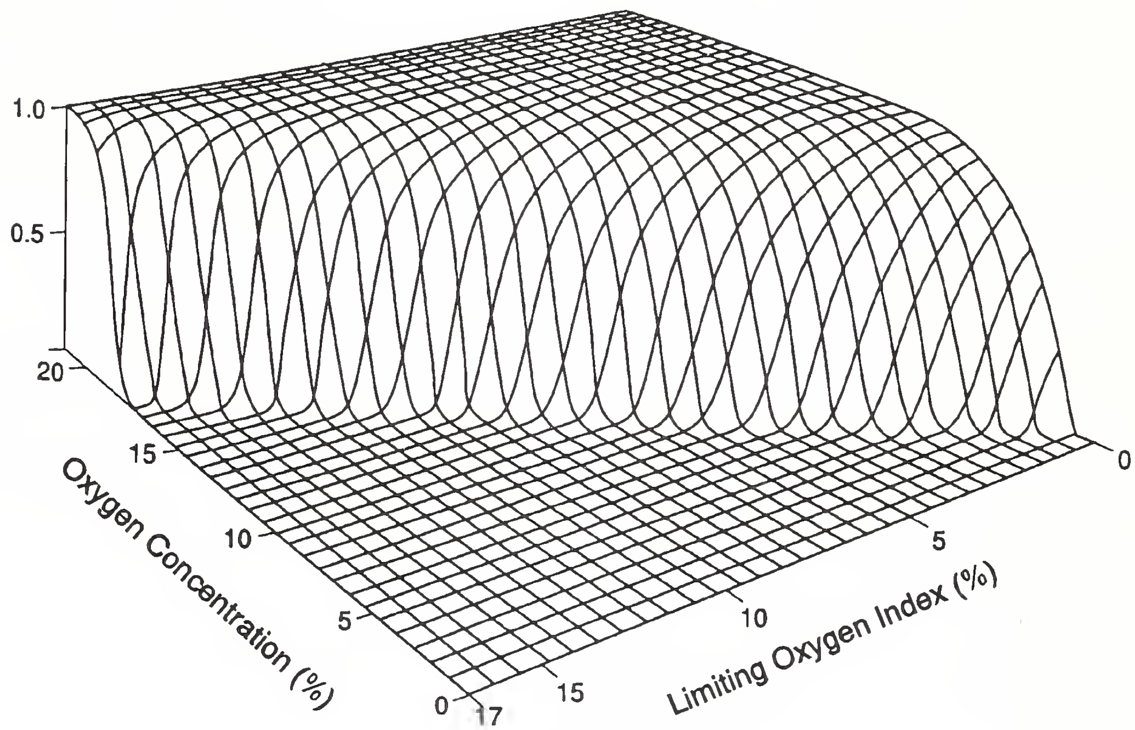


Figure 24. Limit of the fuel oxidation rate, expressed as a fraction, (1.0-EXP(-10.0*O2INDEX)), as a function of oxygen and its limiting index.

effects. The complication arises in that materials such as wood will yield methane in the early stages of burning, and carbon rich products at later times. Thus the H/C and O/C ratios are functions of time. Finally, the production ratios of CO/CO_2, S(soot)/CO_2 are based on the kinetics which in turn is a function of the ambient environment.

7.3.5.6 Source Terms: Hydrogen Chloride Deposition

Production of hydrogen chloride from a fire can result in a serious toxicity problem. It has been shown [204] that significant amounts of the substance can be removed by adsorption by surfaces which contact smoke. In our model, HCl production is treated like any other species. However, an additional term is required to allow for deposition on, and subsequent absorption into, material surfaces.

The physical configuration that we are modeling is a gas layer, either the upper or lower zone, adjacent to a surface, such as a wall. A gas layer is at some temperature T_g with a concomitant density of hydrogen chloride, ρ_{HCl}. The mass transport coefficient is calculated based on the Reynolds analogy with mass and heat transfer: that is, hydrogen chloride is mass being moved convectively in the boundary layer, and some of it simply sticks to the wall surface rather than completing the journey during the convective roll-up associated with eddy diffusion in the boundary layer. The boundary layer at the wall is then in equilibrium with the wall. The latter is a statistical process and is determined by evaporation from the wall and stickiness of the wall for HCl molecules. This latter is greatly influenced by the concentration of water in the gas, in the boundary layer and on the wall itself.

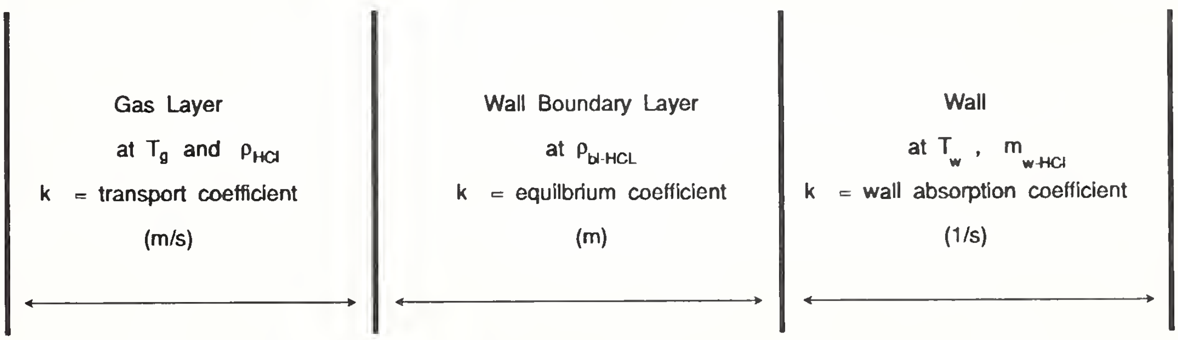


Figure 25. Schematic of hydrogen chloride deposition region.

The rate of addition of mass of hydrogen chloride to the gas layer is given by

$$\frac{d}{dt} m_{HCl} = source - k_c \times \left(\rho_{HCl} - \rho_{blHCl}\right) \times A_w \tag{99}$$

where source is the production rate from the burning object plus flow from other compartments.

For the wall concentration, the rate of addition is

$$\frac{d}{dt} d_{HCl,w} = k_c \times \left(\rho_{HCl} - \rho_{blHCl}\right) - k_s \times m_{HCl,w} \tag{100}$$

where the concentration in the boundary layer, ρ_{blHCl}, is related to the wall surface concentration by the equilibrium constant k_e,

$$\rho_{blHCl} = d_{HCl,w} \, / \, k_e \, . \tag{101}$$

We never actually solve for the concentration in the boundary layer, but it is available, as is a boundary layer temperature if it were of interest. The transfer coefficients are

$$k_c = \frac{\dot{q}}{\Delta T \, \rho_g \, c_p} \tag{102}$$

$$k_e = \frac{b_1 \, e^{1500/T_w}}{1 + b_2 \, e^{1500/T_w} \, \rho_{hcl}} \left(1 + \frac{b_5 \left(\rho_{H_2O}\right)^{b6}}{\left(\rho_{H_2O,sat} - \rho_{H_2O,g}\right)^{b7}} \right) \tag{103}$$

$$k_s = b_3 \, e^{-\left(\frac{b_4}{R \, T_W}\right)} \, . \tag{104}$$

The only values currently available [205] for these quantities are shown in Table 23. The "b" coefficients are parameters which are found by fitting experimental data to eqs (99) through (104). These coefficients reproduce the adsorption and absorption of HCl reasonably well. Note though that error bars for these coefficients have not been reported in the literature.

The experimental basis for poly-(methyl methacrylate) and gypsum cover a sufficiently wide range of conditions that they should be usable in a variety of practical situations. The parameters for the other surfaces do not have much experimental backing and so use should be limited to comparison purposes.

Table 23. Transfer coefficients for HCl deposition

Surface	b_1 (m)	b_2 (m^3/kg)	b_3 (s^{-1})	b_4 (J/g-mol)	b_5 a	b_6 c	b_7 c
Painted Gypsum	0.0063	191.8	0.0587	7476.	193	1.021	0.431
PMMA	9.6×10^{-5}	0.0137	0.0205	7476.	29	1.0	0.431
Ceiling Tile	4.0×10^{-3}	0.0548	0.123	7476.	30[b]	1.0	0.431
Cement Block	1.8×10^{-2}	5.48	0.497	7476.	30[b]	1.0	0.431
Marinite®	1.9×10^{-2}	0.137	0.030	7476.	30[b]	1.0	0.431

a units of b_5 are (m^3/kg)^(b_7-b_6)
b very approximate value, insufficient data for high confidence value
c non-dimensional

7.3.5.7 Source Terms: Mechanical Ventilation

The model for mechanical ventilation is based on the theory of networks. This is a simplified form of Kirchoff's law which says that flow into a node must be balanced by flow out of the node. There is a close analog to electrical networks for which the flow consists of electrons. In the case of ventilation, the flow is formed by molecules of air. The conservation equation differs slightly from that of an electrical system, but the basic ideas carry over. The former case, we have

voltage = current × resistance.

In the present case we have

pressure change = mass flow × resistance.

So the application of network theory is used, although the circuit laws are slightly different. In practice, as with the electrical analog, one solves the problem by summing all of the equations for the nodes, and require that the mass be conserved at each node. Thus we turn the equation around and put it into the form

mass flow = conductance × (pressure drop across a resistance)$^{1/2}$.

For each node, this flow must sum to zero. There are several assumptions which are made in computing this flow in ducts, fans, and elbows. First, we assume unidirectional flow. Given the size of ducts, and the nominal presence of fans, this is quite reasonable. Second, in the conservation law for energy, there is a work term which describes compression or expansion of a volume. There is no such analogous term in the solution of the mass flow equations for ventilation. This is reasonable so long as a ventilation system is not being used to *increase* or *decrease* the pressure within a structure. It is still acceptable for connecting systems at different pressures. Further, the effect that a change in pressure within a duct has on the flow characteristics is likewise ignored. Once again, for most of the cases of interest this is a reasonable assumption. Finally, the particular implementation used here [206] does not allow for reverse flow in the duct system. The difficulty lies in describing how a fan behaves in such a case.

Given that we can describe mass flow in terms of pressure differences and conductance, the conservation equation for each node is

$$\sum_j \dot{m}_{i,j} = 0. \tag{105}$$

The index "j" is a summation over connections to a node, and there is an equation "i" for each node. The remaining problem is to specify the boundary conditions. At each connection to a compartment, the pressure is specified. Then, given that flow is unidirectional, the mass and enthalpy flow into or out of a room can be calculated explicitly. Thus we end up with a set of equations of the form

$$\begin{aligned} f_1(P_1,P_2,\ ...) &= 0 \\ &\vdots \\ f_i(P_1,P_2,\ ...) &= 0 \\ &\vdots \\ f_n(P_1,P_2,\ ...) &= 0. \end{aligned} \tag{106}$$

This is an algebraic set of equations that is solved simultaneously with the equations for flow in the compartments.

The equations describe the relationship between the pressure drop across a duct, the resistance of a duct, and the mass flow. The pressure can be changed by conditions in a compartment, or a fan in line in the duct system. Resistance arises from the finite size of ducts, roughness on surfaces, bends and joints. To carry the electrical analog a little further, fans act like constant voltage sources. The analogy breaks down, however, in that the voltage, current and resistance are related by the square of the current, rather than being linearly proportional. Since we are using the current form of the conservation equation to balance the system, the flow can be recast in terms of a conductance

$$\dot{m} = G\sqrt{\Delta P}. \tag{107}$$

The conductance can be expressed generally as

$$G = \sqrt{\frac{2\rho}{C_0}}\, A_0 \tag{108}$$

where C_0 is the flow coefficient, and A_0 is the area of the inlet, outlet, duct, contraction or expansion joint, coil, damper, bend, filter, and so on. Their values for the most common of these items are tabulated in the ASHRAE Handbook [207].

Ducts are long pipes through which gases can flow. They have been studied much more extensively than other types of connections. For this reason, eq (108) can be put into a form which allows one to characterize the conductance in more detail, depending on the type of duct (e.g., oval, round, or square). The form derives from the Darcy equation and is

$$G = \sqrt{\frac{FL}{2\rho D_e A_0^2}}\,, \tag{109}$$

where F is the friction factor and can be calculated from

$$\frac{1}{\sqrt{F}} = -2\,\log\left(\frac{\epsilon}{3.7\,D_e} + \frac{2.51}{R_e\sqrt{F}}\right). \tag{110}$$

For each node in the system, one has an entry of the form of eq (108). This set of equations is then solved at each time step. In the present form, the solution to the duct system is split from that of the buoyancy driven flow. This is justified based on the long time constant for change of the flow pattern in such a system. Implicit in this assumption is that there is only a very weak interaction between the systems of equations. When we begin to deal with the problem of flow reversal then the fan characteristics will be coupled much more closely with the buoyancy driven flow and we will have to reformulate the solution.

7.3.5.8 Source Terms: Conduction

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

$$\frac{\partial T}{\partial t} = \frac{k}{\rho c} \nabla^2 T \tag{111}$$

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 whose properties can differ. Equation (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 s, 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 36 nodes. 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., [208] 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

$$T_i'(1+\eta) = \frac{\eta}{2}\left(T_{i+1}'+t_{i-1}'\right) + \left(T_i+\frac{\eta}{2}\left(t_{i+1}-2T_i+t_{i-1}\right)\right) \tag{112}$$

and for boundary or edge nodes we have

$$T_1'\left(1+\frac{\eta}{2}\right) = \frac{\eta}{2}\left(T_2'+\frac{\Delta x Q_c}{k}\right) + \left(T_1+\frac{\eta}{2}\left(T_2-T_1+\frac{\Delta x \dot{Q}_c}{k}\right)\right) \tag{113}$$

$$T_N'\left(1+\frac{\eta}{2}\right) = \frac{\eta}{2}\left(T_{N-1}'+\frac{\Delta x Q_c}{k}\right) + \left(T_N+\frac{\eta}{2}\left(T_{N-1}-T_N-\frac{\Delta x \dot{Q}_c}{k}\right)\right) \tag{114}$$

where

$$\eta = \frac{\Delta t}{(\Delta x)^2} \frac{k}{\rho c} \tag{115}$$

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 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.

7.3.5.9 Nomenclature for FAST

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).

Variables used in the mathematical description of the model:

A area (m^2)

- A_u - extended upper wall - ceiling plus wall contiguous to upper layer
- A_l - 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 $\simeq$ 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 (J/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 (s)

$\dot{m}$ 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

$\dot{m}_l$ - total (net) mass flow into the lower layer of a compartment

$\dot{m}_{i,j}^{in}$ - net flow from compartment j into compartment i

$\dot{m}_{i,j}^{out}$ - net flow from compartment i into compartment j

$\dot{m}_e$ - 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_U is the Nusselt number, a function of Gr and Pr. It is not used explicitly 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_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); corresponding energy 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 ($\simeq$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_{lw} - 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 134

Z length (m) used for plume length, layer thickness and height of neutral plane

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 $\simeq$1.4 for air

σ Stefan-Boltzmann constant (5.67×10^{-8} W/m^{2}K^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

7.3.6 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 other than the room of fire origin, with a door which is closed except for a small gap at the bottom, 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. Like all zone models, FAST 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 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 depends 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.

7.4 EXITT

7.4.1 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.

7.4.2 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. As occupants move within the building from node to node, the path assigned is largely based on a shortest path algorithm, smoke conditions. Exit doors are preferred to windows.

All the decision rules programmed in the computer are based on the relevant research and are designed to make the decisions as similar as possible to decisions that building occupants would make.

7.4.2.1 Input Variables and Parameters

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.

Smoke. The program is designed to use the output of the FAST model for distributing smoke throughout the building over time. 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 with which the model is calibrated is the one used by Jin in his studies of human behavior in smoke:

$$OD = \ln\left(\frac{I_0}{I}\right) \tag{116}$$

where I_0 is the initial light intensity which reduced to a value of 1.0 over a path of 1 meter. 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:

$$S = 2 \times OD \frac{D}{H} \tag{117}$$

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 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.

The decision rules and definitions that involve S are based on the following assumptions:

- 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 — 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 [209], these values will be reconsidered as part of the further development of the model.

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. The loudness 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.

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.

7.4.2.2 Decision Rules

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.

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. [210]. 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.

$$T = 70-4(C-20) \qquad (118)$$
$$C = X1+X2+X3+X4$$

$X1$ = A-N

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;

$X2$ 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 m. 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 if the occupant is asleep and $X4=0$ if the occupant is awake. This reflects the fact that more stimuli are require to awake than to alert an occupant. 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 $T = \infty$ (99999 in the computer). This restriction is based on Nober's data which showed occupants usually either responded within 70 s 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 consistent perceptual observation that the intensity of a perception varies directly with the log of the physical stimulus. While this observation has broad applicability, it is not universal and only approximate [211]. 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 [212].

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 should 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.

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.

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.

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 [213]. 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.

Several situations cause investigation to be a low priority. 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 [214]. 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.

- Help Occupant in Same Room. 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.

- Help Occupant in Different Room. 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 *going to the room of that person.* 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 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 supersedes all others is to help someone in the same room before helping an occupant in different room.

7.4.2.3 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 [215]. 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 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 sec 7.4.2.1, 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.

7.4.2.4 Delays, Pauses, and Action Times

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.

Speed. The typical travel speed of each occupant is set at 1.3 m/s for normal conditions, 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), 50% slower than normal if the occupant is assisting another occupant, or 0.845 m/s if the occupant also considers the fire to be serious, or 40% slower than normal if the smoke is bad (i.e., $S > 0.4$) and if the depth of the lower layer is less than 1.5 m, 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.

Delay Times. The delay time, the decision time, and the time to perform assisting actions 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.

Minimum Response Time. The normal (i.e., smoke is not bad) minimum response 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 [210]. The status of sleeping occupants is changed to awake status whenever the remaining response time is 6 s or less.

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.

Decrease in Preparation Time Due to Heavy Smoke. When an occupant is subjected to normal fire stimuli, a 10 s response delay time is assigned to a sleeping occupant and 6 s 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.

Hesitation Due to Not Being Alone. Research by Latane and Darley [216] 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. The threshold for this hesitancy is 30 s to reflect that more stimuli or cues than the "minimum for response" are required to prevent the "hesitation due to not being alone."

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).

7.4.2.5 Smoke Detectors

The building may have from zero to 10 smoke detectors. These smoke detectors are considered 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 0.015, and the depth of the upper layer is 0.15 meters or greater.

7.4.3 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 a probabalistic approach is planned for a future 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. The parameter values incorporated into the model algorithms should be considered approximate. No research has been conducted to quantify their validity.

7.5 TENAB

7.5.1 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 exposure doses due to CO_2, CO, HCN, O_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. Again, at this stage, the model presumes no synergism other than in the N-gas model.

7.5.2 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 section 6. 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 to which the occupant is exposed. From this information, the average layer temperature of the room, the fractional exposure 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, 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, 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, the cause, 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. At the final time, the program records for each occupant, the time, the room occupied, 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.

A discussion of the selection of the critical values used and the derivation of the formulation for the tenability measures are contained in section 6 of this Technical Reference Guide.

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:

person *k* is exposed to lower layer	$H_r\ (t_i) > 1.5$	
person *k* is exposed to lower layer	$1.0 \le H_r\ (t_i) \le 1.5$ $T_r\ (t_i) \ge 50$	
person *k* is exposed to upper layer	$1.0 \le H_r\ (t_i) \le 1.5$ $T_r\ (t_i) < 50$	(119)
person *k* is exposed to upper layer	$H_r\ (t_i) < 1.0$	

7.5.2.1 Fractional Exposure Dose ($FED_k(t_i)$)

The fractional exposure 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).

$$FED_k\ (t_i) = \sum_{j=1}^{i} \left(FEDCO_{2\,k}\ (t_j) + FEDHCN_k\ (t_j) + FEDO_{2\,k}\ (t_j)\right) \qquad (120)$$

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:

$$
\begin{aligned}
FEDCO_k\ (t_j) &= 0 && \overline{CO} = 0\\
CO_{th} &= 1300 && \overline{HCN} > 0\\
CO_{th} &= 1700 && \overline{HCN} = 0\\
D_{CO} &= \overline{CO}\frac{80000}{\overline{CO}-CO_{th}}\left(1.-0.00001\overline{CO_2}\right) && \overline{CO_2} \le 50000\\
D_{CO} &= \overline{CO}\frac{80000}{\overline{CO}-CO_{th}}0.5 && \overline{CO_2} > 50000
\end{aligned}
\qquad (121)
$$

$$
\begin{aligned}
FEDCO_k\ (t_j) &= 0 && D_{CO} < 0 \text{ and } \sum_{n=1}^{j-1} FEDCO_k\ (t_n) \le 0\\
FEDCO_k\ (t_j) &= \overline{CO}\ \frac{\Delta t_j/60}{D_{CO}} && D_{CO} \ge 0 \text{ or } \sum_{n=1}^{j-1} FEDCO_k\ (t_n) > 0
\end{aligned}
$$

where

$$
\begin{aligned}
\overline{CO} &= \frac{CO_{r,layer}\ (t_{j-1})+CO_{r,layer}\ (t_j)}{2}\\
\overline{CO_2} &= \frac{CO_{2\ r,layer}\ (t_{j-1})+CO_{2\ r,layer}\ (t_j)}{2}\\
\overline{HCN} &= \frac{HCN_{r,layer}\ (t_{j-1})+HCN_{r,layer}\ (t_j)}{2}\\
CO_{th} &= \text{carbon monoxide threshold}
\end{aligned}
\qquad (122)
$$

The effect of HCN, $FEDHCN_k(t_j)$, for person k during the time interval

(t_{j-1},t_j) is determined as follows:

$$FEDHCN_k\ (t_j) = 0 \qquad \overline{HCN} = 0$$

$$FEDHCN_k\ (t_j) = \frac{\overline{HCN}\Delta t_j/60}{3100} \qquad \overline{HCN} > 0\ . \tag{123}$$

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

$$FEDO_{2\,k}\ (t_j) = 0 \qquad \overline{O_2} \geq 5.8$$

$$FEDO_{2\,k}\ (t_j) = \frac{\left(5.8-\overline{O_2}\right)\Delta t_j/60}{9.2} \qquad \overline{O_2} < 5.8 \tag{124}$$

where

$$\overline{O_2} = \frac{O_{2\ k,layer}(t_{j-1})+O_{2\ k,layer}(t_j)}{2} \tag{125}$$

7.5.2.2 Fractional Exposure Dose Due to Gases ($FEDP_k(t_i)$)

The fractional exposure 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).

$$FEDP_k\ (t_i) = \sum_{j=1}^{i}\left(\left(FEDCOP_k\ (t_j)+FEDHCNP_k\ (t_j)+FED\right)VP_{CO_2}\ (t_j)+FEDO_2P\ (t_j)\right)\ . \tag{126}$$

The fractional exposure 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:

$$FEDCOP_k\ (t_j) = \frac{0.00082925\ \overline{CO}^{\ 1.036} \Delta t_j/60}{30}.$$

$$FEDHCNP_k\ (t_j) = \frac{4.4\ \Delta t_j/60}{185 - \overline{HCN}} \tag{127}$$

$$FEDO_2P_k = \Delta t_j/60 e^{-7.98+.528(20.9-\overline{O_2})}$$

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

$$VP_{CO_2} = e^{\frac{.2496\overline{CO_2}+1.9086}{6.8}} \tag{128}$$

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

$$FEDCO_2P_k\ (t_j) = \Delta t_j/60\ e^{-6.1623+.5189\overline{CO_2}} \tag{129}$$

7.5.2.3 Temperature ($FEDTEMP_k(t_i)$)

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

$$FEDTP_k\ (t_i) = \sum_{j=1}^{i} \Delta t_j/60\ e^{-5.1849+.0273\overline{T_{kj}}} \tag{130}$$

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

$$\overline{T_k}\ (t_j) = \frac{T_{r,layer}\ (t_{j-1}) + T_{r,layer}\ (t_j)}{2} \tag{131}$$

7.5.2.4 Integrated Concentration-Time ($AccumCT_k(t_i)$)

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

$$AccumCT_k\ (t_i)\ =\ AccumCT_k\ (t_{i-1}) + CT_{r,layer}(t_i) - CT_{r,layer}(t_{i-1}) \tag{132}$$

7.5.2.5 Heat Flux ($Q_k(t_i)$)

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

$$Q_k\ (t_i)\ =\ Q_k\ (t_{i-1}) + \frac{\dot{Q}_{r,layer}\ (t_{i-1})\ +\ \dot{Q}_{r,layer}\ (t_i)}{2} \tag{133}$$

7.5.2.6 Incapacitation and Death

Person k's state (alive, incapacitated, or dead) at time t_i is determined by comparing the values of $FED_k(t_i)$, $FEDP_k(t_i)$, $FEDCO2_k(t_i)$, $FEDTEMP_k(t_i)$, $T_k(t_i)$, $AccumCT_k(t_i)$ and $Q_k(t_i)$ with corresponding incapacitation critical levels or $FED_k(t_i)$, $T_k(t_i)$, or $Q_k(t_i)$ with corresponding critical lethality levels. The incapacitation and lethality critical levels and the Derksen curve for heat 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.

7.5.2.7 Nomenclature Used in TENAB

$AccumCT_k\ (t_i)$	total integrated-time concentration to which person k is exposed by time t_i (g-min/m^3)
$Q_k\ (t_i)$	total accumulated flux to which person k has been exposed by time t_i (KW-min/m^2)
$CO_{r(k),\ layer}\ (t_i)$	amount of carbon monoxide (ppm) in a particular layer of the room occupied by person k at time t_i
$CO_{2\ r(k),\ layer}\ (t_i)$	amount of carbon dioxide (vol %) in a particular layer of the room occupied by person k at time t_i
$CT_{r(k),\ layer}\ (t_i)$	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 — length of the time interval (t_{i-1},t_i) (s)

$FED_k(t_i)$ — total fractional exposure dose due to CO_2, CO, HCN and O_2 by the time t_i for person k

$FEDCO_2P_k(t_i)$ — fractional exposure dose due to carbon dioxide by time t_i for person k (Purser)

$FEDP_k(t_i)$ — total fractional exposure dose due to CO_2, CO, HCN and O_2 by time t_i for person k (Purser)

$FEDTEMP_k(t_i)$ — total fractional exposure dose of convective heat (calculated by a function of temperature) accumulated by person k by time t_i (°C) (Purser)

$\dot{Q}_k(t_i)$ — flux (kW/m^2) in a particular layer of the room occupied by person k at time t_i

$HCN_{r(k),\,layer}(t_i)$ — amount of hydrogen cyanide (ppm) in a particular layer of the room occupied by person k at time t_i

$H_{r(k)}(t_i)$ — interface height (m) in the room occupied by person k at time t_i

$O_{2\;r(k),\,layer}(t_i)$ — amount of oxygen (vol %) in a particular layer of the room occupied by person k at time t_i

$r_k(t_i)$ — room occupied by person k during the time interval (t_{i-1},t_i)

$T_{r(k),\,layer}(t_i)$ — temperature (°C) at time t_i in a particular layer of the room occupied by person k at time t_i

t_i — i-th time step (s)

7.5.3 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 approximate, 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 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.

Most tenability information is based on animal data. 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. The University of Pittsburgh has considered the sub-lethal effects of carbon monoxide (CO) in guinea pigs and mice [217]; but they have not yet resulted in conclusions on appropriate limits for such exposures in humans.

A physiologically based pharmacokinetic approach to predict the rate of COHb formation is being used to examine the correlation between rats and humans at NIST [218]. Based on rat data from NIST and human data from the literature, this work has shown that the *equilibrium levels* of carboxyhemoglobin (COHb) formed in the blood will be the same if rats and humans are exposed to the same concentrations of CO. Since the toxicity of CO is caused by the lack of availability of O_2 due to the binding of CO to hemoglobin, the levels of CO which are incapacitating and lethal to rats are probably close to those that are dangerous to man. However, the rate of formation of COHb will be slower in humans since they have a greater blood volume and a lower ventilation rate. Therefore, the rate at which the human will reach the same level of COHb is slower than that of the rat and thus, at the same atmospheric concentration of CO, the human will have more time to escape.

8 Example Cases

8.1 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, or evaluating the potential impact of code changes.

8.2 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 an initial set of 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 BFRL role was only as facilitator, providing administrative support and background guidance. No BFRL 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 BFRL influence.

Table 24 and Table 25 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.

Table 24. 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 Vognild 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

Figure 6 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 Table 26 and Table 28 and the floor plans are shown in Figure 26 to Figure 28.

One of the most important questions which was addressed by the panels was how well did the example cases represent real situations. This was addressed by posing the set of questions listed below:

> 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 who are 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.

Table 25. 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

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?

Figure 26. Layout of a typical ranch house.

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, the question really asks "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.

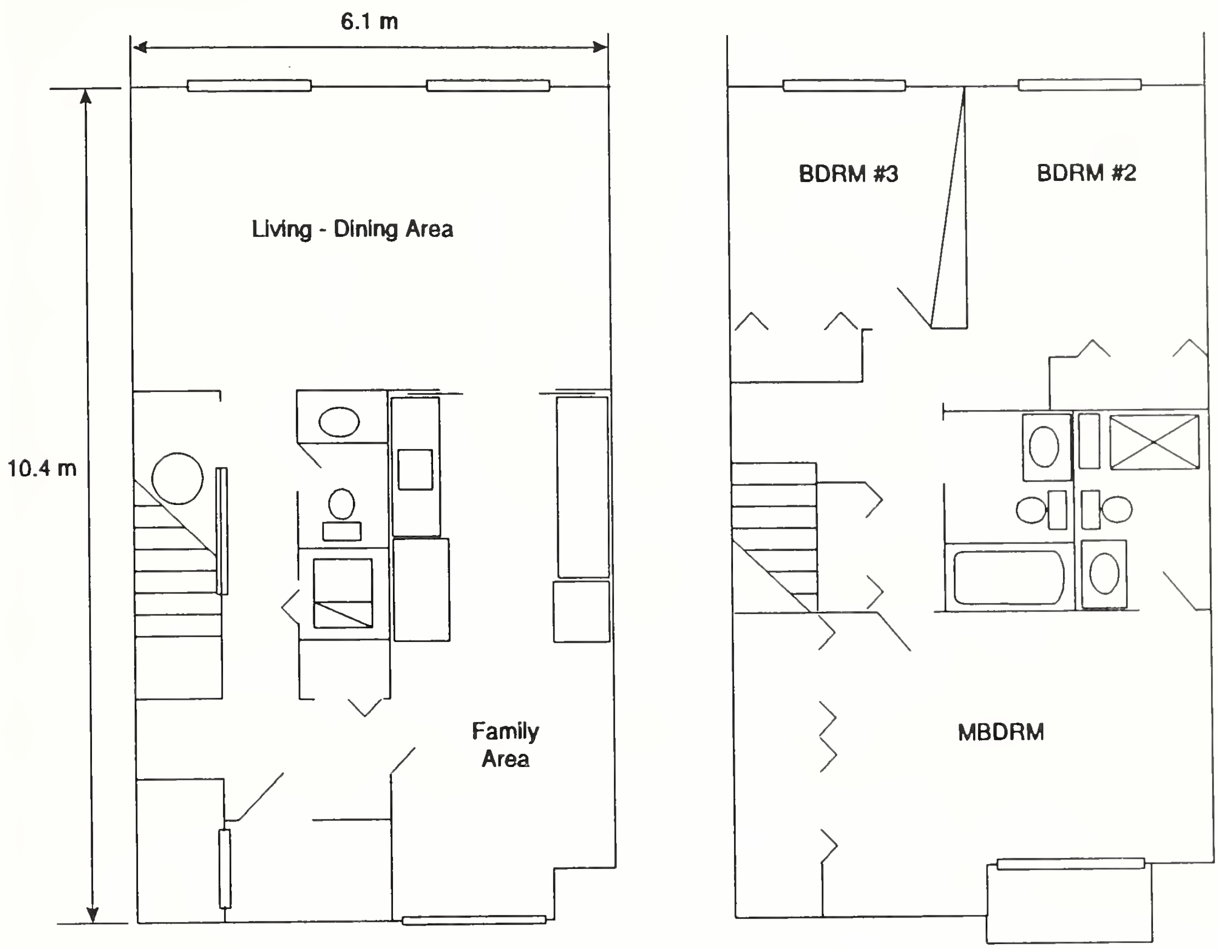


Figure 27. Layout of a typical townhouse.

8.3 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

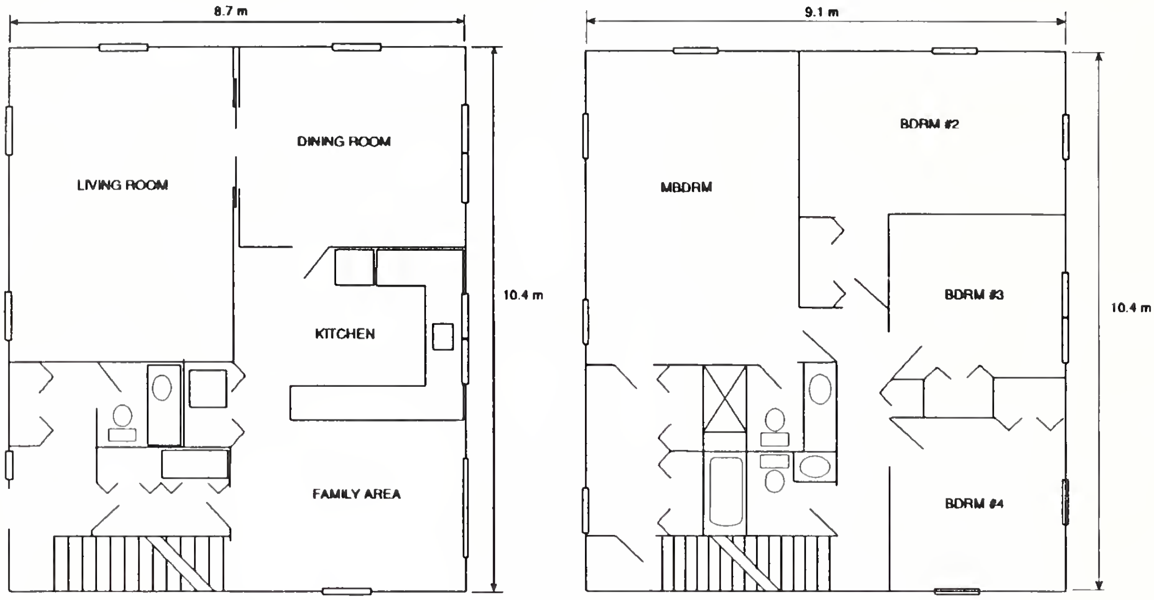


Figure 28. Layout of a typical two-story house.

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.

8.4 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.

Table 26. 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 (consensus). Synthetic drapes throughout, throw rugs throughout (consensus).	

8.5 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.

Table 27. 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
Closet under stairs	hot water heater, household cleaning materials - broom, plastic bucket, paper, rags, etc.
non-interconnected photoelectric smoke detectors (85 decibels), downstairs middle of hall between door to toilet and door to laundry, upstairs between top of stairs and door to bathroom	

8.6 Impact on Occupants

Eight fire scenarios (Table 29 and discussed later in this section) 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 high-temperature, 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 database, 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. In two scenarios (3 and 4), fires were limited 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.

Table 29 summarizes the predicted impact on the occupants in the eight fire scenarios. Almost all occupants safely exited the buildings. The safe egress of the occupants was attributed to the working smoke detectors which provided timely warning before conditions reached dangerous levels.

Table 28. 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	furnished as an 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; non-interconnected ionization smoke detectors (85 decibels), opposite front door, left of door to passageway middle of hall, near door to bedroom #4	

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 29 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 the earlier evacuation based on an earlier warning of the occupants to the presence of the fire. The

Table 29. HAZARD I example case variations

Fire Scenarios[a]	Time to Flashover (min)	(1) With Smoke Detector: Escape Time[b] (min)	(1) With Smoke Detector: Number of Fatalities[c]	(2) Without Smoke Detector: Escape Time[b] (min)	(2) Without Smoke Detector: Number of Fatalities[c]	(3) Immobile Occupant in each room: Time to Fatalities[d] (min)	(3) Immobile Occupant in each room: Number of Fatalities[c]
Ranch House							
1. Smoldering sofa in living room	--[e]	20	0/1	21	0/1	44-49	6/6
2. Grease fire in kitchen	3	1	0/5	1-2	0/5	2-8	6/6
3. Bedding fire in master bedroom	--	1	0/5	2->15[f]	0/5	2->15	5/6
Townhouse							
4. Trash fire in closet	--	1	0/3	6	0/3	2->15	1/6
5. Christmas tree and chair in living room	--	6	2/4	--[g]	4/4	7->40	5/6
Two-story House							
6. Couch and paneling in living room with bedroom doors closed	4	3	0/4	15	0/4	4->25	5/6
7. Couch and paneling in living room with living room and bedroom doors closed	4	3	0/4	25	0/4	4->25	5/6
8. Trash, drapes, and desk in bedroom office	14	6	0/4	7	0/4	7->33	4/6

a For examples with and without smoke detectors, all occupants are assumed capable of escape and make no "mistakes."
b Time needed for all escaping occupants to get out of building. Occupants who arrive at windows are considered to have escaped the building.
c Number of fatalities / number of occupants in building.
d Times over which fatalities occur.
e Flashover did not occur.
f The greater than sign (>) indicates times which are at least greater than the total time of the simulation.
g All occupants are trapped inside the building and die within 37 minutes.

absence of smoke detectors results 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 all occupants become aware of the fire at a much later time and are all trapped inside the building.

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 29). Deaths are predicted in all cases, with some of the deaths occurring in as little as 2 min 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 29, have no established relevance beyond the situations simulated and must not be assumed to apply generally.

8.7 Printed Output from FAST

To understand the computer printouts displayed in the remaining sections, we will first present a simple example and describe, in detail, the output obtained from the fire model. This example is a three compartment scenario, and referenced in the interactive program as 3R. The results obtained by running this data set are shown below.

```
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 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. The particular example comes from the three compartment data file (3R) shown above. 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 found below. 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.

8.7.1 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.

8.7.1.1 Title

```
FAST version 18.2 - created May 16, 1988   An example of a constrained fire
```

8.7.1.2 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
```

8.7.1.3 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
```

8.7.1.4 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
```

8.7.1.5 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

8.7.2 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 s (see the data file above). 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 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.

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

8.8 Detailed Example of a Worked Scenario (Grease Fire in Kitchen)

This scenario (identified as Scenario 2) is described in detail in the Learning section of the Software User's Guide. The results of this scenario are shown in detail here. For all other scenarios, a shorter summary of information is presented. The following information is included for this detailed example:

- Summary of scenario data
- Floor plan drawing
- Input file listing for the FAST model, generated using the MLTFUEL and FAST_in modules of HAZARD I
- Graphs of selected variables generated from the FAST dump files using the FASTplot module of HAZARD I (rate of heat release of the fire, upper layer temperature, lower layer temperature, layer interface position, smoke optical density, carbon monoxide concentration, carbon dioxide concentration, and concentration-time product)
- Printed output from the FAST model

- Input file listing for the EXITT module of HAZARD I
- Printed output from the EXITT module of HAZARD I
- Printed output from the TENAB module of HAZARD I

The input files for the FAST model and for the EXITT module of HAZARD I are included on the HAZARD I system disks for each of the eight original examples cases. Several additional demonstration data files are included on the HAZARD I system disks which provide examples of the use of the capabilities of the FAST model.

8.8.1 Summary of Fire Scenario 2

For scenario 2, a pot of burning vegetable oil exposes overhead cabinets and spills over exposing lower cabinets. There are five occupants in the house ranging in age from 5 to 71.

Building: Ranch house

Occupants: Father aged 30, fully capable and awake, in bathroom off master bedroom.

Mother, aged 30, fully capable and awake, in hallway.

Daughter, aged 7, fully capable and awake, in living room watching television.

Son, aged 5, fully capable and awake, in living room watching television.

Grandmother, aged 71, fully capable and awake, in bedroom 3.

Doors: The following doors are closed: bedroom 3; master bedroom; door to bathroom of master bedroom. The only opening to the outdoors is a partially open window in the master bedroom. Fire room window is closed.

Fire: Pot of burning vegetable oil 12 inches in diameter exposes overhead cabinets and spills over exposing lower cabinets.

Fuel: Burning vegetable oil taken directly from HAZARD I fire property database. Material code CKG001, Cooking oil, corn; cottonseed; in 12-in pan. Kitchen cabinets use a modified wardrobe fire taken from HAZARD I fire property database. Material code CLT001, Wardrobe closet, plywood, FR paint. Peak mass loss rate reduced to accurately simulate kitchen cabinet fire.

Ceilings: Gypsum board, standard, taken directly from HAZARD I materials property database. Material code GBD001.

Walls: Gypsum board, standard, taken directly from HAZARD I materials property database. Material code GBD001.

Floors: 0.15-m-thick concrete slab, taken directly from HAZARD I materials property database. Material code CNC001, Concrete, normal weight, Type I cement, Dolomite aggregate.

8.8.2 Floor Plan and EXITT Building Description for Scenario 2

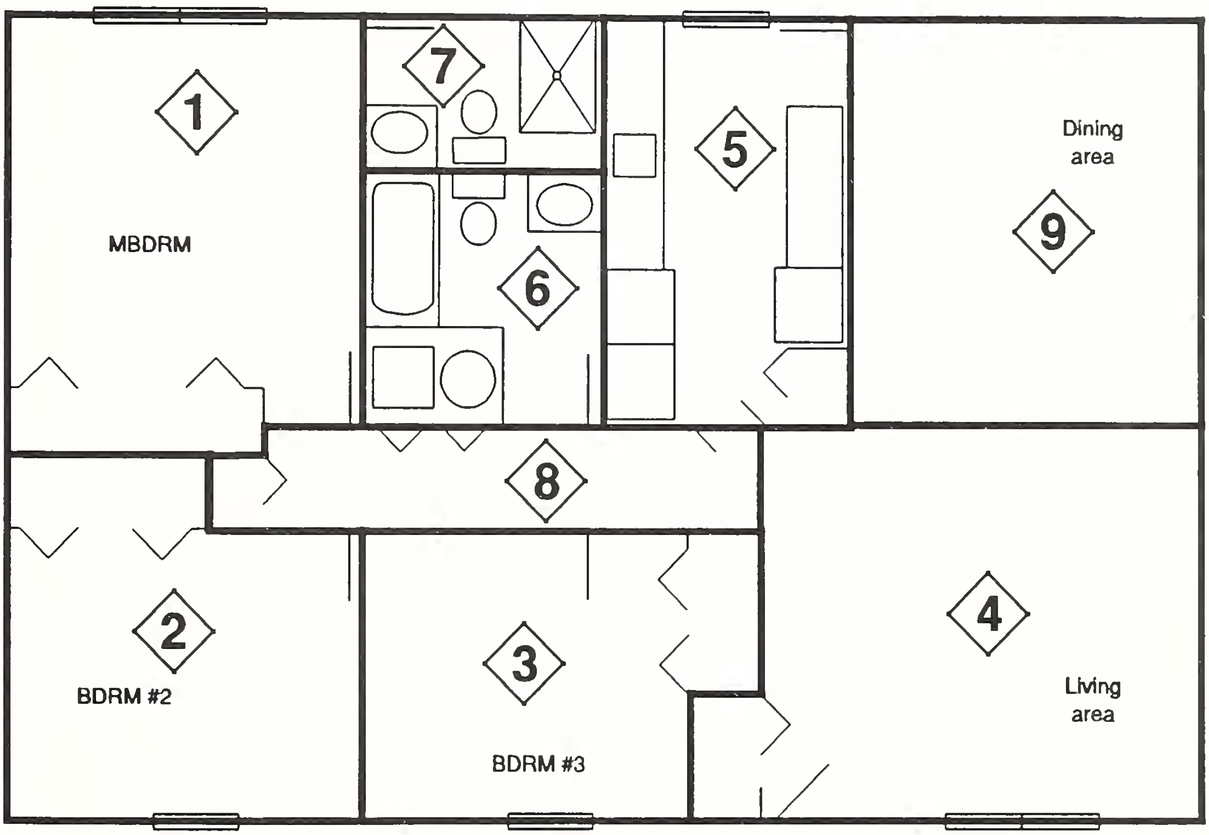


Figure 29. Floor plan and EXITT building description for scenario 2.

8.8.3 FAST Input Data for Scenario 2 (Example Data File SCEN-2.DAT)

```
VERSN   18  Scenario 2, Ranch House, Kitchen Greese Fire
TIMES   2400 100  50   0   0
TAMB   293.  101300.      0.
EAMB   273.  101300.      0.
HI/F     0.00    0.00    0.00    0.00    0.00    0.00
WIDTH    3.60    3.00    3.00    4.50    2.70    1.92
DEPTH    3.80    3.60    3.40    8.10    3.80    8.79
HEIGH    2.40    2.40    2.40    2.40    2.40    2.40
HVENT   1  6  1    1.10    2.10    0.00
HVENT   1  7  1    0.81    1.22    0.91    0.00
HVENT   2  6  1    1.10    2.10    0.00
HVENT   3  6  1    1.10    2.10    0.00
HVENT   4  5  1    1.10    2.10    0.00
HVENT   4  6  1    1.10    2.10    0.00
CVENT   1  6  1    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00
CVENT   1  7  1    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00
CVENT   2  6  1    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00
CVENT   3  6  1    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00
CVENT   4  5  1    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00
CVENT   4  6  1    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00
CEILI GYPSUM     GYPSUM     GYPSUM     GYPSUM     GYPSUM     GYPSUM
WALLS GYPSUM     GYPSUM     GYPSUM     GYPSUM     GYPSUM     GYPSUM
FLOOR CONCRETE   CONCRETE   CONCRETE   CONCRETE   CONCRETE   CONCRETE
CHEMI    16.      0.    6.0     27950000.  300.
LFBO    5
LFBT    2
LFPOS   1
LFMAX   9
FTIME       5.    145.     70.     30.     40.     50.     10.    140.    830.
FMASS   0.0000 0.0042 0.0042 0.0220 0.0506 0.0506 0.0131 0.0256 0.0131 0.0059
FHIGH     0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00
FAREA     1.00    1.00    1.00    1.50    2.00    3.00    3.00    3.00    3.00    3.00
FQDOT   0.00      1.17E+05 1.17E+05 6.15E+05 1.41E+06 1.41E+06 3.66E+05 7.16E+05 3.66E+05 1.65E+05
CT     1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000
HCR    0.080 0.080 0.080 0.080 0.080 0.080 0.080 0.080 0.080 0.080
CO     0.000 0.000 0.000 0.234 0.134 0.134 0.016 0.031 0.063 0.000
OD     0.000 0.000 0.000 0.050 0.031 0.031 0.000 0.000 0.000 0.000
DUMPR  SCEN-2.DMP
```

8.8.4 Selected Graphs from Scenario 2

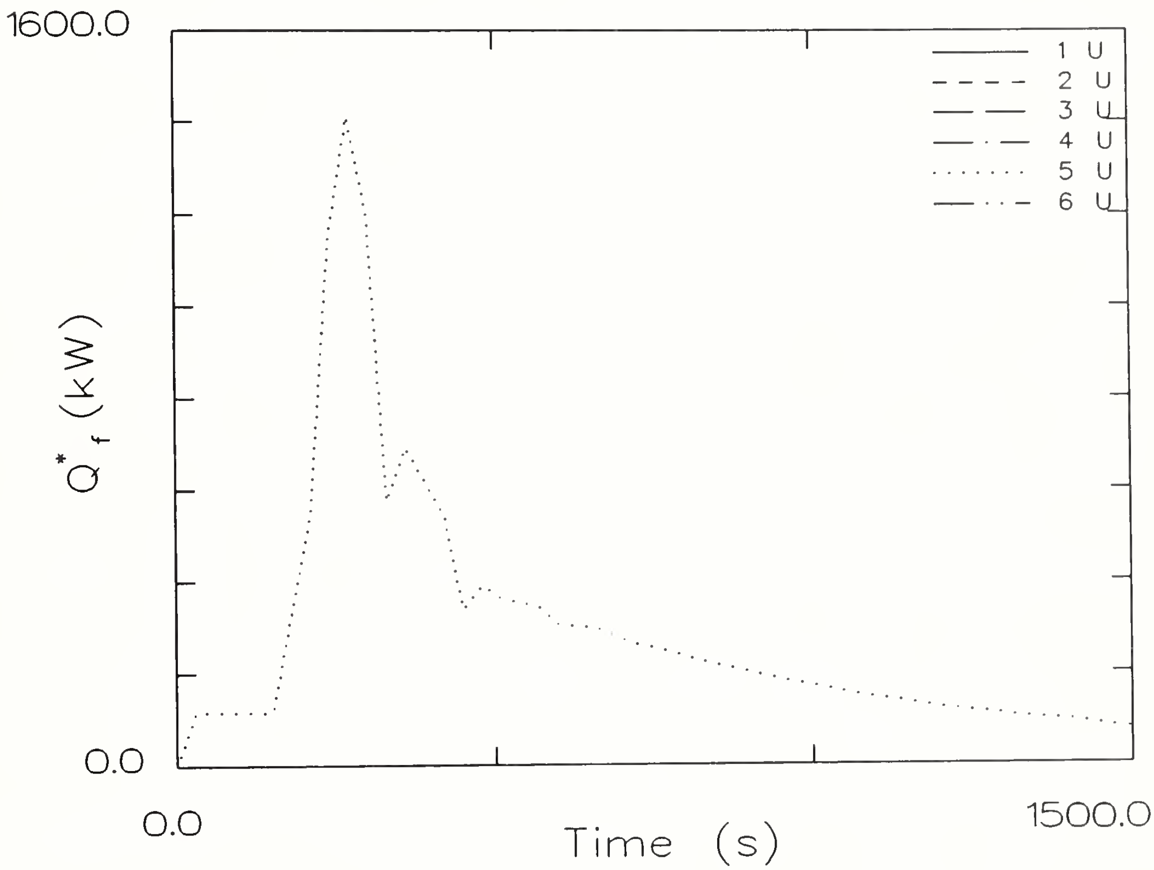


Figure 30. Heat release rate (kW) of a kitchen grease fire in scenario 2.

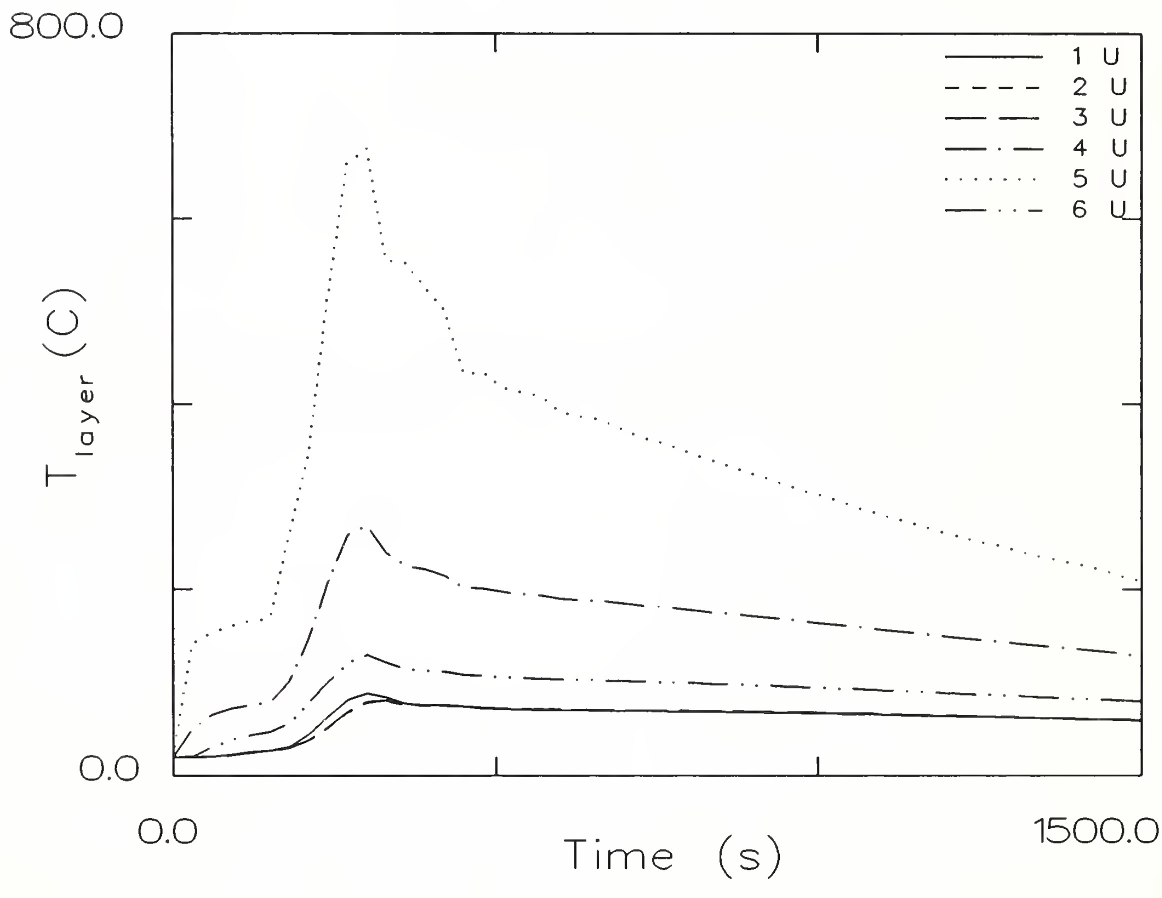


Figure 31. Upper layer temperature (°C) in scenario 2.

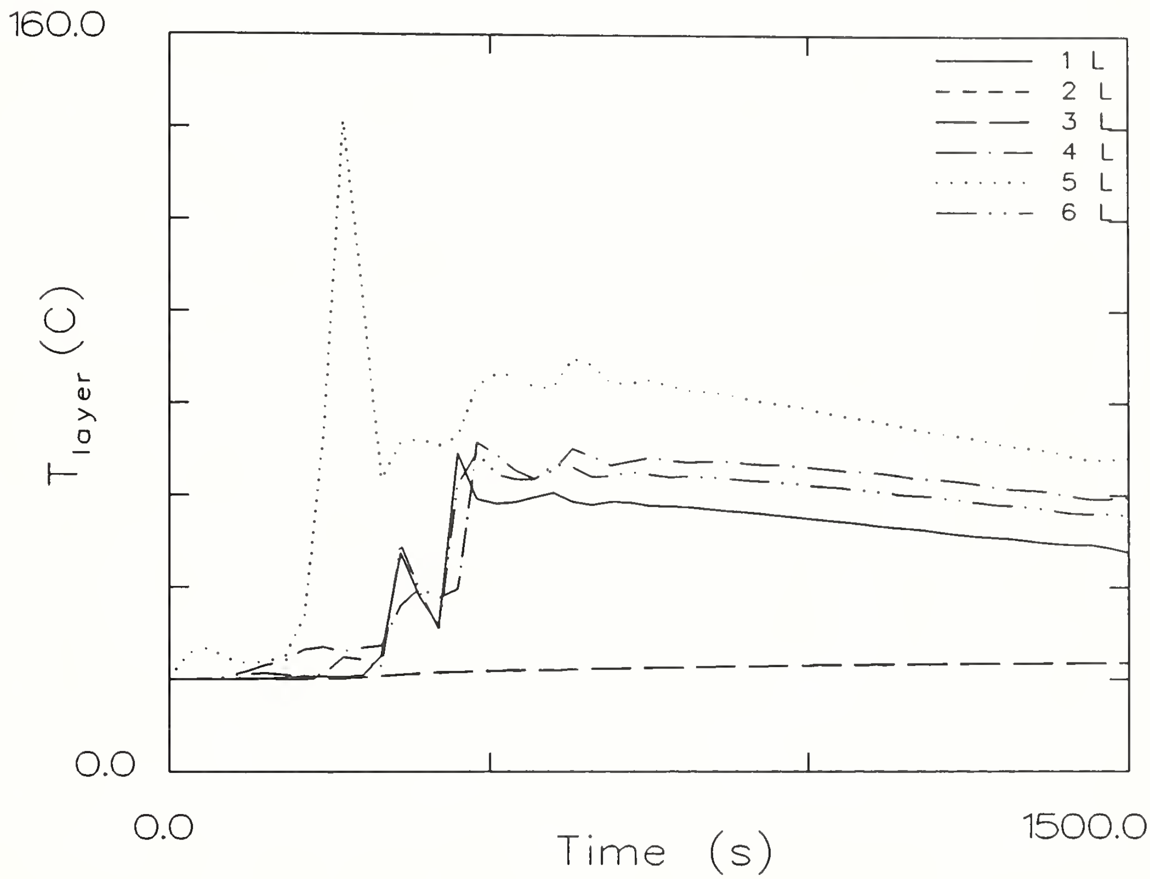


Figure 32. Lower layer temperature (°C) in scenario 2.

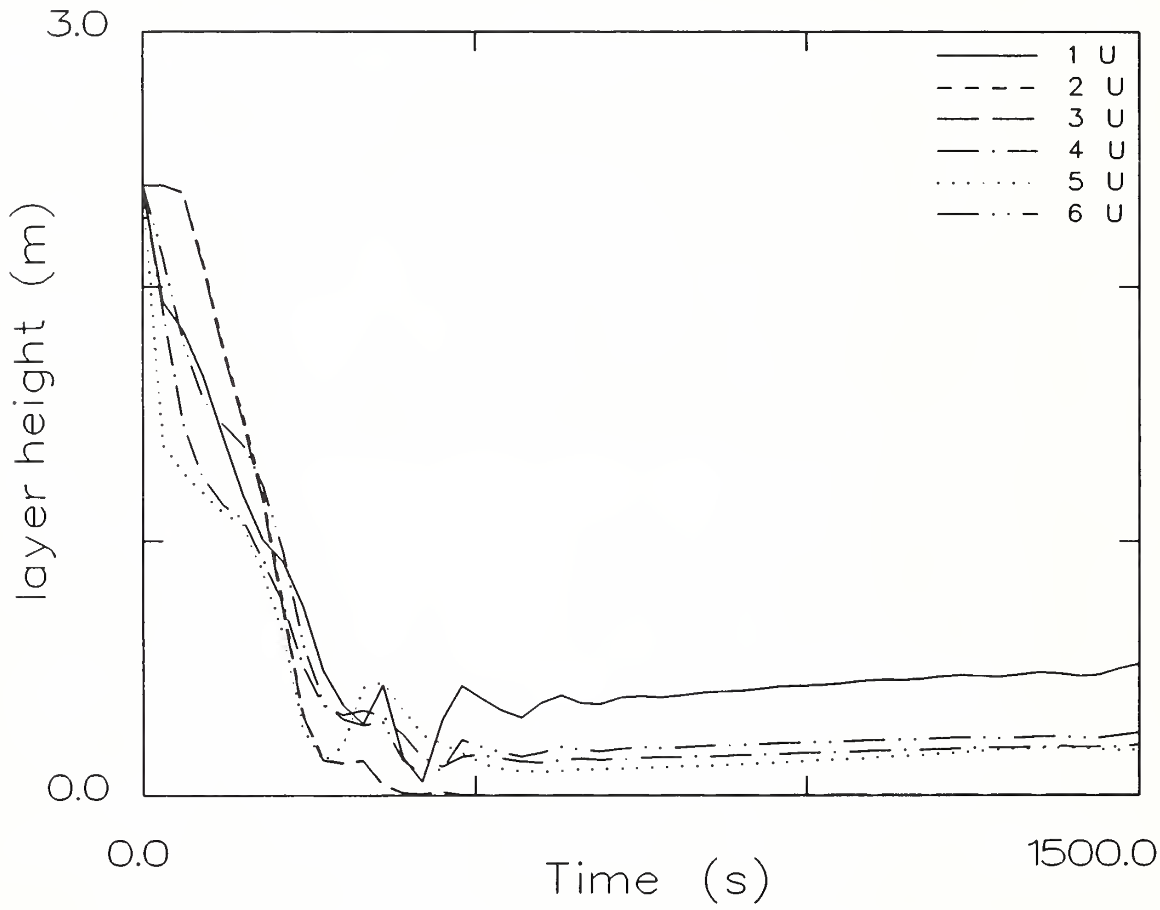


Figure 33. Layer interface height (m) in scenario 2.

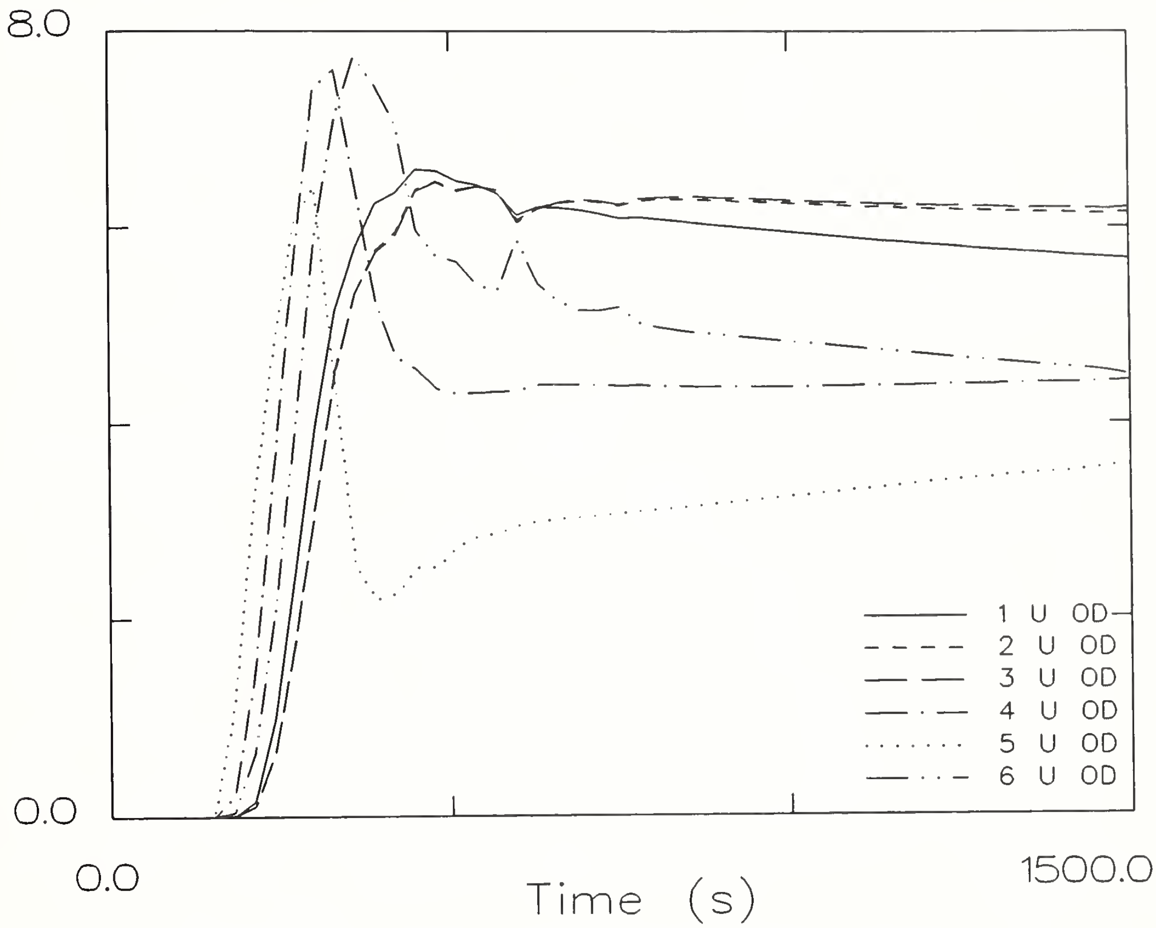


Figure 34. Smoke optical density (m^{-1}) in scenario 2.

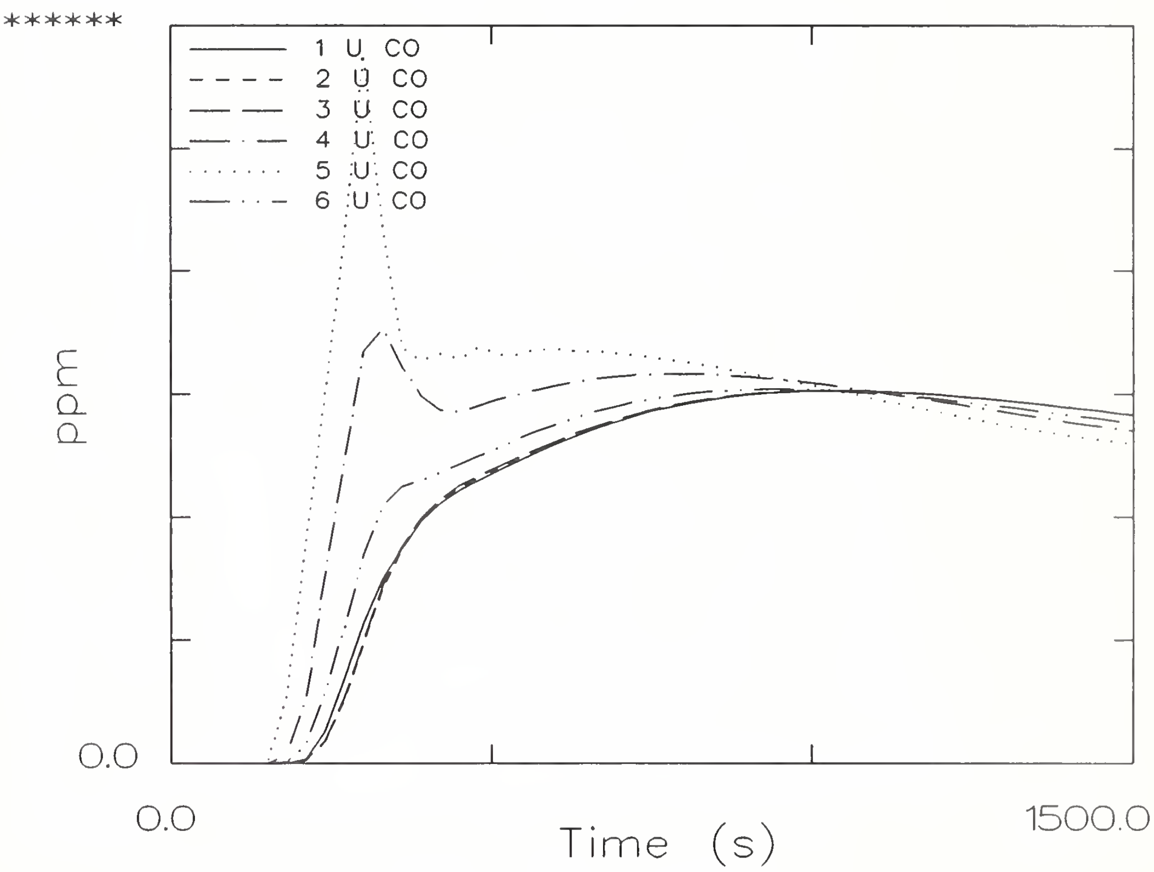


Figure 35. Carbon monoxide concentration (ppm) in scenario 2.

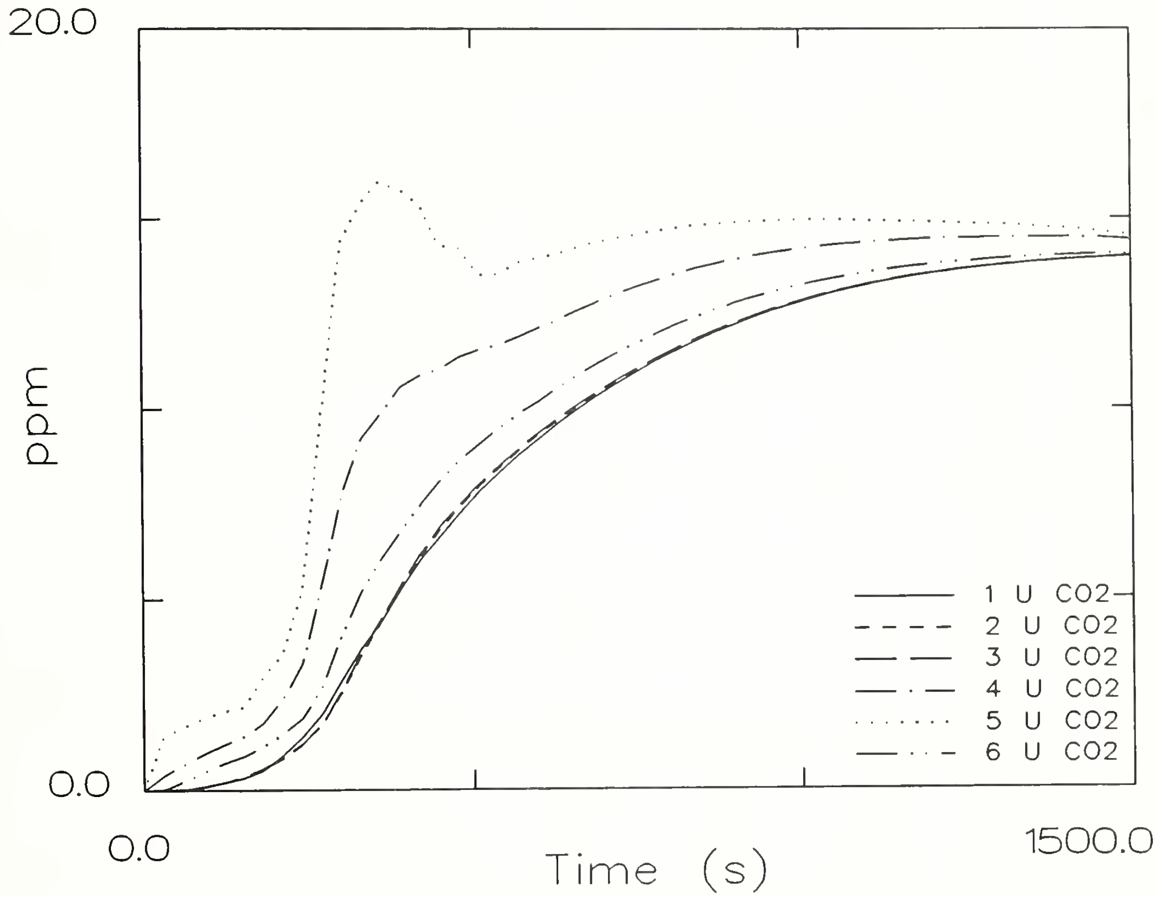


Figure 36. Carbon dioxide concentration (%) in scenario 2.

8.8.5 Printed Output from FAST for Scenario 2

```
FAST version 18.5.2 - created May 1, 1990       Scenario 2, Ranch House, Kitchen Greese Fire

Total compartments =                 6

 FLOOR PLAN

          Width        3.6     3.0     3.0     4.5     2.7     1.9
          Depth        3.8     3.6     3.4     8.1     3.8     8.8
          Height       2.4     2.4     2.4     2.4     2.4     2.4
          Area        13.7    10.8    10.2    36.5    10.3    16.9
          Volume      32.8    25.9    24.5    87.5    24.6    40.5
          Ceiling      2.4     2.4     2.4     2.4     2.4     2.4
          Floor        0.0     0.0     0.0     0.0     0.0     0.0

 NORMAL CONNECTIONS

  1 ( 1)  Width       0.00    0.00    0.00    0.00    0.00    1.10    0.81
          Soffit      0.00    0.00    0.00    0.00    0.00    2.10    1.22
          Sill        0.00    0.00    0.00    0.00    0.00    0.00    0.91
          a.Soffit    0.00    0.00    0.00    0.00    0.00    2.10    1.22
          a.Sill      0.00    0.00    0.00    0.00    0.00    0.00    0.91

  2 ( 1)  Width       0.00    0.00    0.00    0.00    0.00    1.10    0.00
          Soffit      0.00    0.00    0.00    0.00    0.00    2.10    0.00
          Sill        0.00    0.00    0.00    0.00    0.00    0.00    0.00
          a.Soffit    0.00    0.00    0.00    0.00    0.00    2.10    0.00
          a.Sill      0.00    0.00    0.00    0.00    0.00    0.00    0.00

  3 ( 1)  Width       0.00    0.00    0.00    0.00    0.00    1.10    0.00
          Soffit      0.00    0.00    0.00    0.00    0.00    2.10    0.00
          Sill        0.00    0.00    0.00    0.00    0.00    0.00    0.00
          a.Soffit    0.00    0.00    0.00    0.00    0.00    2.10    0.00
          a.Sill      0.00    0.00    0.00    0.00    0.00    0.00    0.00

  4 ( 1)  Width       0.00    0.00    0.00    0.00    1.10    1.10    0.00
          Soffit      0.00    0.00    0.00    0.00    2.10    2.10    0.00
          Sill        0.00    0.00    0.00    0.00    0.00    0.00    0.00
          a.Soffit    0.00    0.00    0.00    0.00    2.10    2.10    0.00
          a.Sill      0.00    0.00    0.00    0.00    0.00    0.00    0.00

  5 ( 1)  Width       0.00    0.00    0.00    1.10    0.00    0.00    0.00
          Soffit      0.00    0.00    0.00    2.10    0.00    0.00    0.00
          Sill        0.00    0.00    0.00    0.00    0.00    0.00    0.00
          a.Soffit    0.00    0.00    0.00    2.10    0.00    0.00    0.00
          a.Sill      0.00    0.00    0.00    0.00    0.00    0.00    0.00

  6 ( 1)  Width       1.10    1.10    1.10    1.10    0.00    0.00    0.00
          Soffit      2.10    2.10    2.10    2.10    0.00    0.00    0.00
          Sill        0.00    0.00    0.00    0.00    0.00    0.00    0.00
          a.Soffit    2.10    2.10    2.10    2.10    0.00    0.00    0.00
          a.Sill      0.00    0.00    0.00    0.00    0.00    0.00    0.00

 THERE ARE NO FAN CONNECTIONC


 Material names

  Ceiling:     GYPSUM    GYPSUM    GYPSUM    GYPSUM    GYPSUM    GYPSUM
  Walls:       GYPSUM    GYPSUM    GYPSUM    GYPSUM    GYPSUM    GYPSUM
  Floor:       CONCRETE  CONCRETE  CONCRETE  CONCRETE  CONCRETE  CONCRETE
```

Thermal data base used: THERMAL.TPF

Name	Conductivity	Spec.heat	Density	Thickness	Emissivity	HCL B's (1->4)				**Codes**
CONCRETE	1.75	1.000E+03	2.200E+03	0.150	0.940	0.00E+00	0.00E+00	0.00E+00	0.00E+00	188 U
GYPSUM	0.160	900.	790.	1.600E-02	0.900	6.30E-03	1.92E+02	5.87E-02	7.48E+03	38 U

Compartment of origin is	5
Print interval (seconds)	100
Number of fire specification intervals is	9
Total time (seconds)	2400
Fire position	1
Limiting oxygen index (%) =	6.0
Initial relative humidity (%) =	0.0

Fire type is a SPECIFIED (CONSTRAINED)

Pyrolysis temperature (K) =	300.
Ambient air temperature (K) =	293.
Ambient reference pressure (Pa) =	101300.
Reference elevation (m) =	0.
External ambient temperature (K) =	273.
External reference pressure (Pa) =	101300.
Reference elevation (m) =	0.

Fmass=	0.00	4.20E-03	4.20E-03	2.20E-02	5.06E-02	5.06E-02	1.31E-02	2.56E-02	1.31E-02	5.90E-03
Hcomb=	2.79E+07	2.79E+07	2.79E+07	2.80E+07	2.79E+07	2.79E+07	2.79E+07	2.80E+07	2.79E+07	2.80E+07
Fqdot=	0.00	1.17E+05	1.17E+05	6.15E+05	1.41E+06	1.41E+06	3.66E+05	7.16E+05	3.66E+05	1.65E+05
Fhigh=	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C/CO2=	0.00	0.00	0.00	5.00E-02	3.10E-02	3.10E-02	0.00	0.00	0.00	0.00
CO/CO2=	0.00	0.00	0.00	0.23	0.13	0.13	1.60E-02	3.10E-02	6.30E-02	0.00
H/C=	8.00E-02	8.00E-02	8.00E-02	8.00E-02	8.00E-02	8.00E-02	8.00E-02	8.00E-02	8.00E-02	8.00E-02
CT=	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Ftime=	5.0	1.45E+02	70.	30.	40.	50.	10.	1.40E+02	8.30E+02	

Dump file = SCEN-2.DMP

Time = 0.0 seconds.

Upper temp(K)	293.0	293.0	293.0	293.0	293.0	293.0	
Lower temp(K)	293.0	293.0	293.0	293.0	293.0	293.0	273.0
Upper vol(m**3)	0.0	0.0	0.0	0.1	0.0	0.0	
Layer depth(m)	0.0	0.0	0.0	0.0	0.0	0.0	
Ceiling temp(K)	293.0	293.0	293.0	293.0	293.0	293.0	
Up wall temp(K)	293.0	293.0	293.0	293.0	293.0	293.0	
Low wall temp(K)	293.0	293.0	293.0	293.0	293.0	293.0	
Floor temp(K)	293.0	293.0	293.0	293.0	293.0	293.0	
Plume flow(kg/s)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	
Pyrol rate(kg/s)	0.000E+00	0.000E+00	0.000E+00	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	
	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	0.000E+00	0.000E+00	0.000E+00	
Plume in ll(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	
Vent fire(W)	0.000E+00	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	0.000E+00	0.000E+00	0.000E+00	
Pressure(Pa)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	

Time = 100.0 seconds.

Upper temp(K)	296.5	294.8	294.8	346.3	439.2	311.3	
Lower temp(K)	293.1	293.0	293.0	294.1	300.4	293.9	273.0
Upper vol(m**3)	10.2	3.9	3.8	47.6	14.3	15.7	
Layer depth(m)	0.7	0.4	0.4	1.3	1.4	0.9	
Ceiling temp(K)	293.3	293.1	293.1	305.0	337.7	295.7	
Up wall temp(K)	293.2	293.1	293.1	302.1	328.6	295.0	
Low wall temp(K)	293.1	293.0	293.0	295.7	303.3	293.4	
Floor temp(K)	293.0	293.0	293.0	293.4	294.5	293.1	
Plume flow(kg/s)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	4.652E-01	0.000E+00	
Pyrol rate(kg/s)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	4.200E-03	0.000E+00	
Fire size(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.170E+05	0.000E+00	
	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	0.000E+00	0.000E+00	0.000E+00	
Plume in ll(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.170E+05	0.000E+00	
Vent fire(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
On target(W/m^2)	2.005E+01	1.003E+01	1.031E+01	3.956E+02	1.683E+03	1.138E+02	
Pressure(Pa)	4.715E-01	7.461E-01	7.449E-01	2.766E-01	-6.337E-01	6.098E-01	

Time = 200.0 seconds.

Upper temp(K)	308.9	304.3	304.5	396.9	601.9	339.8	
Lower temp(K)	293.6	293.0	293.0	302.3	309.5	295.1	273.0
Upper vol(m**3)	19.6	13.8	13.3	63.0	19.0	22.5	
Layer depth(m)	1.4	1.3	1.3	1.7	1.9	1.3	
Ceiling temp(K)	295.0	294.3	294.4	318.8	398.5	301.8	
Up wall temp(K)	294.5	294.0	294.1	313.1	381.5	299.7	
Low wall temp(K)	293.4	293.2	293.3	300.7	330.1	294.6	
Floor temp(K)	293.1	293.0	293.0	294.1	298.3	293.2	
Plume flow(kg/s)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	7.846E-01	0.000E+00	
Pyrol rate(kg/s)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.691E-02	0.000E+00	
Fire size(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	4.724E+05	0.000E+00	
	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	0.000E+00	0.000E+00	0.000E+00	
Plume in ll(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	4.724E+05	0.000E+00	
Vent fire(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
On target(W/m^2)	9.762E+01	6.812E+01	6.924E+01	9.845E+02	6.988E+03	3.361E+02	
Pressure(Pa)	4.053E+00	4.727E+00	4.719E+00	3.411E+00	1.542E+00	4.249E+00	

Time = 300.0 seconds.

Upper temp(K)	357.5	340.5	341.3	539.3	965.8	396.5	
Lower temp(K)	293.9	293.3	293.3	308.9	423.9	302.0	273.0
Upper vol(m**3)	24.2	23.7	22.4	73.9	22.8	33.3	
Layer depth(m)	1.8	2.2	2.2	2.0	2.2	2.0	
Ceiling temp(K)	308.6	303.2	303.4	385.8	774.5	324.1	
Up wall temp(K)	305.0	300.8	300.9	370.3	748.9	317.5	
Low wall temp(K)	296.7	296.0	296.1	336.8	713.0	301.8	
Floor temp(K)	293.5	293.4	293.4	299.7	359.0	294.3	
Plume flow(kg/s)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	7.016E-01	0.000E+00	
Pyrol rate(kg/s)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	4.310E-02	0.000E+00	
Fire size(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.202E+06	0.000E+00	
	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	0.000E+00	0.000E+00	0.000E+00	
Plume in ll(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.202E+06	0.000E+00	
Vent fire(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
On target(W/m^2)	5.061E+02	3.427E+02	3.492E+02	4.356E+03	4.866E+04	9.780E+02	
Pressure(Pa)	3.561E+00	3.702E+00	3.673E+00	1.172E+00	-2.332E+00	2.776E+00	

Time = 400.0 seconds.

Upper temp(K)	341.1	339.1	339.6	492.5	811.6	379.4	
Lower temp(K)	308.7	294.2	294.3	313.8	350.7	310.4	273.0
Upper vol(m**3)	30.3	25.6	24.2	80.8	23.3	38.1	
Layer depth(m)	2.2	2.4	2.4	2.2	2.3	2.3	
Ceiling temp(K)	310.8	308.0	308.3	393.1	699.0	328.6	
Up wall temp(K)	307.1	304.8	305.0	378.0	678.7	321.7	
Low wall temp(K)	299.8	298.7	298.8	347.7	644.0	306.9	
Floor temp(K)	294.0	293.9	294.0	302.7	363.3	295.2	
Plume flow(kg/s)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	2.985E-01	0.000E+00	
Pyrol rate(kg/s)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	2.114E-02	0.000E+00	
Fire size(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	5.909E+05	0.000E+00	
	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	0.000E+00	0.000E+00	0.000E+00	
Plume in ll(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	5.909E+05	0.000E+00	
Vent fire(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
On target(W/m^2)	3.474E+02	3.297E+02	3.341E+02	2.901E+03	2.405E+04	7.531E+02	
Pressure(Pa)	-1.731E+00	-1.745E+00	-1.764E+00	-4.335E+00	-6.996E+00	-2.629E+00	

Time = 500.0 seconds.

Upper temp(K)	335.1	335.3	335.7	470.0	721.4	371.1	
Lower temp(K)	319.0	294.8	294.8	342.8	381.1	331.7	273.0
Upper vol(m**3)	25.3	25.9	24.4	80.9	23.6	36.1	
Layer depth(m)	1.8	2.4	2.4	2.2	2.3	2.1	
Ceiling temp(K)	311.2	309.7	309.9	392.5	645.5	329.9	
Up wall temp(K)	307.5	306.3	306.5	378.4	628.4	323.1	
Low wall temp(K)	301.8	300.2	300.3	353.9	603.2	310.8	
Floor temp(K)	294.1	294.3	294.3	304.0	361.6	295.7	
Plume flow(kg/s)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	2.474E-01	0.000E+00	
Pyrol rate(kg/s)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.301E-02	0.000E+00	
Fire size(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	3.636E+05	0.000E+00	
	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	0.000E+00	0.000E+00	0.000E+00	
Plume in ll(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	3.636E+05	0.000E+00	
Vent fire(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
On target(W/m^2)	2.958E+02	2.971E+02	3.008E+02	2.337E+03	1.486E+04	6.545E+02	
Pressure(Pa)	-2.592E+00	-2.916E+00	-2.935E+00	-5.537E+00	-8.092E+00	-3.473E+00	

Time = 600.0 seconds.

Upper temp(K)	334.0	334.4	334.8	462.2	691.2	368.8	
Lower temp(K)	324.7	295.0	295.0	333.3	369.4	330.3	273.0
Upper vol(m**3)	28.3	25.9	24.4	82.8	24.0	37.9	
Layer depth(m)	2.1	2.4	2.4	2.3	2.3	2.2	
Ceiling temp(K)	311.8	310.8	311.1	393.8	626.3	331.2	
Up wall temp(K)	308.2	307.4	307.6	380.1	611.0	324.5	
Low wall temp(K)	303.6	301.2	301.3	357.8	587.0	313.4	
Floor temp(K)	294.3	294.5	294.5	304.9	360.5	296.0	
Plume flow(kg/s)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.858E-01	0.000E+00	
Pyrol rate(kg/s)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.215E-02	0.000E+00	
Fire size(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	2.994E+05	0.000E+00	
	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	0.000E+00	0.000E+00	0.000E+00	
Plume in ll(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	2.994E+05	0.000E+00	
Vent fire(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
On target(W/m^2)	2.865E+02	2.895E+02	2.932E+02	2.158E+03	1.246E+04	6.276E+02	
Pressure(Pa)	-2.446E+00	-2.566E+00	-2.581E+00	-5.207E+00	-7.760E+00	-3.418E+00	

Time = 700.0 seconds.

Upper temp(K)	333.2	333.5	334.0	456.0	668.0	366.7	
Lower temp(K)	323.3	295.2	295.2	335.9	368.3	329.7	273.0
Upper vol(m**3)	28.1	25.9	24.4	82.4	23.9	37.7	
Layer depth(m)	2.1	2.4	2.4	2.3	2.3	2.2	
Ceiling temp(K)	312.5	311.7	312.0	394.0	607.7	332.2	
Up wall temp(K)	308.9	308.2	308.4	381.0	594.5	325.7	
Low wall temp(K)	304.6	302.0	302.1	360.4	570.1	315.1	
Floor temp(K)	294.4	294.7	294.7	305.5	358.7	296.3	
Plume flow(kg/s)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.933E-01	0.000E+00	
Pyrol rate(kg/s)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.128E-02	0.000E+00	
Fire size(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	2.679E+05	0.000E+00	
	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	0.000E+00	0.000E+00	0.000E+00	
Plume in ll(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	2.679E+05	0.000E+00	
Vent fire(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
On target(W/m^2)	2.794E+02	2.823E+02	2.859E+02	2.023E+03	1.082E+04	6.046E+02	
Pressure(Pa)	-2.357E+00	-2.502E+00	-2.522E+00	-5.011E+00	-7.429E+00	-3.083E+00	

Time = 800.0 seconds.

Upper temp(K)	332.3	332.6	333.1	449.3	644.3	364.7	
Lower temp(K)	322.1	295.4	295.4	337.4	366.6	330.0	273.0
Upper vol(m**3)	27.5	25.9	24.4	81.9	23.8	37.3	
Layer depth(m)	2.0	2.4	2.4	2.2	2.3	2.2	
Ceiling temp(K)	313.0	312.4	312.7	393.5	588.9	332.9	
Up wall temp(K)	309.5	308.9	309.1	381.2	578.0	326.6	
Low wall temp(K)	305.4	302.6	302.7	361.9	552.8	316.5	
Floor temp(K)	294.4	294.8	294.8	305.9	356.7	296.4	
Plume flow(kg/s)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.978E-01	0.000E+00	
Pyrol rate(kg/s)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.041E-02	0.000E+00	
Fire size(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	2.381E+05	0.000E+00	
	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	0.000E+00	0.000E+00	0.000E+00	
Plume in ll(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	2.381E+05	0.000E+00	
Vent fire(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
On target(W/m^2)	2.722E+02	2.749E+02	2.784E+02	1.883E+03	9.304E+03	5.819E+02	
Pressure(Pa)	-2.271E+00	-2.428E+00	-2.447E+00	-4.855E+00	-7.193E+00	-3.020E+00	

Time = 900.0 seconds.

Upper temp(K)	331.4	331.8	332.2	441.6	616.9	362.4	
Lower temp(K)	320.5	295.5	295.6	338.2	363.9	330.1	273.0
Upper vol(m**3)	26.4	25.9	24.5	81.6	23.7	36.7	
Layer depth(m)	1.9	2.4	2.4	2.2	2.3	2.2	
Ceiling temp(K)	313.4	313.0	313.3	392.1	569.7	333.3	
Up wall temp(K)	310.0	309.5	309.7	380.8	561.0	327.2	
Low wall temp(K)	306.0	303.2	303.3	362.5	535.1	317.5	
Floor temp(K)	294.5	294.9	295.0	306.1	354.6	296.6	
Plume flow(kg/s)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.943E-01	0.000E+00	
Pyrol rate(kg/s)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	9.543E-03	0.000E+00	
Fire size(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	2.012E+05	0.000E+00	
	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	0.000E+00	0.000E+00	0.000E+00	
Plume in ll(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	2.012E+05	0.000E+00	
Vent fire(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
On target(W/m^2)	2.646E+02	2.679E+02	2.713E+02	1.730E+03	7.753E+03	5.568E+02	
Pressure(Pa)	-2.295E+00	-2.483E+00	-2.497E+00	-4.843E+00	-7.108E+00	-3.205E+00	

Time = 1000.0 seconds.

Upper temp(K)	330.4	330.9	331.3	434.4	589.4	360.1	
Lower temp(K)	319.8	295.7	295.8	336.6	359.0	330.1	273.0
Upper vol(m**3)	25.8	25.9	24.4	81.7	23.7	36.6	
Layer depth(m)	1.9	2.4	2.4	2.2	2.3	2.2	
Ceiling temp(K)	313.7	313.4	313.7	390.5	552.3	333.5	
Up wall temp(K)	310.3	310.0	310.2	380.0	545.7	327.6	
Low wall temp(K)	306.5	303.7	303.8	362.6	519.0	318.3	
Floor temp(K)	294.6	295.0	295.1	306.3	352.7	296.7	
Plume flow(kg/s)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.783E-01	0.000E+00	
Pyrol rate(kg/s)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	8.676E-03	0.000E+00	
Fire size(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.591E+05	0.000E+00	
	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	0.000E+00	0.000E+00	0.000E+00	
Plume in ll(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.591E+05	0.000E+00	
Vent fire(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
On target(W/m^2)	2.568E+02	2.608E+02	2.639E+02	1.593E+03	6.392E+03	5.325E+02	
Pressure(Pa)	-2.489E+00	-2.716E+00	-2.732E+00	-4.984E+00	-7.100E+00	-3.277E+00	

Time = 1100.0 seconds.

Upper temp(K)	329.8	330.1	330.5	429.8	576.0	358.3	
Lower temp(K)	320.7	295.8	295.8	333.7	353.5	328.4	273.0
Upper vol(m**3)	26.9	25.9	24.4	81.7	23.6	37.1	
Layer depth(m)	2.0	2.4	2.4	2.2	2.3	2.2	
Ceiling temp(K)	313.9	313.6	313.9	388.5	538.5	333.4	
Up wall temp(K)	310.6	310.3	310.5	378.9	533.6	327.8	
Low wall temp(K)	306.9	304.0	304.2	362.1	505.4	318.9	
Floor temp(K)	294.6	295.1	295.2	306.3	351.0	296.8	
Plume flow(kg/s)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.742E-01	0.000E+00	
Pyrol rate(kg/s)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	7.808E-03	0.000E+00	
Fire size(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.463E+05	0.000E+00	
	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	0.000E+00	0.000E+00	0.000E+00	
Plume in ll(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.463E+05	0.000E+00	
Vent fire(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
On target(W/m^2)	2.514E+02	2.543E+02	2.574E+02	1.508E+03	5.794E+03	5.135E+02	
Pressure(Pa)	-2.345E+00	-2.505E+00	-2.520E+00	-4.714E+00	-6.766E+00	-3.138E+00	

Time = 1200.0 seconds.

Upper temp(K)	328.6	328.8	329.2	423.3	561.2	355.6	
Lower temp(K)	317.3	295.9	296.0	335.0	352.7	326.6	273.0
Upper vol(m**3)	26.1	25.9	24.4	80.6	23.3	36.4	
Layer depth(m)	1.9	2.4	2.4	2.2	2.3	2.2	
Ceiling temp(K)	313.9	313.7	313.9	385.6	521.9	332.9	
Up wall temp(K)	310.7	310.5	310.7	376.8	518.7	327.6	
Low wall temp(K)	306.9	304.3	304.5	361.0	489.9	319.0	
Floor temp(K)	294.6	295.2	295.2	306.2	348.8	296.8	
Plume flow(kg/s)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.922E-01	0.000E+00	
Pyrol rate(kg/s)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	6.941E-03	0.000E+00	
Fire size(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.437E+05	0.000E+00	
	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	0.000E+00	0.000E+00	0.000E+00	
Plume in ll(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.437E+05	0.000E+00	
Vent fire(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
On target(W/m^2)	2.422E+02	2.436E+02	2.466E+02	1.395E+03	5.177E+03	4.867E+02	
Pressure(Pa)	-2.114E+00	-2.310E+00	-2.326E+00	-4.382E+00	-6.330E+00	-2.824E+00	

Time = 1300.0 seconds.

Upper temp(K)	327.3	327.7	328.1	415.5	530.3	353.2	
Lower temp(K)	316.2	296.3	296.4	333.3	348.5	327.2	273.0
Upper vol(m**3)	24.8	25.8	24.4	81.2	23.5	36.1	
Layer depth(m)	1.8	2.4	2.4	2.2	2.3	2.1	
Ceiling temp(K)	313.8	313.7	313.9	382.8	506.3	332.4	
Up wall temp(K)	310.8	310.6	310.8	374.9	504.5	327.5	
Low wall temp(K)	307.2	304.5	304.7	359.6	475.6	319.3	
Floor temp(K)	294.6	295.3	295.3	306.2	347.2	296.9	
Plume flow(kg/s)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.555E-01	0.000E+00	
Pyrol rate(kg/s)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	6.073E-03	0.000E+00	
Fire size(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	9.361E+04	0.000E+00	
	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	0.000E+00	0.000E+00	0.000E+00	
Plume in ll(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	9.361E+04	0.000E+00	
Vent fire(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
On target(W/m^2)	2.313E+02	2.350E+02	2.378E+02	1.265E+03	4.044E+03	4.625E+02	
Pressure(Pa)	-2.537E+00	-2.800E+00	-2.814E+00	-4.850E+00	-6.658E+00	-3.332E+00	

Time = 1400.0 seconds.

Upper temp(K)	326.9	326.8	327.2	415.2	543.8	352.0	
Lower temp(K)	313.5	296.0	296.1	329.6	343.7	321.0	273.0
Upper vol(m**3)	28.9	25.9	24.4	81.1	23.2	37.7	
Layer depth(m)	2.1	2.4	2.4	2.2	2.3	2.2	
Ceiling temp(K)	313.6	313.4	313.7	380.3	498.9	331.7	
Up wall temp(K)	310.8	310.6	310.8	373.1	497.6	327.1	
Low wall temp(K)	307.1	304.6	304.8	358.2	466.7	319.1	
Floor temp(K)	294.7	295.3	295.3	306.0	345.8	296.9	
Plume flow(kg/s)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.796E-01	0.000E+00	
Pyrol rate(kg/s)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	5.900E-03	0.000E+00	
Fire size(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.359E+05	0.000E+00	
	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	0.000E+00	0.000E+00	0.000E+00	
Plume in ll(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.359E+05	0.000E+00	
Vent fire(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
On target(W/m^2)	2.285E+02	2.277E+02	2.305E+02	1.260E+03	4.518E+03	4.500E+02	
Pressure(Pa)	-1.790E+00	-1.898E+00	-1.915E+00	-3.859E+00	-5.689E+00	-2.377E+00	

Time = 1500.0 seconds.

Upper temp(K)	325.1	325.7	326.0	403.6	494.0	348.6	
Lower temp(K)	312.0	296.9	296.9	332.9	352.9	324.6	273.0
Upper vol(m**3)	23.5	25.8	24.4	81.0	23.6	35.4	
Layer depth(m)	1.7	2.4	2.4	2.2	2.3	2.1	
Ceiling temp(K)	313.4	313.3	313.6	376.9	480.9	330.9	
Up wall temp(K)	310.7	310.6	310.8	370.6	481.2	326.7	
Low wall temp(K)	307.2	304.8	304.9	356.4	453.1	319.1	
Floor temp(K)	294.7	295.3	295.4	305.9	344.3	296.9	
Plume flow(kg/s)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.426E-01	0.000E+00	
Pyrol rate(kg/s)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	5.900E-03	0.000E+00	
Fire size(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	5.376E+04	0.000E+00	
	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	0.000E+00	0.000E+00	0.000E+00	
Plume in ll(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	5.376E+04	0.000E+00	
Vent fire(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
On target(W/m^2)	2.140E+02	2.186E+02	2.211E+02	1.081E+03	2.944E+03	4.170E+02	
Pressure(Pa)	-2.725E+00	-3.094E+00	-3.110E+00	-5.017E+00	-6.656E+00	-3.451E+00	

Time = 1600.0 seconds.

Upper temp(K)	325.9	324.9	325.2	412.0	547.1	350.1	
Lower temp(K)	307.8	296.1	296.2	326.6	339.1	316.6	273.0
Upper vol(m**3)	28.9	25.9	24.4	80.9	23.0	37.8	
Layer depth(m)	2.1	2.4	2.4	2.2	2.2	2.2	
Ceiling temp(K)	313.2	312.9	313.2	375.4	483.7	330.2	
Up wall temp(K)	310.6	310.4	310.6	369.4	483.0	326.3	
Low wall temp(K)	306.7	304.8	304.9	355.1	450.8	318.7	
Floor temp(K)	294.7	295.4	295.4	305.8	343.7	296.9	
Plume flow(kg/s)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.893E-01	0.000E+00	
Pyrol rate(kg/s)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	5.900E-03	0.000E+00	
Fire size(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.647E+05	0.000E+00	
	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	0.000E+00	0.000E+00	0.000E+00	
Plume in ll(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.647E+05	0.000E+00	
Vent fire(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
On target(W/m^2)	2.204E+02	2.127E+02	2.154E+02	1.210E+03	4.636E+03	4.312E+02	
Pressure(Pa)	-1.105E+00	-1.168E+00	-1.183E+00	-3.091E+00	-4.962E+00	-1.703E+00	

Time = 1700.0 seconds.

Upper temp(K)	325.2	325.7	326.1	406.0	510.6	349.1	
Lower temp(K)	316.4	297.2	297.3	324.4	337.8	323.8	273.0
Upper vol(m**3)	26.2	25.8	24.3	83.5	23.9	37.3	
Layer depth(m)	1.9	2.4	2.4	2.3	2.3	2.2	
Ceiling temp(K)	313.3	313.1	313.4	374.8	477.0	330.3	
Up wall temp(K)	310.8	310.6	310.8	369.1	476.7	326.4	
Low wall temp(K)	307.3	305.0	305.1	354.3	445.6	319.0	
Floor temp(K)	294.8	295.4	295.4	306.0	343.9	297.0	
Plume flow(kg/s)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.009E-01	0.000E+00	
Pyrol rate(kg/s)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	5.900E-03	0.000E+00	
Fire size(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	8.468E+04	0.000E+00	
	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	0.000E+00	0.000E+00	0.000E+00	
Plume in ll(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	8.468E+04	0.000E+00	
Vent fire(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
On target(W/m^2)	2.154E+02	2.192E+02	2.218E+02	1.116E+03	3.418E+03	4.216E+02	
Pressure(Pa)	-2.500E+00	-2.689E+00	-2.701E+00	-4.727E+00	-6.516E+00	-3.302E+00	

Time = 1800.0 seconds.

Upper temp(K)	323.9	323.1	323.4	400.6	525.6	345.6	
Lower temp(K)	304.7	296.4	296.5	329.2	342.5	316.8	273.0
Upper vol(m**3)	25.4	25.9	24.4	78.9	22.7	35.6	
Layer depth(m)	1.9	2.4	2.4	2.2	2.2	2.1	
Ceiling temp(K)	312.7	312.6	312.9	370.5	464.2	328.9	
Up wall temp(K)	310.4	310.3	310.5	365.7	464.6	325.4	
Low wall temp(K)	306.4	304.9	305.1	352.3	435.2	318.2	
Floor temp(K)	294.7	295.4	295.5	305.7	341.9	296.9	
Plume flow(kg/s)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	2.273E-01	0.000E+00	
Pyrol rate(kg/s)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	5.900E-03	0.000E+00	
Fire size(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.650E+05	0.000E+00	
	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	0.000E+00	0.000E+00	0.000E+00	
Plume in ll(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.650E+05	0.000E+00	
Vent fire(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
On target(W/m^2)	2.050E+02	1.987E+02	2.009E+02	1.037E+03	3.888E+03	3.890E+02	
Pressure(Pa)	-8.583E-01	-1.081E+00	-1.094E+00	-2.749E+00	-4.566E+00	-1.404E+00	

Time = 1900.0 seconds.

Upper temp(K)	325.9	325.5	325.8	411.3	539.5	350.0	
Lower temp(K)	304.0	297.1	297.2	319.5	333.8	308.3	273.0
Upper vol(m**3)	31.3	25.7	24.3	83.4	23.5	39.2	
Layer depth(m)	2.3	2.4	2.4	2.3	2.3	2.3	
Ceiling temp(K)	313.1	312.8	313.0	373.2	477.6	329.6	
Up wall temp(K)	310.8	310.5	310.7	368.0	475.9	326.1	
Low wall temp(K)	306.7	305.1	305.2	352.7	441.7	318.4	
Floor temp(K)	294.8	295.5	295.5	306.0	343.8	297.1	
Plume flow(kg/s)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.268E-01	0.000E+00	
Pyrol rate(kg/s)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	5.900E-03	0.000E+00	
Fire size(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.441E+05	0.000E+00	
	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	0.000E+00	0.000E+00	0.000E+00	
Plume in ll(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.441E+05	0.000E+00	
Vent fire(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
On target(W/m^2)	2.204E+02	2.173E+02	2.201E+02	1.199E+03	4.363E+03	4.304E+02	
Pressure(Pa)	-1.832E+00	-1.886E+00	-1.905E+00	-3.890E+00	-5.719E+00	-2.272E+00	

Time = 2000.0 seconds.

Upper temp(K)	323.2	323.8	324.1	393.3	459.3	344.2	
Lower temp(K)	305.1	297.8	297.8	333.1	356.5	320.4	273.0
Upper vol(m**3)	21.4	25.7	24.3	79.0	23.4	33.8	
Layer depth(m)	1.6	2.4	2.4	2.2	2.3	2.0	
Ceiling temp(K)	312.7	312.7	313.0	369.5	454.7	328.8	
Up wall temp(K)	310.6	310.5	310.7	365.0	455.4	325.5	
Low wall temp(K)	306.7	305.2	305.3	351.4	428.2	318.4	
Floor temp(K)	294.8	295.5	295.5	306.0	342.3	297.1	
Plume flow(kg/s)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.602E-01	0.000E+00	
Pyrol rate(kg/s)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	5.900E-03	0.000E+00	
Fire size(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	2.509E+04	0.000E+00	
	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	0.000E+00	0.000E+00	0.000E+00	
Plume in ll(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	2.509E+04	0.000E+00	
Vent fire(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
On target(W/m^2)	1.994E+02	2.046E+02	2.069E+02	9.342E+02	2.095E+03	3.763E+02	
Pressure(Pa)	-3.033E+00	-3.608E+00	-3.621E+00	-5.401E+00	-6.848E+00	-3.974E+00	

Time = 2100.0 seconds.

Upper temp(K)	324.9	323.2	323.5	407.5	537.4	347.8	
Lower temp(K)	302.2	296.6	296.7	322.6	334.4	312.3	273.0
Upper vol(m**3)	28.6	25.8	24.4	80.4	22.8	37.5	
Layer depth(m)	2.1	2.4	2.4	2.2	2.2	2.2	
Ceiling temp(K)	312.6	312.2	312.5	369.3	465.9	328.3	
Up wall temp(K)	310.5	310.2	310.4	364.8	464.3	325.2	
Low wall temp(K)	306.2	305.0	305.2	350.3	430.5	317.9	
Floor temp(K)	294.8	295.5	295.5	305.9	342.5	297.1	
Plume flow(kg/s)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.989E-01	0.000E+00	
Pyrol rate(kg/s)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	5.900E-03	0.000E+00	
Fire size(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.650E+05	0.000E+00	
	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	0.000E+00	0.000E+00	0.000E+00	
Plume in ll(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.650E+05	0.000E+00	
Vent fire(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
On target(W/m^2)	2.125E+02	1.998E+02	2.023E+02	1.140E+03	4.288E+03	4.091E+02	
Pressure(Pa)	-9.568E-01	-1.040E+00	-1.053E+00	-2.914E+00	-4.749E+00	-1.614E+00	

Time = 2200.0 seconds.

Upper temp(K)	324.9	325.1	325.4	406.4	521.9	348.4	
Lower temp(K)	316.5	297.5	297.6	316.1	332.5	313.1	273.0
Upper vol(m**3)	29.5	25.7	24.3	84.4	23.9	39.1	
Layer depth(m)	2.2	2.4	2.4	2.3	2.3	2.3	
Ceiling temp(K)	312.8	312.6	312.8	370.6	469.0	328.8	
Up wall temp(K)	310.7	310.5	310.7	365.9	466.8	325.7	
Low wall temp(K)	306.8	305.2	305.4	350.3	433.3	318.0	
Floor temp(K)	294.9	295.6	295.6	306.3	343.9	297.2	
Plume flow(kg/s)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	9.096E-02	0.000E+00	
Pyrol rate(kg/s)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	5.900E-03	0.000E+00	
Fire size(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.151E+05	0.000E+00	
	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	0.000E+00	0.000E+00	0.000E+00	
Plume in ll(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.151E+05	0.000E+00	
Vent fire(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
On target(W/m^2)	2.130E+02	2.143E+02	2.169E+02	1.123E+03	3.769E+03	4.150E+02	
Pressure(Pa)	-2.303E+00	-2.415E+00	-2.437E+00	-4.399E+00	-6.176E+00	-2.656E+00	

Time = 2300.0 seconds.

Upper temp(K)	321.7	322.0	322.3	385.2	456.5	340.4	
Lower temp(K)	299.4	298.6	299.1	330.2	354.5	314.8	273.0
Upper vol(m**3)	20.8	25.9	24.5	76.7	22.9	32.9	
Layer depth(m)	1.5	2.4	2.4	2.1	2.2	1.9	
Ceiling temp(K)	312.2	312.2	312.4	365.1	441.6	327.2	
Up wall temp(K)	310.3	310.3	310.5	361.4	442.3	324.5	
Low wall temp(K)	305.9	305.2	305.4	348.4	417.0	317.4	
Floor temp(K)	294.8	295.6	295.6	306.1	341.3	297.2	
Plume flow(kg/s)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	2.068E-01	0.000E+00	
Pyrol rate(kg/s)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	5.900E-03	0.000E+00	
Fire size(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	7.622E+04	0.000E+00	
	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	0.000E+00	0.000E+00	0.000E+00	
Plume in ll(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	7.622E+04	0.000E+00	
Vent fire(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
On target(W/m^2)	1.887E+02	1.909E+02	1.929E+02	8.254E+02	2.035E+03	3.416E+02	
Pressure(Pa)	-2.192E+00	-2.847E+00	-2.857E+00	-4.319E+00	-5.793E+00	-3.072E+00	

```
Time = 2400.0 seconds.

   Upper temp(K)      324.7      323.3      323.7      407.2      536.7      347.6
   Lower temp(K)      300.9      297.1      297.3      319.4      331.8      309.1      273.0
 Upper vol(m**3)       29.8       25.8       24.3       81.4       23.0       38.2
  Layer depth(m)        2.2        2.4        2.4        2.2        2.2        2.3
 Ceiling temp(K)      312.4      312.0      312.2      367.8      463.6      327.6
 Up wall temp(K)      310.5      310.1      310.3      363.5      460.8      324.8
Low wall temp(K)      305.9      305.1      305.2      348.5      426.1      317.4
   Floor temp(K)      294.9      295.6      295.6      306.3      343.0      297.2

Plume flow(kg/s)  0.000E+00  0.000E+00  0.000E+00  0.000E+00  1.750E-01  0.000E+00
Pyrol rate(kg/s)  0.000E+00  0.000E+00  0.000E+00  0.000E+00  5.900E-03  0.000E+00
    Fire size(W)  0.000E+00  0.000E+00  0.000E+00  0.000E+00  1.650E+05  0.000E+00
                  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  0.000E+00  0.000E+00  0.000E+00
  Plume in ll(W)  0.000E+00  0.000E+00  0.000E+00  0.000E+00  1.650E+05  0.000E+00
    Vent fire(W)  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00
On target(W/m^2)  2.110E+02  2.008E+02  2.034E+02  1.135E+03  4.265E+03  4.078E+02
    Pressure(Pa) -1.226E+00 -1.287E+00 -1.301E+00 -3.191E+00 -5.019E+00 -1.844E+00
```

8.8.6 Input Data for EXITT for Scenario 2 (Example Data File SCEN-2.BLD)

```
ROOMS 6 21
NODESTOFAST 1 2 3 4 5 6 1 4 6 1 6 6 4 4 8 8 8 7 8 7 8
NODESTOEXITT 1 2 3 4 5 6 7 9 8 1 8 8 4 9 1 2 3 4 4 9 5
NODEHGT 2.4 2.4 2.4 2.4 2.4 2.4 2.4 2.4 2.4 2.4
        2.4 2.4 2.4 2.4 2.4 2.4 2.4 2.4 2.4 2.4 2.4
FLRHGT  0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
        0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
AMBNOISE 35 35 35 35 35 35 35 55 35 35 35 35 55 55 35 35 35 35 35 55 35
DETECTORS 1 -9 9
          71 83 71 83 83 83 59 83 95 71 95 95 83 83 71 83 71 83 83 83 83
NODETONODE 27
 1 10 1.89     1 11 3.41     1 15 1.83
 2 11 2.71     2 16 1.52
 3  9 2.13     3 17 1.52
 4  8 4.27     4 13 2.38     4 18 3.13     4 19 2.13
 5 12 2.74     5 14 3.35     5 21 2.13
 6  9 2.51
 7 10 1.68
 8 13 3.30     8 14 2.05     8 20 2.13
 9 11 2.06     9 12 2.44
10 11 4.27    10 15 1.57
12 13 1.57
13 18 3.69
14 20 1.50    14 21 1.93
OCCUPANTS 5
30 30 71 7 5
1 0 0 0 1
1 1 1 1 1
7 9 3 4 4
0 0 0 0 0
0. 0. 0. 0. 0.
-1. -1. -1. -1. -1.
```

8.8.7 Printed Output from EXITT for Scenario 2

```
EXITT Version:  18.4 - Creation Date: 12/28/89 - Run Date: 05/29/91
FAST DUMP FILE   :  SCEN-2.DMP
BUILDING/OCCUPANT FILE: SCEN-2.BLD
EXITT OUTPUT FILE     : SCEN-2.EXT
EXITT DUMP FILE       : SCEN-2.EVA


NO. OF ROOMS (RUN WITH FAST)       6
NO. OF DOORS                       2
NO. OF WINDOWS                     5
TOTAL NUMBER OF NODES             21
```

EXITT NODE NUMBER	EXITT ROOM NUMBER	FAST ROOM NUMBER	ROOM HEIGHT (M)	FLOOR HEIGHT (M)
1	1	1	2.4	0.0
2	2	2	2.4	0.0
3	3	3	2.4	0.0
4	4	4	2.4	0.0
5*	5	5	2.4	0.0
6	6	6	2.4	0.0
7	7	1	2.4	0.0
8	9	4	2.4	0.0
9	8	6	2.4	0.0
10	1	1	2.4	0.0
11	8	6	2.4	0.0
12	8	6	2.4	0.0
13	4	4	2.4	0.0
14	9	4	2.4	0.0
15	1	8	2.4	0.0
16	2	8	2.4	0.0
17	3	8	2.4	0.0
18	4	7	2.4	0.0
19	4	8	2.4	0.0
20	9	7	2.4	0.0
21	5	8	2.4	0.0

* INDICATES NODE IS IN BURN ROOM

NODE NUMBER	NOISE LEVEL (DECIBELS)
1	35
2	35
3	35
4	35
5	35
6	35
7	35
8	55
9	35
10	35
11	35
12	35
13	55
14	55
15	35
16	35
17	35
18	35
19	35
20	55
21	35

NUMBER OF SMOKE DETECTORS: 1

SMOKE DET NO.	NODE	ACTIVATION TIME (SEC)
1	9	DETERMINED BY EXITT TO BE 150.0 SECONDS

EXITT NODE NUMBER	ALARM LEVEL (DECIBELS)
	1
1	71
2	83
3	71
4	83
5	83
6	83
7	59
8	83
9	95
10	71
11	95
12	95
13	83
14	83
15	71
16	83
17	71
18	83
19	83
20	83
21	83

EDGE LIST

FROM NODE	TO NODE	DISTANCE (M)
1 -	10	1.89
-	11	3.41
-	15	1.83
2 -	11	2.71
-	16	1.52
3 -	9	2.13
-	17	1.52
4 -	8	4.27
-	13	2.38
-	18	3.13
-	19	2.13
5 -	12	2.74
-	14	3.35
-	21	2.13
6 -	9	2.51
7 -	10	1.68
8 -	4	4.27
-	13	3.30
-	14	2.05
-	20	2.13
9 -	3	2.13
-	6	2.51
-	11	2.06
-	12	2.44
10 -	1	1.89
-	7	1.68
-	11	4.27
-	15	1.57
11 -	1	3.41
-	2	2.71
-	9	2.06
-	10	4.27

12 -	5	2.74
-	9	2.44
-	13	1.57
13 -	4	2.38
-	8	3.30
-	12	1.57
-	18	3.69
14 -	5	3.35
-	8	2.05
-	20	1.50
-	21	1.93
15 -	1	1.83
-	10	1.57
16 -	2	1.52
17 -	3	1.52
18 -	4	3.13
-	13	3.69
19 -	4	2.13
20 -	8	2.13
-	14	1.50
21 -	5	2.13
-	14	1.93

TOTAL NUMBER OF DIRECTED EDGES 54

NUMBER OF PEOPLE 5

PERSON	LOCATION	AGE	SEX	STATE	SLEEP PENALTY	REQUIRE ASSISTANCE	TRAVEL SPEED
1	7	30	MALE	AWAKE	0.0	NO	1.30
2	9	30	FEMALE	AWAKE	0.0	NO	1.30
3	3	71	FEMALE	AWAKE	0.0	NO	1.30
4	4	7	FEMALE	AWAKE	0.0	NO	1.30
5	4	5	MALE	AWAKE	0.0	NO	1.30

ACTIONS TAKEN BY PERSON 1

NODE	ROOM	TIME	SAV- ING	SAVED BY	DESTI- NATION	ACTION
7	1	0.0	--	--	--	INITIAL POSITION
7	1	159.0	--	--	5	INVESTIGATE FIRE
10	1	160.3	--	--	5	ARRIVE AT NEW NODE
11	6	163.6	--	--	5	ARRIVE AT NEW NODE
11	6	163.6	--	--	--	SAW SMOKE - END INVESTIGATION
11	6	163.6	--	--	--	LEAVE BUILDING
9	6	164.8	--	--	18	ARRIVE AT NEW NODE
12	6	166.2	--	--	18	ARRIVE AT NEW NODE
13	4	168.3	--	--	18	ARRIVE AT NEW NODE
18	7	170.4	--	--	18	LEAVE BUILDING THROUGH DOOR

ACTIONS TAKEN BY PERSON 2

NODE	ROOM	TIME	SAV- ING	SAVED BY	DESTI- NATION	ACTION
9	6	0.0	--	--	--	INITIAL POSITION
9	6	159.0	--	--	5	INVESTIGATE FIRE
12	6	160.9	--	--	5	ARRIVE AT NEW NODE
12	6	160.9	--	--	5	BAD SMOKE - CURRENT ACTION STOPPED
12	6	163.9	--	--	--	LEAVE BUILDING
13	4	165.9	--	--	18	ARRIVE AT NEW NODE
18	7	168.1	--	--	18	LEAVE BUILDING THROUGH DOOR

ACTIONS TAKEN BY PERSON 3

NODE	ROOM	TIME	SAV-ING	SAVED BY	DESTI-NATION	ACTION
3	3	0.0	--	--	--	INITIAL POSITION
3	3	159.0	--	--	5	INVESTIGATE FIRE
9	6	160.6	--	--	5	ARRIVE AT NEW NODE
9	6	161.6	--	--	--	ALERTED BY ANOTHER - END INVESTIGATION
9	6	163.6	--	--	--	LEAVE BUILDING
12	6	165.1	--	--	18	ARRIVE AT NEW NODE
13	4	167.1	--	--	18	ARRIVE AT NEW NODE
18	7	169.3	--	--	18	LEAVE BUILDING THROUGH DOOR

ACTIONS TAKEN BY PERSON 4

NODE	ROOM	TIME	SAV-ING	SAVED BY	DESTI-NATION	ACTION
4	4	0.0	--	--	--	INITIAL POSITION
4	4	157.0	--	--	--	LEAVE BUILDING
18	7	158.9	--	--	18	LEAVE BUILDING THROUGH DOOR

ACTIONS TAKEN BY PERSON 5

NODE	ROOM	TIME	SAV-ING	SAVED BY	DESTI-NATION	ACTION
4	4	0.0	--	--	--	INITIAL POSITION
4	4	157.0	--	--	--	LEAVE BUILDING
18	7	158.9	--	--	18	LEAVE BUILDING THROUGH DOOR

8.8.8 Printed Output from TENAB for Scenario 2

```
FAST  Version:  18.5
TENAB Version:  18.4 - Creation Date: 12/28/89 - Run Date: 05/29/91


FAST DUMP FILE   :  SCEN-2.DMP
EXITT DUMP FILE  :  SCEN-2.EVA
TENAB OUTPUT FILE:  SCEN-2.TEN
TENAB DUMP FILE  :  NUL


OCCUPANT    NODE NUMBER    ROOM NUMBER    FLOOR ELEVATION    ENTER TIME (S)
    1            7              1              0.00               0.0
                10              1              0.00             160.3
                11              6              0.00             163.6
                 9              6              0.00             164.8
                12              6              0.00             166.2
                13              4              0.00             168.3
                18            DOOR             0.00             170.4
    2            9              6              0.00               0.0
                12              6              0.00             160.9
                13              4              0.00             165.9
                18            DOOR             0.00             168.1
    3            3              3              0.00               0.0
                 9              6              0.00             160.6
                12              6              0.00             165.1
                13              4              0.00             167.1
                18            DOOR             0.00             169.3
    4            4              4              0.00               0.0
                18            DOOR             0.00             158.9
    5            4              4              0.00               0.0
                18            DOOR             0.00             158.9

FACTORS          INCAPACITATION LEVEL    LETHAL LEVEL
FED1                       0.5               1.0
TEMP1 DEG C               65.0             100.0
CT    (G-MIN/M3)         450.0             900.0
FED2                       1.0
TEMP2                      1.0
FED3                       1.0



PERSON  1
  TIME NODE  CONDITION      CAUSE   FED1       TEMP1      CT          FLUX
                                    FED2       TEMP2
                                    FED3
 (SEC)                                                    (G-MIN/M3) (KW-SEC/M2)
   180.   13  INCAPACITATED  TEMP1 0.000E+00  0.952E+02  0.182E+01  0.489E+01
                                   0.219E-02  0.308E-02
                                   0.636E-02
   180.   18  ESCAPE               0.000E+00  0.952E+02  0.182E+01  0.489E+01
                                   0.219E-02  0.308E-02
                                   0.636E-02
  2400.   18  FINAL TIME           0.000E+00  0.952E+02  0.182E+01  0.489E+01
                                   0.219E-02  0.308E-02
                                   0.636E-02
```

```
PERSON  2
  TIME NODE  CONDITION      CAUSE   FED1        TEMP1       CT          FLUX
                                    FED2        TEMP2
                                    FED3
 (SEC)                                                      (G-MIN/M3)  (KW-SEC/M2)
   170.  13  INCAPACITATED  TEMP1  0.000E+00   0.930E+02   0.473E+01   0.162E+02
                                   0.268E-02   0.797E-02
                                   0.697E-02
   170.  18  ESCAPE                0.000E+00   0.930E+02   0.473E+01   0.162E+02
                                   0.268E-02   0.797E-02
                                   0.697E-02
  2400.  18  FINAL TIME            0.000E+00   0.930E+02   0.473E+01   0.162E+02
                                   0.268E-02   0.797E-02
                                   0.697E-02


PERSON  3
  TIME NODE  CONDITION      CAUSE   FED1        TEMP1       CT          FLUX
                                    FED2        TEMP2
                                    FED3
 (SEC)                                                      (G-MIN/M3)  (KW-SEC/M2)
   170.  13  INCAPACITATED  TEMP1  0.000E+00   0.942E+02   0.706E+00   0.419E+01
                                   0.227E-02   0.430E-02
                                   0.615E-02
   170.  18  ESCAPE                0.000E+00   0.942E+02   0.706E+00   0.419E+01
                                   0.227E-02   0.430E-02
                                   0.615E-02
  2400.  18  FINAL TIME            0.000E+00   0.942E+02   0.706E+00   0.419E+01
                                   0.227E-02   0.430E-02
                                   0.615E-02


PERSON  4
  TIME NODE  CONDITION      CAUSE   FED1        TEMP1       CT          FLUX
                                    FED2        TEMP2
                                    FED3
 (SEC)                                                      (G-MIN/M3)  (KW-SEC/M2)
   160.   4  INCAPACITATED  TEMP1  0.000E+00   0.813E+02   0.139E+01   0.497E+02
                                   0.188E-02   0.764E-02
                                   0.598E-02
   160.  18  ESCAPE                0.000E+00   0.813E+02   0.139E+01   0.497E+02
                                   0.188E-02   0.764E-02
                                   0.598E-02
  2400.  18  FINAL TIME            0.000E+00   0.813E+02   0.139E+01   0.497E+02
                                   0.188E-02   0.764E-02
                                   0.598E-02


PERSON  5
  TIME NODE  CONDITION      CAUSE   FED1        TEMP1       CT          FLUX
                                    FED2        TEMP2
                                    FED3
 (SEC)                                                      (G-MIN/M3)  (KW-SEC/M2)
   160.   4  INCAPACITATED  TEMP1  0.000E+00   0.813E+02   0.139E+01   0.497E+02
                                   0.188E-02   0.764E-02
                                   0.598E-02
   160.  18  ESCAPE                0.000E+00   0.813E+02   0.139E+01   0.497E+02
                                   0.188E-02   0.764E-02
                                   0.598E-02
  2400.  18  FINAL TIME            0.000E+00   0.813E+02   0.139E+01   0.497E+02
                                   0.188E-02   0.764E-02
                                   0.598E-02
```

```
FED1  - THE FRACTIONAL EFFECTIVE DOSE DUE TO
        CO,CO2,HCN AND O2 BASED ON THE HAZARD I
        TENAB FED PLUS AN OXYGEN TERM
FED2  - THE FRACTIONAL EFFECTIVE DOSE DUE TO
        CO,CO2,HCN AND O2 BASED ON PURSER'S
        EQUATIONS
FED3  - THE FRACTIONAL EFFECTIVE DOSE DUE TO
        CO2 BASED ON PURSER'S EQUATIONS
TEMP1 - THE AVERAGE TEMPERATURE OF THE
        LAYER OF THE ROOM TO WHICH THE
        PERSON IS EXPOSED - IT IS THE
        SAME AS TEMP USED IN THE HAZARD I TENAB
TEMP2 - THE FRACTIONAL EFFECTIVE DOSE DUE TO
        CONVECTIVE HEAT BASED ON PURSER'S
        EQUATIONS


* IF PERSON IS WAITING AT A WINDOW, HE IS CONSIDERED TO BE
AT THE NODE (ROOM) FROM WHICH HE CAME PRIOR TO REACHING THE WINDOW
THIS ALLOWS HIM TO CONTINUE TO BE EXPOSED TO THE ROOM FIRE CONDITIONS
```

8.9 Smoldering Cigarette in Sofa of the Ranch House

For scenario 1, a smoldering cigarette in the sofa in the living room of the ranch house is the fire source. The single occupant of the house is an intoxicated sleeping male.

BUILDING: Ranch house

OCCUPANT: Male aged 30, sleeping in master bedroom. He has a sleeping penalty (that is, it is difficult for him to wake up) because of alcohol in his blood.

DOORS: All interior doors are open. The only opening to the outdoors is a partially open window in the master bedroom.

FIRE: Smoldering cigarette in left corner of sofa. The smoldering fire is followed by a flaming fire.

FUEL: Flaming fire taken directly from HAZARD I fire property database. Material code UPS001, Upholstered sofa, F32, wood frame, polyurethane foam, olefin cover fabric. Smoldering fire adapted from cigarette ignition data discussed by Babrauskas and Krasny as a ramp function fire which grows from 0 to 76 kW in 2700 s.

CEILINGS: Gypsum board, standard, taken directly from HAZARD I materials property database. Material code GBD001.

WALLS: Gypsum board, standard, taken directly from HAZARD I materials property database. Material code GBD001.

FLOORS: 0.15-m-thick concrete slab, taken directly from HAZARD I materials property database. Material code CNC001, Concrete, normal weight, Type I cement, Dolomite aggregate.

8.9.1 FAST Input File: SCEN-1.DAT

```
VERSN   18  Scenario 1, Ranch House, Smoldering Cigarette
TIMES   5100 500  50   0   0
TAMB   293.  101300.     0.
EAMB   273.  101300.     0.
HI/F     0.00    0.00    0.00    0.00    0.00    0.00
WIDTH    3.60    3.00    3.00    4.50    2.70    1.92
DEPTH    3.80    3.60    3.40    8.10    3.80    8.79
HEIGH    2.40    2.40    2.40    2.40    2.40    2.40
HVENT   1  6  1    1.10    2.10    0.00
HVENT   1  7  1    0.81    1.22    0.91    0.00
HVENT   2  6  1    1.10    2.10    0.00
HVENT   3  6  1    1.10    2.10    0.00
HVENT   4  5  1    1.10    2.10    0.00
HVENT   4  6  1    1.10    2.10    0.00
CVENT   1  6  1    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00
CVENT   1  7  1    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00
CVENT   2  6  1    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00
CVENT   3  6  1    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00
CVENT   4  5  1    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00
CVENT   4  6  1    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00
CEILI GYPSUM    GYPSUM    GYPSUM    GYPSUM    GYPSUM    GYPSUM
WALLS GYPSUM    GYPSUM    GYPSUM    GYPSUM    GYPSUM    GYPSUM
FLOOR CONCRETE  CONCRETE  CONCRETE  CONCRETE  CONCRETE  CONCRETE
CHEMI     0.     0.   6.0    18900000.  300.
LFBO    4
LFBT    2
LFPOS   1
LFMAX   9
FTIME   2700.   100.    50.    65.    75.   110.   100.   700.  1200.
FMASS  0.0000 0.0040 0.0080 0.0320 0.1650 0.1480 0.0210 0.0120 0.0030 0.0000
FHIGH    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00
FAREA    0.03    0.60    0.80    1.00    3.00    3.00    1.50    1.00    0.50    0.50
FQDOT  0.00     7.56E+04 1.51E+05 6.05E+05 3.12E+06 2.80E+06 3.97E+05 2.27E+05 5.67E+04 0.00
CT     1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000
HCR    0.080 0.080 0.080 0.080 0.080 0.080 0.080 0.080 0.080 0.080
CO     0.050 0.150 0.017 0.017 0.018 0.020 0.019 0.012 0.012 0.012
OD     0.000 0.012 0.016 0.011 0.027 0.036 0.007 0.007 0.007 0.007
DUMPR SCEN-1.DMP
```

8.9.2 Sample Output

```
 Time = 5000.0 seconds.

   Upper temp(K)       314.9      314.8      315.1      349.1      334.7      325.5
   Lower temp(K)       303.9      299.8      301.1      320.3      303.0      312.5      273.0
 Upper vol(m**3)        22.1       25.9       24.4       74.2       24.6       33.9
  Layer depth(m)         1.6        2.4        2.4        2.0        2.4        2.0
 Ceiling temp(K)       310.8      310.8      310.9      344.6      329.1      321.2
 Up wall temp(K)       310.0      310.0      310.2      346.8      329.0      320.8
Low wall temp(K)       306.7      305.7      305.9      338.4      320.2      316.5
   Floor temp(K)       295.2      296.1      296.1      309.2      301.6      297.8

Plume flow(kg/s)   0.000E+00  0.000E+00  0.000E+00  2.982E-02  0.000E+00  0.000E+00
Pyrol rate(kg/s)   0.000E+00  0.000E+00  0.000E+00  2.500E-04  0.000E+00  0.000E+00
    Fire size(W)   0.000E+00  0.000E+00  0.000E+00  4.725E+03  0.000E+00  0.000E+00
                   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  0.000E+00  0.000E+00  0.000E+00
  Plume in ll(W)   0.000E+00  0.000E+00  0.000E+00  4.725E+03  0.000E+00  0.000E+00
    Vent fire(W)   0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00
On target(W/m^2)   1.387E+02  1.385E+02  1.400E+02  4.217E+02  2.917E+02  2.172E+02
    Pressure(Pa)  -1.781E+00 -2.061E+00 -2.068E+00 -2.969E+00 -2.817E+00 -2.358E+00
```

8.10 Mattress Fire in Bedroom of Ranch House

For scenario 3, an electric heater too close to combustible bed linens ignites the bedding of a double bed in a bedroom of the ranch house. Five occupants are in the house.

BUILDING: Ranch house

OCCUPANTS: Father aged 30, fully capable and awake, in master bedroom.

Mother, aged 30, fully capable and awake, in master bedroom.

Daughter, aged 7, fully capable and awake, in bathtub.

Son, aged 5, fully capable and awake, in living room watching television.

Grandmother, aged 71, fully capable and awake, in living room watching television.

DOORS: The bathroom, bedroom 2, and master bedroom doors are closed. The only opening to the outdoors is a partially open window in the master bedroom. Fire room window is closed.

FIRE: Electric heater too close to combustible bed linens.

FUEL: Double bed, bedding, and night table taken directly from HAZARD I fire properties database, material code BED002.

CEILINGS: Gypsum board, standard, taken directly from HAZARD I materials property database. Material code GBD001.

WALLS: Gypsum board, standard, taken directly from HAZARD I materials property database. Material code GBD001.

FLOORS: 0.15-m-thick concrete slab, taken directly from HAZARD I materials property database. Material code CNC001, Concrete, normal weight, Type I cement, Dolomite aggregate.

8.10.1 FAST Input File: SCEN-3.DAT

```
VERSN   18  Scenario 3, Ranch House, Flaming Mattress
TIMES    900  50  20  20   0
TAMB   293.  101300.      0.
EAMB   273.  101300.      0.
HI/F     0.00   0.00   0.00   0.00   0.00   0.00
WIDTH    3.60   3.00   2.70   4.50   2.70   3.05
DEPTH    3.80   3.60   3.80   8.10   3.80   5.50
HEIGH    2.40   2.40   2.40   2.40   2.40   2.40
HVENT   1  6  1   0.01   2.10   0.00
HVENT   1  7  1   0.81   1.22   0.91   0.00
HVENT   2  6  1   0.01   2.10   0.00
HVENT   3  6  1   0.01   2.10   0.00
HVENT   4  5  1   1.10   2.10   0.00
HVENT   4  6  1   1.10   2.10   0.00
CVENT   1  6  1   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00
CVENT   1  7  1   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00
CVENT   2  6  1   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00
CVENT   3  6  1   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00
CVENT   4  5  1   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00
CVENT   4  6  1   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00
CEILI GYPSUM    GYPSUM    GYPSUM    GYPSUM    GYPSUM    GYPSUM
WALLS GYPSUM    GYPSUM    GYPSUM    GYPSUM    GYPSUM    GYPSUM
FLOOR CONCRETE  CONCRETE  CONCRETE  CONCRETE  CONCRETE  CONCRETE
CHEMI    0.     0.   6.0    18100000.  300.
LFBO   2
LFBT   2
LFPOS  1
LFMAX  8
FTIME    260.    20.    20.    60.    70.   120.   180.   770.
FMASS  0.0000 0.0165 0.1930 0.1770 0.3760 0.3760 0.1220 0.0410 0.0165
FHIGH    0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
FAREA    0.50   0.50   0.50   0.50   0.50   0.50   0.50   0.50   0.50
FQDOT  0.00      2.99E+05 3.49E+06 3.20E+06 6.81E+06 6.81E+06 2.21E+06 7.42E+05 2.99E+05
CT     1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000
HCR    0.080 0.080 0.080 0.080 0.080 0.080 0.080 0.080 0.080
CO     0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.013
OD     0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.013
DUMPR  SCEN-3.DMP
```

8.10.2 Sample Output

```
Time =  900.0 seconds.

     Upper temp(K)      299.8      328.4      294.3      300.3      296.1      309.7
     Lower temp(K)      295.0      319.4      293.3      294.6      293.4      300.0      273.0
   Upper vol(m**3)       26.6       15.4       18.9       83.5       24.1       34.3
    Layer depth(m)        1.9        1.4        1.8        2.3        2.3        2.0
   Ceiling temp(K)      296.6      335.3      294.0      298.6      295.2      309.0
   Up wall temp(K)      295.9      329.8      293.9      297.6      294.8      306.8
  Low wall temp(K)      294.6      323.4      293.4      296.0      294.2      301.6
     Floor temp(K)      293.2      299.3      293.1      293.5      293.2      294.5

  Plume flow(kg/s)  0.000E+00  3.561E-02  0.000E+00  0.000E+00  0.000E+00  0.000E+00
  Pyrol rate(kg/s)  0.000E+00  3.559E-02  0.000E+00  0.000E+00  0.000E+00  0.000E+00
      Fire size(W)  0.000E+00  2.531E+01  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
    Plume in ul(W)  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00
    Plume in ll(W)  0.000E+00  2.531E+01  0.000E+00  0.000E+00  0.000E+00  0.000E+00
      Vent fire(W)  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00
  On target(W/m^2)  3.980E+01  2.403E+02  7.527E+00  4.275E+01  1.774E+01  1.030E+02
      Pressure(Pa) -2.665E-01  2.556E+01  2.066E+01  1.980E+01  1.997E+01  1.948E+01
```

8.11 Closet Fire in Townhouse

For scenario 4, household cleaning materials in a closet beneath the stairs are ignited by an electric arc from a malfunctioning hot water heater. Three occupants are in the house.

BUILDING: Townhouse

OCCUPANTS: Mother, aged 30, fully capable but asleep watching TV in living room.

Infant asleep in bedroom 3.

Boy aged 2 asleep in bedroom 2.

DOORS: All doors open except door to closet beneath stairs. The only opening to the outdoors is a partially opened window in the living room/dining room area.

FIRE: Originates in storage area under stairs. Fire caused by electric arc from hot water heater igniting household cleaning materials.

FUEL: Trash bags and paper taken directly from HAZARD I fire properties database, material code TRB001.

CEILINGS: Gypsum board, standard, taken directly from HAZARD I materials property database. Material code GBD001.

WALLS: Gypsum board, standard, taken directly from HAZARD I materials property database. Material code GBD001.

FLOORS: First floor is 0.15-m-thick concrete slab, taken directly from HAZARD I materials property database. Material code CNC001, Concrete, normal weight, Type I cement, Dolomite aggregate. Second floor is Douglas fir plywood, taken directly from HAZARD I materials property database. Material code DFP001, Douglas fir plywood, 10% moisture.

8.11.1 FAST Input File: SCEN-4.DAT

```
VERSN   18   Scenario 4, Townhouse, Cleaning Materials in Clos
TIMES    900  50  20   0   0
TAMB   293.  101300.      0.
EAMB   273.  101300.      0.
HI/F     0.00   0.00   0.00   0.00   2.70   2.70
WIDTH    8.19   2.10   1.20   1.20   5.30   2.90
DEPTH    4.91   5.20   2.10   3.00   3.30   6.10
HEIGH    2.40   2.40   2.40   4.90   2.40   2.40
HVENT   1  2  1    1.10   2.10   0.00
HVENT   1  2  2    1.10   2.10   0.00
HVENT   1  7  1    1.10   0.20   0.00   0.00
HVENT   2  3  1    1.10   0.02   0.00
HVENT   2  4  1    1.10   2.10   0.00
HVENT   4  5  1    1.10   4.80   2.70
HVENT   5  6  1    1.10   2.10   0.00
CEILI GYPSUM    GYPSUM    GYPSUM    GYPSUM    GYPSUM    GYPSUM
WALLS GYPSUM    GYPSUM    GYPSUM    GYPSUM    GYPSUM    GYPSUM
FLOOR CONCRETE  CONCRETE  CONCRETE  CONCRETE  WOOD      WOOD
CHEMI     0.     0.   6.0     16029950.  300.
LFBO    3
LFBT    2
LFPOS   1
LFMAX   9
FTIME     60.     60.     60.     60.     60.     60.     60.     60.    120.
FMASS  0.0000 0.0218 0.0203 0.0130 0.0068 0.0037 0.0037 0.0012 0.0025 0.0000
FHIGH    0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
FAREA    0.50   0.50   0.50   0.50   0.50   0.50   0.50   0.50   0.50   0.50
FQDOT  0.00      3.50E+05 3.25E+05 2.40E+05 1.10E+05 6.00E+04 6.00E+04 2.00E+04 4.00E+04 0.00
CT     1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000
HCR    0.080 0.080 0.080 0.080 0.080 0.080 0.080 0.080 0.080 0.080
CO     0.019 0.019 0.019 0.019 0.019 0.019 0.019 0.019 0.019 0.109
OD     0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.013
DUMPR  SCEN-4.DMP
```

8.11.2 Sample Output

```
 Time =  900.0 seconds.

   Upper temp(K)       293.3        294.1        323.9        293.3        293.0        293.0
   Lower temp(K)       292.8        293.8        306.5        293.3        293.0        293.0        273.0
 Upper vol(m**3)        47.1         13.9          5.9          9.8         20.4          0.3
  Layer depth(m)         1.2          1.3          2.3          2.7          1.2          0.0
 Ceiling temp(K)       293.3        294.1        323.7        293.2        293.0        293.0
 Up wall temp(K)       293.2        293.9        322.1        293.2        293.0        293.0
Low wall temp(K)       293.1        293.6        316.5        293.1        293.0        293.0
   Floor temp(K)       293.0        293.1        297.8        293.0        293.0        293.0

Plume flow(kg/s)   0.000E+00    0.000E+00    0.000E+00    0.000E+00    0.000E+00    0.000E+00
Pyrol rate(kg/s)   0.000E+00    0.000E+00    0.000E+00    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
                   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    0.000E+00    0.000E+00    0.000E+00
  Plume in ll(W)   0.000E+00    0.000E+00    0.000E+00    0.000E+00    0.000E+00    0.000E+00
    Vent fire(W)   0.000E+00    0.000E+00    0.000E+00    0.000E+00    0.000E+00    0.000E+00    0.000E+00
On target(W/m^2)   1.422E+00    6.004E+00    2.050E+02    1.485E+00    0.000E+00    0.000E+00
    Pressure(Pa)  -9.940E-02   -1.383E-01   -2.787E-01   -1.145E-01    1.445E-01    1.458E-01
```

8.12 Christmas Tree Fire in Living Room of Townhouse

For scenario 5, an electrical fire in the living room ignites a natural Christmas tree. Four occupants are in the house.

BUILDING: Townhouse

OCCUPANTS: Father, aged 25, fully capable but asleep in bedroom 1.

Mother, aged 23, fully capable but asleep in bedroom 1.

Infant asleep in bedroom 3.

Boy aged 2 asleep in bedroom 2.

DOORS: All bedroom doors closed.

FIRE: Electrical fire in living room ignites natural Christmas tree in living room. Bean bag chair is second item to ignite.

FUEL: Christmas tree and bean bag chair taken directly from HAZARD I fire properties database, material code CTR001 for Christmas tree (Christmas tree, spruce, dry) and CHR001 for bean bag chair (bean bag, vinyl PS foam beads). Species (CO_2, CO, and OD) were not available for the Christmas tree. Approximate values for the species have been used.

CEILINGS: Gypsum board, standard, taken directly from HAZARD I materials property database. Material code GBD001.

WALLS: Gypsum board, standard, taken directly from HAZARD I materials property database. Material code GBD001.

FLOORS: First floor is 0.15-m-thick concrete slab, taken directly from HAZARD I materials property database. Material code CNC001, Concrete, normal weight, Type I cement, Dolomite aggregate. Second floor is Douglas fir plywood, taken directly from HAZARD I materials property database. Material code DFP001, Douglas fir plywood, 10% moisture.

8.12.1 FAST Input File: SCEN-5.DAT

```
VERSN   18  Scenario 5, Townhouse, Christmas Tree in Li
TIMES   1200 100  25   0   0
TAMB   293.  101300.      0.
EAMB   273.  101300.      0.
HI/F     0.00    0.00    0.00    0.00    2.70    2.70
WIDTH    8.19    2.10    1.20    1.20    5.30    2.90
DEPTH    4.91    5.20    2.10    3.00    3.30    6.10
HEIGH    2.40    2.40    2.40    4.90    2.40    2.40
HVENT   1  2  1    1.10    2.10    0.00
HVENT   1  2  2    1.10    2.10    0.00
HVENT   1  7  1    1.10    0.20    0.00    0.00
HVENT   2  3  1    1.10    0.02    0.00
HVENT   2  4  1    1.10    2.10    0.00
HVENT   4  5  1    1.10    4.80    2.70
HVENT   5  6  1    1.10    2.10    0.00
CVENT   1  2  1    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00
CVENT   1  2  2    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00
CVENT   1  7  1    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00
CVENT   2  3  1    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00
CVENT   2  4  1    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00
CVENT   4  5  1    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00
CVENT   5  6  1    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00
CEILI GYPSUM     GYPSUM     GYPSUM     GYPSUM     GYPSUM     GYPSUM
WALLS GYPSUM     GYPSUM     GYPSUM     GYPSUM     GYPSUM     GYPSUM
FLOOR CONCRETE   CONCRETE   CONCRETE   CONCRETE   WOOD       WOOD
CHEMI     0.     0.   6.0     32800000.  300.
LFBO   1
LFBT   2
LFPOS  1
LFMAX 12
FTIME    300.     20.     30.     50.     50.    150.     75.    175.    170.     80.    400.    300.
FMASS  0.0000 0.0000 0.0200 0.0200 0.0050 0.0035 0.0018 0.0033 0.0150 0.0144 0.0046 0.0016 0.0000
FHIGH    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00
FAREA    0.50    0.50    0.50    0.50    0.50    0.50    0.50    0.50    0.50    0.50    0.50    0.50    0.50
FQDOT  0.00 0.00 6.56E+05 6.56E+05 1.64E+05 1.15E+05 5.90E+04 1.08E+05 4.92E+05 4.72E+05 1.51E+05 5.25E+04 0.00
CT     1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000
```

```
HCR   0.080 0.080 0.080 0.080 0.080 0.080 0.080 0.080 0.080 0.080 0.080 0.080 0.080
CO    0.019 0.019 0.019 0.019 0.019 0.019 0.019 0.019 0.019 0.019 0.019 0.019 0.019
OD    0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.013
DUMPR SCEN-5.DMP
```

8.12.2 Sample Output

```
  Time = 1200.0 seconds.

    Upper temp(K)      464.7      416.6      294.9      363.7      329.1      309.6
    Lower temp(K)      350.6      341.9      293.0      329.1      309.6      299.1      273.0
   Upper vol(m**3)      62.7       16.0        1.0       13.5       41.9       42.4
    Layer depth(m)       1.6        1.5        0.4        3.7        2.4        2.4
   Ceiling temp(K)     422.9      377.7      293.4      336.1      311.2      299.4
    Up wall temp(K)    409.5      366.6      293.3      329.4      307.9      298.2
   Low wall temp(K)    385.0      337.0      293.1      309.9      301.4      295.8
     Floor temp(K)     309.7      299.5      293.0      294.6      310.1      299.2

   Plume flow(kg/s)  4.647E-01  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00
   Pyrol rate(kg/s)  3.850E-03  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00
       Fire size(W)  1.264E+05  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
     Plume in ul(W)  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00
     Plume in ll(W)  1.264E+05  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00
       Vent fire(W)  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00
  On target(W/m^2)   2.215E+03  1.283E+03  1.065E+01  5.717E+02  2.461E+02  1.028E+02
       Pressure(Pa) -6.958E-01 -8.899E-02 -2.322E-01  7.133E-01  6.953E+00  7.634E+00
```

8.13 Family Room Fire in Two-Story House with Doors Open

For scenario 6, a cigarette fire in the sofa in the family room spreads to the panelling in the room. Four occupants are in the house.

BUILDING: Two-story detached house

OCCUPANTS: Father, aged 45, fully capable but asleep in bedroom 1.

Mother, aged 40, fully capable but asleep in bedroom 1.

Boy, aged 16, asleep in bedroom 2, sleeping penalty 15.

Girl, aged 14, asleep in bedroom 3.

DOORS: All doors downstairs open; all bedroom doors closed.

FIRE: Cigarette fire in family room sofa spreads to panelling.

FUEL: Sofa taken directly from HAZARD I fire properties database, material code UPS001 (Upholstered sofa, F32, wood frame, PU foam, FR olefin). Data for panelling taken from test R1 and R5 in reference [2].

CEILINGS: Gypsum board, standard, taken directly from HAZARD I materials property database. Material code GBD001.

WALLS: Gypsum board, standard, taken directly from HAZARD I materials property database. Material code GBD001.

FLOORS: First floor is 0.15-m-thick concrete slab, taken directly from HAZARD I materials property database. Material code CNC001, Concrete, normal weight, Type I cement, Dolomite aggregate. Second floor is Douglas fir plywood, taken directly from HAZARD I materials property database. Material code DFP001, Douglas fir plywood, 10% moisture.

8.13.1 FAST Input File: SCEN-6.DAT

```
VERSN   18   Scenario 6, Sofa and Paneling in Family Room
TIMES   1500 100  30   0   0
TAMB   293.  101300.      0.
EAMB   273.  101300.      0.
HI/F     0.00   0.00   0.00   0.00   0.00   2.70
WIDTH    3.20   3.00   7.40   3.09   1.00   6.00
DEPTH    4.30   4.30   5.20   3.09   7.90   9.50
HEIGH    2.40   2.40   2.40   2.40   4.90   2.40
HVENT   1  2  1   1.10   2.10   0.00
HVENT   1  4  1   1.10   2.10   0.00
HVENT   1  7  1   1.10   0.20   0.00   0.00
HVENT   2  3  1   1.10   2.10   0.00
HVENT   3  4  1   1.10   2.10   0.00
HVENT   3  5  1   1.10   2.10   0.00
HVENT   5  6  1   0.01   4.80   2.70
CEILI GYPSUM    GYPSUM    GYPSUM    GYPSUM    GYPSUM    GYPSUM
WALLS GYPSUM    GYPSUM    GYPSUM    GYPSUM    GYPSUM    GYPSUM
FLOOR CONCRETE  CONCRETE  CONCRETE  CONCRETE  CONCRETE  WOOD
CHEMI     0.     0.   6.0     18100000.  300.
LFBO    1
LFBT    2
LFPOS   1
LFMAX  13
FTIME    100.    50.    65.    75.   110.    30.    50.   120.    40.    40.   150.   180.   490.
FMASS  0.0000 0.0040 0.0080 0.0320 0.1650 0.1530 0.2240 0.2450 0.1990 0.3760 0.3760 0.1220 0.0410 0.0000
FHIGH    0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
FAREA    0.50   0.50   0.50   0.50   0.50   0.50   0.50   0.50   0.50   0.50   0.50   0.50   0.50   0.00
FQDOT  0.00       7.24E+04 1.45E+05 5.79E+05 2.99E+06 2.77E+06 4.05E+06 4.43E+06 3.60E+06 6.81E+06 6.81E+06
2.21E+06 7.42E+05 0.00
CT     1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000
HCR    0.080 0.080 0.080 0.080 0.080 0.080 0.080 0.080 0.080 0.080 0.080 0.080 0.080 0.080
CO     0.019 0.019 0.019 0.019 0.019 0.019 0.019 0.019 0.019 0.019 0.019 0.019 0.019 0.019
OD     0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.013
DUMPR  SCEN-6.DMP
```

8.13.2 Sample Output

```
 Time = 1500.0 seconds.

   Upper temp(K)      407.5      369.7      340.9      371.4      315.9      293.3
   Lower temp(K)      324.4      321.7      318.3      320.9      312.2      293.3      273.0
 Upper vol(m**3)       23.7       24.2       72.0       17.6       31.6      130.8
  Layer depth(m)        1.7        1.9        1.9        1.8        4.0        2.3
 Ceiling temp(K)      399.8      352.1      325.7      354.0      307.4      293.2
 Up wall temp(K)      399.1      347.4      321.8      349.3      305.4      293.2
Low wall temp(K)      378.9      334.4      315.3      334.8      302.8      293.1
   Floor temp(K)      317.8      301.2      296.7      301.5      294.0      293.2

Plume flow(kg/s)  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00
Pyrol rate(kg/s)  0.000E+00  0.000E+00  0.000E+00  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
                  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  0.000E+00  0.000E+00  0.000E+00
  Plume in ll(W)  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00
    Vent fire(W)  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00
On target(W/m^2)  1.140E+03  6.378E+02  3.461E+02  6.578E+02  1.458E+02  1.788E+00
    Pressure(Pa) -8.067E-01 -7.625E-01 -1.318E-02 -8.831E-01  6.100E-01  5.542E+00
```

8.14 Family Room Fire in Two-Story House with Doors Open

For scenario 7, A cigarette fire in the sofa in the family room spreads to the panelling in the room. Four occupants are in the house.

BUILDING: Two-story detached house

OCCUPANTS: Father, aged 45, fully capable but asleep in bedroom 1.

Mother, aged 40, fully capable but asleep in bedroom 1.

Boy, aged 16, asleep in bedroom 2, sleeping penalty 15.

Girl, aged 14, asleep in bedroom 3.

DOORS: Doors to passageway between kitchen/family room and front hall closed; other downstairs doors downstairs open; all bedroom doors closed.

FIRE: Cigarette fire in family room sofa spreads to panelling.

FUEL: Sofa taken directly from HAZARD I fire properties database, material code UPS001 (Upholstered sofa, F32, wood frame, PU foam, FR olefin). Data for panelling taken from test R1 and R5 in reference [2].

CEILINGS: Gypsum board, standard, taken directly from HAZARD I materials property database. Material code GBD001.

WALLS: Gypsum board, standard, taken directly from HAZARD I materials property database. Material code GBD001.

FLOORS: First floor is 0.15-m-thick concrete slab, taken directly from HAZARD I materials property database. Material code CNC001, Concrete, normal weight, Type I cement, Dolomite aggregate. Second floor is Douglas fir plywood, taken directly from HAZARD I materials property database. Material code DFP001, Douglas fir plywood, 10% moisture.

8.14.1 FAST Input File: SCEN-7.DAT

```
VERSN   18   Scenario 7, Sofa and Paneling in Family Room
TIMES   1500 100  30   0   0
TAMB   293.  101300.      0.
EAMB   273.  101300.      0.
HI/F     0.00   0.00   0.00   0.00   0.00   2.70
WIDTH    3.20   3.00   7.40   3.09   1.00   6.00
DEPTH    4.30   4.30   5.20   3.09   7.90   9.50
HEIGH    2.40   2.40   2.40   2.40   4.90   2.40
HVENT   1  2  1   1.10   2.10   0.00
HVENT   1  4  1   0.01   2.10   0.00
HVENT   1  7  1   1.10   0.20   0.00   0.00
HVENT   2  3  1   1.10   2.10   0.00
HVENT   3  4  1   0.01   2.10   0.00
HVENT   3  5  1   1.10   2.10   0.00
HVENT   5  6  1   0.01   4.80   2.70
CEILI GYPSUM    GYPSUM    GYPSUM    GYPSUM    GYPSUM    GYPSUM
WALLS GYPSUM    GYPSUM    GYPSUM    GYPSUM    GYPSUM    GYPSUM
FLOOR CONCRETE  CONCRETE  CONCRETE  CONCRETE  CONCRETE  WOOD
CHEMI     0.     0.   6.0     18100000.  300.
LFBO   1
LFBT   2
LFPOS  1
LFMAX 13
FTIME    100.    50.    65.    75.   110.    30.    50.   120.    40.    40.   150.   180.   490.
FMASS  0.0000 0.0040 0.0080 0.0320 0.1650 0.1530 0.2240 0.2450 0.1990 0.3760 0.3760 0.1220 0.0410 0.0000
FHIGH    0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
FAREA    0.50   0.50   0.50   0.50   0.50   0.50   0.50   0.50   0.50   0.50   0.50   0.50   0.50   0.00
FQDOT  0.00 7.24E+4 1.45E+5 5.79E+5 2.99E+6 2.77E+6 4.05E+6 4.43E+6 3.60E+6 6.81E+6 6.81E+6 2.21E+6 7.42E+5 0.00
CT     1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000
HCR    0.080 0.080 0.080 0.080 0.080 0.080 0.080 0.080 0.080 0.080 0.080 0.080 0.080 0.080
CO     0.019 0.019 0.019 0.019 0.019 0.019 0.019 0.019 0.019 0.019 0.019 0.019 0.019 0.019
OD     0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.013
DUMPR  SCEN-7.DMP
```

8.14.2 Sample Output

Time = 1500.0 seconds.

Upper temp(K)	457.0	398.2	349.1	308.7	319.2	293.3	
Lower temp(K)	320.1	323.5	319.2	295.9	314.2	293.3	273.0
Upper vol(m**3)	23.7	23.4	71.3	21.3	32.2	132.8	
Layer depth(m)	1.7	1.8	1.9	2.2	4.1	2.3	
Ceiling temp(K)	451.2	374.2	328.2	302.2	307.7	293.2	
Up wall temp(K)	447.3	367.0	323.5	300.8	305.5	293.2	
Low wall temp(K)	417.8	347.0	316.0	297.7	302.7	293.1	
Floor temp(K)	327.2	304.1	296.7	293.8	294.0	293.2	
Plume flow(kg/s)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	
Pyrol rate(kg/s)	0.000E+00	0.000E+00	0.000E+00	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	
	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	0.000E+00	0.000E+00	0.000E+00	
Plume in ll(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	
Vent fire(W)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
On target(W/m^2)	2.044E+03	1.002E+03	4.220E+02	9.681E+01	1.699E+02	1.871E+00	
Pressure(Pa)	-1.187E+00	-1.229E+00	-1.423E-01	1.058E+00	5.388E-01	6.871E+00	

8.15 Office Fire in Two-Story House

For scenario 8, a fire in a trash can next to a desk exposes window drapery. Four occupants are in the house.

BUILDING: Two-story detached house

OCCUPANTS: Father, aged 45, fully capable but asleep in family room.

Mother, aged 40, fully capable in kitchen.

Boy, aged 16, fully capable in bedroom 2 listening to loud stereo.

Girl, aged 14, fully capable in kitchen.

DOORS: All doors open except door to bedroom 2 closed.

FIRE: Fire in trash can next to desk exposes window drapery. Bedroom 4 serves as a home office.

FUEL: All material and fire properties taken directly from HAZARD I fire properties database. Material code WPB001 (wastepaper basket, polyethylene, milk cartons) is first item ignited. Material code CTN001 (curtain, cotton, 0.31 kg/m^2) is second item to ignite. Material code TLV001 (television set, B/W, wood cabinet) with total mass increased to approximately 30 kg is used to simulate office desk.

CEILINGS: Gypsum board, standard, taken directly from HAZARD I materials property database. Material code GBD001.

WALLS: Gypsum board, standard, taken directly from HAZARD I materials property database. Material code GBD001.

FLOORS: First floor is 0.15-m-thick concrete slab, taken directly from HAZARD I materials property database. Material code CNC001, Concrete, normal weight, Type I cement, Dolomite aggregate. Second floor is Douglas fir plywood, taken directly from HAZARD I materials property database. Material code DFP001, Douglas fir plywood, 10% moisture.

8.15.1 FAST Input File: SCEN-8.DAT

```
VERSN   18   Scenario 8, Office / Bedroom Fire
TIMES   2000 100  40   0   0
TAMB   293.  101300.      0.
EAMB   273.  101300.      0.
HI/F     0.00   0.00   2.70   2.70   2.70   2.70
WIDTH   10.00   1.00   3.00   3.00   3.00   4.00
DEPTH    6.40   9.00   3.20   3.20   4.80   5.80
HEIGH    2.40   4.90   2.40   2.40   2.40   2.40
HVENT   1  2  1   1.10   2.10   0.00
HVENT   1  7  1   1.10   0.20   0.00   0.00
HVENT   2  3  1   1.10   4.80   2.70
HVENT   2  4  1   1.10   4.80   2.70
HVENT   2  5  1   0.01   4.80   2.70
HVENT   2  6  1   1.10   4.80   2.70
CEILI GYPSUM    GYPSUM    GYPSUM    GYPSUM    GYPSUM    GYPSUM
WALLS GYPSUM    GYPSUM    GYPSUM    GYPSUM    GYPSUM    GYPSUM
FLOOR CONCRETE  CONCRETE  CONCRETE  CONCRETE  CONCRETE  WOOD
CHEMI     0.     0.   6.0     18100000.  300.
LFBO   3
LFBT   2
LFPOS  1
LFMAX  8
FTIME    240.    110.     25.    225.    250.    600.    400.    150.
FMASS  0.0000 0.0001 0.0008 0.0180 0.0070 0.0400 0.0240 0.0120 0.0050
FHIGH    0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
FAREA    0.50   0.50   0.50   0.50   0.50   0.50   0.50   0.50   0.50
FQDOT  0.00      1.81E+03 1.45E+04 3.26E+05 1.27E+05 7.24E+05 4.34E+05 2.17E+05 9.05E+04
CT     1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000
HCR    0.080 0.080 0.080 0.080 0.080 0.080 0.080 0.080 0.080
CO     0.019 0.019 0.019 0.019 0.019 0.019 0.019 0.019 0.019
OD     0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.013
DUMPR SCEN-8.DMP
```

8.15.2 Sample Output

```
Time = 2000.0 seconds.

   Upper temp(K)      294.9      376.2      443.9      347.2      297.6      341.9
   Lower temp(K)      292.8      299.3      319.8      299.9      293.9      326.9      273.0
 Upper vol(m**3)      149.0       19.5       22.9       23.0       29.6       55.6
  Layer depth(m)        2.3        2.2        2.4        2.4        2.1        2.4
 Ceiling temp(K)      294.5      354.5      416.9      331.2      295.6      327.5
 Up wall temp(K)      294.3      350.2      415.6      327.6      295.3      324.2
Low wall temp(K)      294.0      307.1      392.2      317.4      294.4      315.4
   Floor temp(K)      293.2      295.4      324.6      298.4      293.2      326.9

Plume flow(kg/s)  0.000E+00  0.000E+00  3.221E-02  0.000E+00  0.000E+00  0.000E+00
Pyrol rate(kg/s)  0.000E+00  0.000E+00  5.000E-03  0.000E+00  0.000E+00  0.000E+00
    Fire size(W)  0.000E+00  0.000E+00  4.940E+04  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
  Plume in ul(W)  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00
  Plume in ll(W)  0.000E+00  0.000E+00  4.940E+04  0.000E+00  0.000E+00  0.000E+00
    Vent fire(W)  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00
On target(W/m^2)  1.061E+01  7.139E+02  1.774E+03  4.037E+02  2.695E+01  3.554E+02
     Pressure(Pa) -1.544E-01 -3.248E-01 -9.584E-01  1.244E+00  3.078E+00  1.405E+00
```

8.16 School Building Fire

Aus [53] used HAZARD I to provide an alternative for code equivalency determination as described in section 2.5.1. As a test, an actual case from California was examined using this process. The question involved a small school building which was found in violation of the Uniform Building Code (UBC) with respect to the required separation of alternate exits. The analysis performed examined several alternative approaches to compliance with the intent of the code, with a significant variation in cost. The two story structure is bordered by a balcony on one side limiting exit travel. The scenario included here is one of several examined by Aus. It is presented to show the application of HAZARD I to an existing building. This example illustrates the use of HAZARD I for applications other than residences. Although obviously not a residential structure, the scale of the building and the fire are similar to those in residences. For this example, only the FAST input file and a sample output (at the ending time of the simulation) are shown below.

8.16.1 FAST Input File: SCHOOL.DAT

```
VERSN   18          SCHOOL FIRE #1
TIMES   1000 100  20  25   0
TAMB   300.  101300.      0.
EAMB   300.  101300.      0.
HI/F     0.00    0.00    0.00    0.00    0.00    0.00
WIDTH    9.10    9.10    9.10    9.10    2.00    3.00
DEPTH    4.30    4.30    4.30    4.30   30.00    3.00
HEIGH    2.30    2.30    2.30    2.30    2.30    2.30
HVENT   1  5  1   0.91   2.00   0.00
HVENT   2  5  1   0.91   2.00   0.00
HVENT   2  7  1   0.91   2.00   1.00    0.00
HVENT   3  5  1   0.01   2.00   0.00
HVENT   4  5  1   0.01   2.00   0.00
HVENT   4  7  1   0.91   2.00   1.00    0.00
HVENT   5  6  1   0.91   2.00   0.00
HVENT   5  7  1   1.20   2.30   0.00    0.00
HVENT   5  7  2   1.20   2.30   0.00    0.00
CEILI GYPSUM    GYPSUM    GYPSUM    GYPSUM    GYPSUM    GYPSUM
WALLS GYPSUM    GYPSUM    GYPSUM    GYPSUM    GYPSUM    GYPSUM
FLOOR CONCRETE  CONCRETE  CONCRETE  CONCRETE  CONCRETE  CONCRETE
CHEMI    16.     0.   3.0     17450000.  300.
LFBO    6
LFBT    2
LFPOS   1
LFMAX 14
FTIME      60.     60.     40.     20.     30.     30.     35.     25.     50.    110.    100.    200.    500.   1200.
FMASS  0.0000 0.0232 0.0251 0.0240 0.0328 0.0447 0.1074 0.1829 0.1753 0.1630 0.0255 0.0157 0.0147 0.0060 0.0028
FHIGH    0.25    0.25    0.25    0.25    0.25    0.25    0.25    0.25    0.25    0.25    0.25    0.25    0.25    0.25    0.25
FAREA    0.50    0.50    0.50    0.50    0.50    0.50    0.50    0.50    0.50    0.50    0.50    0.50    0.50    0.50    0.50
CT    1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000
HCR   0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333
CO    0.000 0.000 0.000 0.000 0.009 0.017 0.017 0.018 0.018 0.020 0.019 0.002 0.000 0.000 0.000
OD    0.000 0.016 0.016 0.016 0.013 0.011 0.017 0.027 0.030 0.036 0.007 0.000 0.000 0.000 0.000
DUMPR SCHOOL.DMP
```

8.16.2 Sample Output

```
   Time = 1000.0 seconds.

     Upper temp(K)        314.6       317.7       300.6       300.5       414.8       548.4
     Lower temp(K)        310.4       309.7       300.0       300.0       315.9       355.1       300.0
   Upper vol(m**3)         41.4        21.8        17.1        16.0        25.0         8.2
    Layer depth(m)          1.1         0.6         0.4         0.4         0.4         0.9
   Ceiling temp(K)        311.5       314.4       300.4       300.3       392.4       569.0
   Up wall temp(K)        309.7       312.2       300.3       300.3       384.1       570.7
  Low wall temp(K)        306.4       307.1       300.2       300.2       342.8       531.5
     Floor temp(K)        300.9       301.1       300.0       300.0       309.4       372.5

  Plume flow(kg/s)    0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00   5.317E-01
  Pyrol rate(kg/s)    0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00   1.052E-02
      Fire size(W)    0.000E+00   0.000E+00   0.000E+00   0.000E+00   4.280E-03   9.568E+04
                      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   0.000E+00   0.000E+00   0.000E+00
    Plume in ll(W)    0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00   9.568E+04
      Vent fire(W)    0.000E+00   0.000E+00   0.000E+00   0.000E+00   4.280E-03   0.000E+00   3.527E-07
  On target(W/m^2)    9.550E+01   1.178E+02   3.947E+00   3.067E+00   1.213E+03   4.644E+03
      Pressure(Pa)   -5.626E-01  -5.257E-01  -1.757E-01  -2.063E-02  -7.272E-01  -2.023E+00
```

8.17 Mechanical Ventilation

In this example, the mechanical ventilation capabilities of FAST are demonstrated. Four keywords in the FAST input file implement this capability for a simple fan-forced ventilation system:

- MVOPN – describe an opening between a compartment and the ventilation system,
- MVDCT – describe a piece of (circular) duct work,
- MVFAN – give the pressure - flow relationship for a fan, and
- INELV – specify **interior** node elevations.

For this example, a simple three room test case is used. As before, only the FAST input data file and a sample of the output is presented.

8.17.1 FAST Input File: HVAC.DAT

```
VERSN   18   SSU1
TIMES    180  30   4   0   0
TAMB   288.  101300.      0.
EAMB   288.  101300.      0.
HI/F     0.00   0.00   0.00
WIDTH   10.00  10.00  10.00
DEPTH   10.00  10.00  10.00
HEIGH    5.00   5.00   5.00
HVENT   1  4  1   1.00   2.10   0.00   0.00
HVENT   2  4  1   1.00   2.10   0.00   0.00
HVENT   3  4  1   1.00   2.10   0.00   0.00
CVENT   1  4  1   1.00   1.00   1.00
CVENT   2  4  1   1.00   1.00   1.00
CVENT   3  4  1   1.00   1.00   1.00
MVDCT  1 2 5. .15 .19E-3  3.30  .01767  0. 0.
MVDCT  3 4 5. .15 .19E-3  2.94  .01767  0. 0.
MVDCT  5 6 5. .15 .19E-3  3.30  .01767  0. 0.
MVDCT  7 8 5. .15 .19E-3  2.94  .01767  0. 0.
MVFAN  2 3   0.0 140.   0.140 3.170E-04 -1.803E-05  1.898E-07 -8.104E-10
MVFAN  6 7   0.0 140.   0.140 3.170E-04 -1.803E-05  1.898E-07 -8.104E-10
MVOPN  1 1 H 4.5 1.
MVOPN  2 4 H 4.5 1.
MVOPN  1 5 H 4.5 1.
MVOPN  3 8 H 4.5 1.
INELV  2  4.4   3 4.4  6 4.4  7 4.4
CEILI OFF       WB        GLASS
WALLS OFF       WB        GLASS
FLOOR OFF       WB        GLASS
CHEMI    16.   50.  10.0    10000000.  300.
LFBO   1
LFBT   2
LFPOS  1
LFMAX  2
FTIME    120.  1800.
FMASS  0.0100 0.0500 0.0500
FHIGH    0.00   0.00   0.00
FAREA    0.00   0.00   0.00
FQDOT  1.00E+05 5.00E+05 5.00E+05
HCL   0.200 0.200 0.200
HCR   0.333 0.333 0.333
```

```
CO    1.000 1.000 1.000
OD    0.000 0.000 0.000
DUMPR HVAC.DMP
```

8.17.2 Sample Output

```
   Time =   180.0 seconds.

     Upper temp(K)         464.0        288.0        288.0
     Lower temp(K)         288.0        290.6        290.6        288.0
   Upper vol(m**3)         361.2          0.5          0.5
    Layer depth(m)           3.6          0.0          0.0
   Ceiling temp(K)         464.0        288.0        288.0
   Up wall temp(K)         464.0        288.0        288.0
  Low wall temp(K)         288.0        288.0        288.0
     Floor temp(K)         288.0        288.0        288.0
     c hcl(mg/m^2)          0.00         0.00         0.00
    uw hcl(mg/m^2)          0.00         0.00         0.00
    lw hcl(mg/m^2)          0.00        16.69         0.00
     f hcl(mg/m^2)          0.00         1.55         0.00

  Plume flow(kg/s)     1.222E+00    0.000E+00    0.000E+00
  Pyrol rate(kg/s)     5.000E-02    0.000E+00    0.000E+00
      Fire size(W)     5.000E+05    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)     5.000E+05    0.000E+00    0.000E+00
      Vent fire(W)     0.000E+00    0.000E+00    0.000E+00    1.045E-02
  On target(W/m^2)     2.226E+03    0.000E+00    0.000E+00
      Pressure(Pa)     7.804E-01    5.341E-03    5.341E-03
```

8.18 Hotel Lobby Fire

In this deceptively simple example, an extremely large fire (peak heat release rate 30MW) is simulated in a large hotel lobby (32.3 x 9.4 x 4.2 m). Although clearly not residential in scale, the relative scale of the fire and the openings when compared to the room size is similar to those in residences. This would lend some confidence to the results of the predictions. As with any simulation, the user's expertise should serve as a reality check on the predicted results.

8.18.1 FAST Input File: LOBBY.DAT

```
VERSN   18     LARGE HOTEL LOBBY
TIMES    360  20   8  10   0
TAMB   300.  101300.      0.
EAMB   300.  101310.      0.
HI/F     0.00
WIDTH   32.30
DEPTH    9.40
HEIGH    4.20
HVENT   1  2  1   7.30   1.20   0.00   0.00
HVENT   1  2  2   2.40   1.20   0.00   0.00
CVENT   1  2  1   1.00   1.00   1.00   1.00   1.00
CVENT   1  2  2   1.00   1.00   1.00   1.00   1.00
CEILI DEFAULT
WALLS DEFAULT
FLOOR DEFAULT
CHEMI     0.    0.   2.0    12300000.  288.
LFBO   1
LFBT   2
LFPOS  2
LFMAX  4
FTIME     10.    60.    10.   280.
FMASS  0.0000 2.4390 2.4390 1.1382 1.1382
FHIGH    0.35   0.35   0.35   0.35   0.35
FAREA    5.60   5.60   5.60   5.60   5.60
FQDOT  0.00     3.00E+07 3.00E+07 1.40E+07 1.40E+07
CT    1.000 1.000 1.000 1.000 1.000
HCR   0.333 0.333 0.333 0.333 0.333
CO    0.000 0.000 0.000 0.000 0.000
OD    0.050 0.049 0.038 0.019 0.000
DUMPR LOBA.DMP
WINDOW      0     0  -100  1280  1024    1100
GRAPH 1  100.  050.  0.  600.  475.  10.  3 TIME  HEIGHT
GRAPH 2  100.  550.  0.  600.  940.  10.  3 TIME  CELSIUS
GRAPH 3  720.  050.  0.  1250. 475.  10.  3 TIME  FIRE_SIZE(kW)
GRAPH 4  720.  550.  0.  1250. 940.  10.  3 TIME  O¦D2¦O(%)
INTERFA 0 0 0 0 1     1 U
TEMPERA 0 0 0 0 2     1 U
HEAT    0 0 0 0 3     1 U
O2      0 0 0 0 4     1 U
```

8.18.2 Sample Output

```
   Time =  360.0 seconds.

     Upper temp(K)        917.1
     Lower temp(K)        494.4        300.0
   Upper vol(m**3)       1050.8
    Layer depth(m)          3.5
   Ceiling temp(K)        809.8
   Up wall temp(K)        792.5
  Low wall temp(K)        777.2
     Floor temp(K)        741.2

  Plume flow(kg/s)    4.377E+00
  Pyrol rate(kg/s)    1.138E+00
      Fire size(W)    9.782E+06
                      0.000E+00
    Plume in ul(W)    0.000E+00
    Plume in ll(W)    9.782E+06
```

```
     Vent fire(W)    0.000E+00  5.346E+06
 On target(W/m^2)    3.944E+04
     Pressure(Pa)    7.860E+00
```

8.19 Opening and Closing Doors and Windows

In this example, the CVENT keyword in the FAST input file is used to simulate the opening and closing of doors and windows during the course of a fire in a two-story house. Although the opening and closing times in this example are arbitrary; they could also be based upon occupant actions predicted by the EXITT or breakage of windows caused by elevated temperature or other criteria in the rooms (through multiple runs of the two modules). For this example, only the FAST input file and a sample output (at the ending time of the simulation) is shown below.

8.19.1 FAST Input File: CVENT.DAT

```
VERSN   18 HOUSE FIRE WITH VENT OPENING AND CLOSING
TIMES     600  30  15  15   0
TAMB   300.  101300.      0.
EAMB   300.  101300.      0.
HI/F     0.00   0.00   0.00   0.00   2.44   2.44
WIDTH    3.35   7.82   5.49   3.35   4.16   3.81
DEPTH    7.01   2.94   1.96   1.04   4.16   3.94
HEIGH    2.44   2.44   2.44   4.88   2.44   2.44
HVENT   1  3  1   1.07   2.44   0.00
HVENT   1  7  1   1.83   1.83   0.00   0.00
HVENT   2  3  1   1.02   2.44   0.00
HVENT   3  4  1   1.02   2.44   0.00
HVENT   3  7  1   1.02   2.44   0.00   0.00
HVENT   4  5  1   1.00   4.00   2.44
HVENT   5  6  1   0.81   2.03   0.00
HVENT   6  7  1   1.00   1.00   0.50   0.00
CVENT   1  3  1   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00
CVENT   1  7  1   0.01   0.01   0.01   0.01   1.00   1.00   1.00   1.00   1.00
CVENT   2  3  1   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00
CVENT   3  4  1   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00
CVENT   3  7  1   0.00   0.00   0.00   1.00   1.00   1.00   1.00   1.00   1.00
CVENT   4  5  1   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00
CVENT   5  6  1   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00
CVENT   6  7  1   0.00   0.00   0.00   0.00   0.00   0.00   1.00   1.00   1.00
CEILI GYPSUM    GYPSUM    GYPSUM    GYPSUM    GYPSUM    GYPSUM
WALLS GYPSUM    GYPSUM    GYPSUM    GYPSUM    GYPSUM    GYPSUM
FLOOR PINEWOOD  PINEWOOD  PINEWOOD  PINEWOOD  PINEWOOD  PINEWOOD
CHEMI    16.     0.   6.0    15900000.  300.
LFBO   2
LFBT   2
LFPOS  1
LFMAX  8
FTIME     30.     70.     50.     1.     49.     1.     39.    800.
FMASS  0.0000 0.0314 0.0817 0.3330 0.3330 0.3000 0.3000 0.3000 0.3000
FHIGH    0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
FAREA    0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
FQDOT  0.00      4.99E+05 1.30E+06 5.29E+06 5.29E+06 4.77E+06 4.77E+06 4.77E+06 4.77E+06
CT     1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000
HCR    0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
CO     0.034 0.030 0.040 0.034 0.034 0.034 0.034 0.034 0.034
```

```
OD     0.000 0.000 0.040 0.000 0.000 0.000 0.000 0.000 0.000
DUMPR  CVENT.DMP
```

8.19.2 Sample Output

```
   Time =   600.0 seconds.

     Upper temp(K)        749.9      1382.9      1427.0       865.9       623.4       509.5
     Lower temp(K)        344.6       982.4       418.6       430.1       434.5       357.8       300.0
   Upper vol(m**3)         23.1        50.1        10.8        10.5        42.2        36.1
    Layer depth(m)          1.0         2.2         1.0         3.0         2.4         2.4
   Ceiling temp(K)        614.7      1334.4      1354.9       747.0       497.1       407.7
   Up wall temp(K)        591.9      1324.7      1343.2       726.2       477.0       392.5
  Low wall temp(K)        488.0      1325.7      1273.9       483.5       459.6       370.2
     Floor temp(K)        453.8      1184.6      1062.6       450.1       437.9       360.5

  Plume flow(kg/s)   0.000E+00  2.687E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00
  Pyrol rate(kg/s)   0.000E+00  3.000E-01  0.000E+00  0.000E+00  0.000E+00  0.000E+00
      Fire size(W)   5.080E-02  2.572E+06  2.189E+06  5.930E-02  0.000E+00  0.000E+00
                     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  0.000E+00  0.000E+00  0.000E+00
    Plume in ll(W)   0.000E+00  2.572E+06  0.000E+00  0.000E+00  0.000E+00  0.000E+00
      Vent fire(W)   5.080E-02  0.000E+00  2.189E+06  5.930E-02  0.000E+00  0.000E+00  1.059E-01
  On target(W/m^2)   1.738E+04  2.058E+05  2.334E+05  3.126E+04  8.063E+03  3.343E+03
      Pressure(Pa)  -1.501E+00 -7.973E+00 -3.627E+00 -4.092E+00  6.792E+00  7.104E+00
```

8.20 Interaction of Mechanical Ventilation and HCl Deposition

An example of the interaction of mechanical ventilation with hydrogen chloride deposition (HCl) can be shown using the following data file:

```
VERSN   18 SSU1
TIMES   180  30  0   0   0
TAMB    288.  101300.        0.
HI/F    0.0   0.0  0.0
WIDTH   10.0  10.0 10.
DEPTH   10.0  10.0 10.
HEIGH   5.    5.0   5.
HVENT   1  4    1  1.0  2.1   0.0
HVENT   2  4    1  1.0  2.1   0.0
HVENT   3  4    1  1.0  2.1   0.0
CEILI   OFF WB  GLASS
FLOOR   OFF WB  GLASS
WALLS   OFF WB  GLASS
LFBT    2
LFMAX   2
CHEMI   16. 50. 10. 10000000. 300.
FMASS   0.05 0.05 0.05
FTIME   120.   1800.
HCL     .1    .1   .1
CO      .10    .10  .10
HCR     0.    0.   0.
MVDCT  1 2 5. .15 .19E-3  3.30  .01767  0. 0.
MVDCT  3 4 5. .15 .19E-3  2.94  .01767  0. 0.
MVDCT  5 6 5. .15 .19E-3  3.30  .01767  0. 0.
MVDCT  7 8 5. .15 .19E-3  2.94  .01767  0. 0.
MVFAN  2 3   0.0 140.   0.140 3.170E-04 -1.803E-05  1.898E-07 -8.104E-10
```

```
MVFAN  6 7   0.0 140.    0.140 3.170E-04 -1.803E-05  1.898E-07 -8.104E-10
MVOPN  1 1  H 4.5 1.
MVOPN  2 4  H 4.5 1.
MVOPN  1 5  H 4.5 1.
MVOPN  3 8  H 4.5 1.
INELV  2  4.4   3 4.4   6 4.4   7 4.4
```

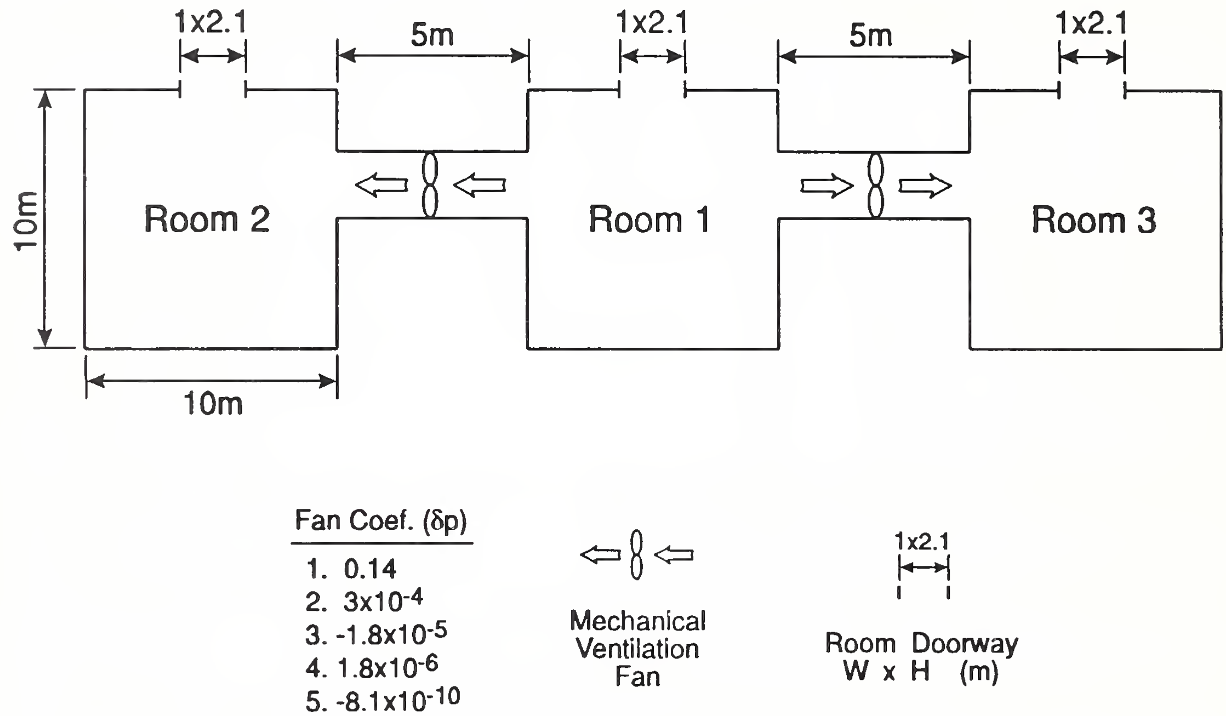


Figure 37. Plan diagram of the geometry used in the mechanical ventilation and HCl deposition calculation.

In this case, there are three compartments, each with a normal vent only to the outside. The three compartments are connected to each other by mechanical ventilation ducts. The compartment layout is shown in Figure 37, with compartment #2 on the left, compartment #1 in the center and compartment #3 on the right hand side of the figure. The fire is in the center compartment (#1) and a pair of fans blows the fire gases into the other two compartments (#2 and #3). The wall lining for the second compartment is wall board, and for the third compartment glass. The two compartments are symmetric in that all openings to the outside are the same size and the fans have the same pressure curves, so flow will be the same to both sides. The fire is small, and the pyrolyzate contains 10% hydrogen chloride, to emphasize the effect of mechanical ventilation and deposition.

Figure 38 shows the difference in the HCl concentration in the *lower* layer of the two compartments not containing the fire. With no wall adsorption, the concentrations of HCl in the two gas layers would be the same. As can be seen, the deposition onto the wall is influenced by the concentration in the environment, with the HCl concentration lower in the room which is lined with gypsum.

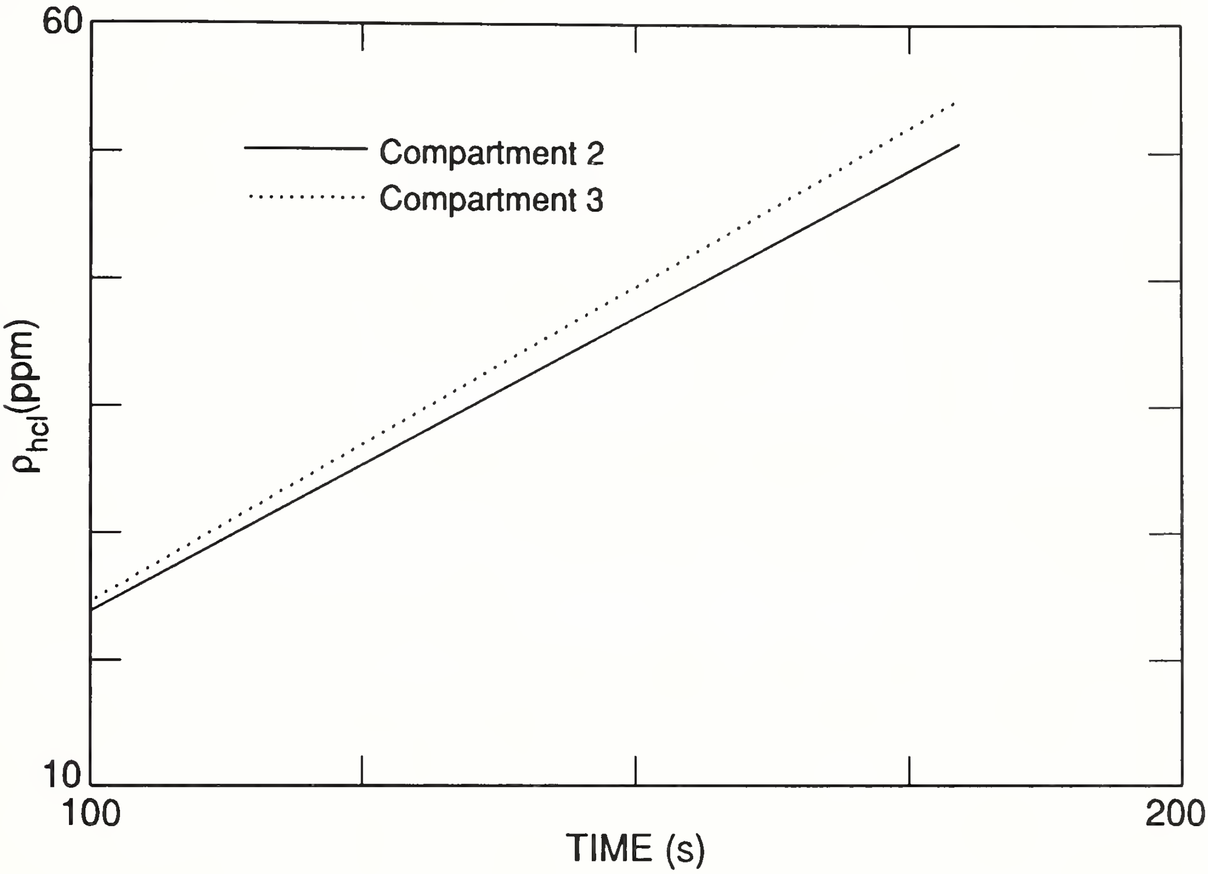


Figure 38. HCl concentration in the lower layer of compartments 2 and 3.

8.21 Specification of Graphical Output from FAST

Several examples are included with the HAZARD I software which illustrate the specification of graphical output for the FAST model.

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 data set produces two views of a building along with a table of selected quantities calculated during the simulation.

```
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
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9 Future Plans

The Hazard Methodology is intended as a tool to aid in understanding the consequences of unwanted fires. A significant effort at the Building and Fire Research Laboratory is aimed at solving this problem. The primary intention of the Hazard Methodology is to make available the research that is done by the Center in pursuit of this goal.

HAZARD I is a prototype of a general purpose fire hazard assessment method. The scope of this prototype, its database 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 goal is to make this research available in a usable way. The hope is that the tedium associated with applying a multiplicity of formulae to solve a problem will be alleviated to some extent. This is particularly important with a field that is as complex as fire research.

The automatic transfer of information from one set of calculations to another is important to avoid unnecessary errors and repetitive data entry. The quest is to provide a tool which will aid rather than hinder. This is not an attempt to make the application of such methods trivial, but rather to provide a mechanism to allow researchers, fire protection engineers, code officials and others access to the most current understanding of the behavior of fires. To reach this goal, we try to improve the physical basis of the model (see the "model improvements" section below). At the same time, we hope to allow more extensive calculations, such as long corridors, three dimensional effects (the "capabilities and processing power" section), and to use faster computers, distributed processing, automatic transfer of data and a more intuitive interface. Finally, we have the human factors aspect. How much does fire really cost? Since our knowledge of a situation is not perfect, what range of results might one expect given a most likely scenario (see the "human factors and cost" section).

These improvements divide into four avenues for improvements in the Hazard Methodology:

1) Increase the number and improve the capability of the physical phenomena which are modeled,
2) Improve the usability of the package,
3) Provide derivative applications, and
4) Expand the scope of the use of the methodology.

Points two and three can logically be combined, so we can display this on a three dimensional diagram (Figure 39). In providing improvements in the phenomenology, we are moving up the vertical axis. We can not proceed with other improvements, until we reach a sufficient level of physical understanding. Thus, this is the path which we will pursue in all cases. To expand the scope of the use of the methodology, we are moving back into the page and dealing with the human and economic aspects of the problem. Examples include combining the egress and tenability models, extending the methodology to large buildings with the rules for congestion and queuing, parameter analysis, risk, and cost of fire and fire protection schemes. Along the horizontal axis, we are dealing with improvements in usability, spinoffs, and the really powerful instantiation of the model such as multiple platform capabilities and the 3D CAD front end.

Our natural inclination is to improve the physics of the model, or increase the phenomena which are included — move up the vertical axis of the diagram. The next step is to provide the "what if" capability and include a spectrum of calculations reflecting the uncertainty in the data available. Finally, there are many spinoffs. For example, an important application would be to those who design buildings and ships. To do that, we have to deal with the 3D CAD model that architects use. Also, use of the model in the field for code compliance (performance based) and fire investigation are useful applications.

9.1 Capabilities and Processing Power (Horizontal Axis)

For fire investigation, we could have a portable computer (hand held) which allowed one to walk through a building (before or after) and catalog the contents of a building. This could be brought back to the office and used directly as input to the model for geometric specification and data initialization. As the model becomes more sophisticated, and the complexity increases, researchers, code officials, and everyone else will have to depend on such stratagems. There simply is not enough time to fuss with all of the details. This is equivalent to moving along the horizontal axis of the figure. This is the arena which should allow us to pursue the goal of a better qualitative understanding of fires, and well as doing more of it faster.

9.2 Human Factors and Dollars (Axis into the page)

As the concept of fire safe structures takes hold, the questions of how much does some improvement cost, how much will it save, and what are the likely actions of those involved in a fire will arise. This is the axis back into the page. We should get to the first step, statistics, as part of the current plan for Hazard 1.n. However, new rules for large buildings, risk analysis and economic analysis are well beyond what we can do presently. One area we have not discussed explicitly is the

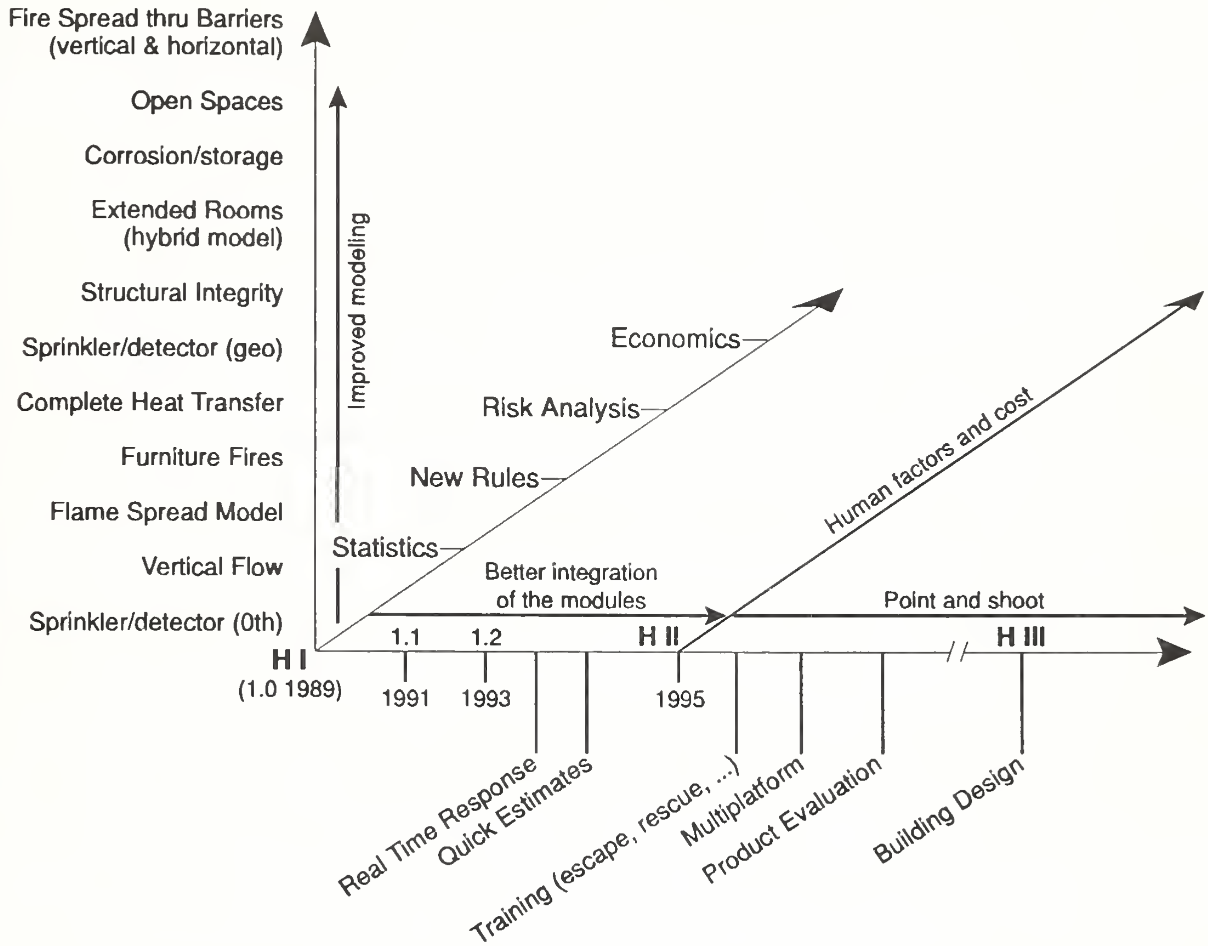

Figure 39. Map for improving the hazard methodology.

valuation of a building or system subject to a fire, and what the worst or most probable fire and concomitant dollar loss would be. Such a capability would be on top of that for estimating the effect of fire. Initially, 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.

9.3 Model Improvements (Vertical Axis)

This deals with improvements in the model itself. Beyond what we have today, we see the following as minimum improvements to present the concept to the whole of the fire related community (We include in this general audience the code officials, FPE's, and designers.):

Flow through vertical openings (holes in floor/ceiling)
Better integration of mechanical ventilation with the model
Construction design files (databases used for building and ship design)
Self consistent fire - both a flame spread model and a pyrolysis model
Species generation CO/CO_2, that is vitiation effects on combustion and toxicity
General radiation model - odd shapes and heat transfer between compartments
Two directional heat transfer in walls (non-congruent thermocline)
Better detector and other sensor activation (include new detectors)
Agglomeration and deposition of smoke
Suppression - include fire size, drop size and distance effects, geometry of the fire (hidden)
Multiple layers, zones (hybrid modification) - a must for detector siting
Experimental correlations for flow up shafts and *stairways*
Modifications to all modules to utilize DBase form of databases
Corrosion - add on for HCl - important for semiconductor industry and warehouses.
Simple (and quick) estimates

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 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. The obvious conclusion is that our understanding of fire is imperfect. As we continue to plumb the depths of this problem, both the direction and scope of the methodology will be influenced by what users say is needed as well as the results which evolve naturally from the Laboratory's research efforts.

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This report describes 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 for 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.

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