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Hazard I.
Volume 1: Fire Hazard Assessment Method

R. W. Bukowski, W. W. Jones, B. M. Levin, C. L. Forney, S. W. Stiefel,
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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, ***Secretary***
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, ***Director***

INTENT AND USE

The algorithms, procedures, and computer programs described in this report constitute a first, prototype version of a methodology for predicting the consequences to the occupants of a building resulting from the involvement of particular product(s) 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. This computer executed hazard analysis 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. The primary reason for its release at this stage is to gain the input of the fire community in identifying needed improvements to its completeness, practicability, and usefulness in addressing current questions of fire safety. Any conclusions drawn from analyses using this hazard analysis methodology are solely the responsibility of the user.

Written or verbal feedback on successes or failures with this product are encouraged. They should be directed to:

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INSTALLING THE SOFTWARE

The HAZARD I software will operate only on systems configured as described in section 1.3 of this report. To install the software, simply insert disk#1 into the "A" drive and type A:INSTALL. You will be asked to select the type of graphics card/monitor used on the computer (only the drivers for that display will be installed) and to confirm whether DBASE III+ is installed on the hard disk (and the name of the directory containing the DBASE III+ files). If it is not, the data base files will not be installed since they cannot be used without DBASE III+. The installation program will prompt the user to insert each of the remaining disks in sequence and verifies that the proper disk has been inserted. It will place all of the software into a directory called HAZARDI. Once the software has been successfully installed, all programs are run from a menu obtained by typing HAZARD while in the HAZARDI directory. NOTE: It is strongly suggested that the user read completely through this report first, and then become familiar with the software by running through the example problem discussed in Chapter 3.

PREFACE

What Hazard I is

HAZARD I is a prototype method to assess the relative contribution of specific products to the overall hazards of fire and smoke in buildings. The method has currently been developed for scenarios in single family residences. The user must compose the scenario and interpret the solution so he must be astute and knowledgeable in fire safety applications. Many of the computational steps have been translated into user-friendly computer codes. We anticipate that the experience gained from the use of HAZARD I will establish a basis for future improvements and additions to its scope.

What it consists of

HAZARD I provides statistical information on fires in the United States to assist the user in selecting fire scenarios appropriate for the context of use of the product. It also provides a database containing thermophysical information on common building materials, some representative house designs, and fire data on some furnishings. This computerized database is provided to simplify the hazard computations.

The computations consist of three main elements: (1) a fire and smoke transport model; (2) a people response and egress model; and (3) tenability criteria for evaluating the impact of the various fire hazard parameters on human death and injury.

The fire and smoke transport model requires the input of data on generation rates of energy and combustion products. Currently, these data are prescribed from burn experiments or estimated from small scale results. The temperature and various combustion product concentrations are then computed in the upper smoke layer of each room.

The model for people response and egress is the first attempt to systematically predict how people will behave in fire. It is based on human factors data and traffic flow analysis applied to fire situations.

The tenability criteria referenced in this study are based on the best available information in the literature for work performed largely with rodents. While reference values are given, the user must decide on the specific criteria to be applied to the analysis being conducted. The computer output is designed to facilitate an understanding of the sensitivity of the results to the criteria selected.

You can help

We need your input on the use and needs for future improvements or additions to the scope of HAZARD I. We believe the concept of developing a complete systems analysis of the hazards of fire and their impact on people is sound and necessary. To be widely applicable, a hazard method must meet the needs of its various users. Therefore, we solicit your comments and suggestions.

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CHAPTER 1. INTRODUCTION

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

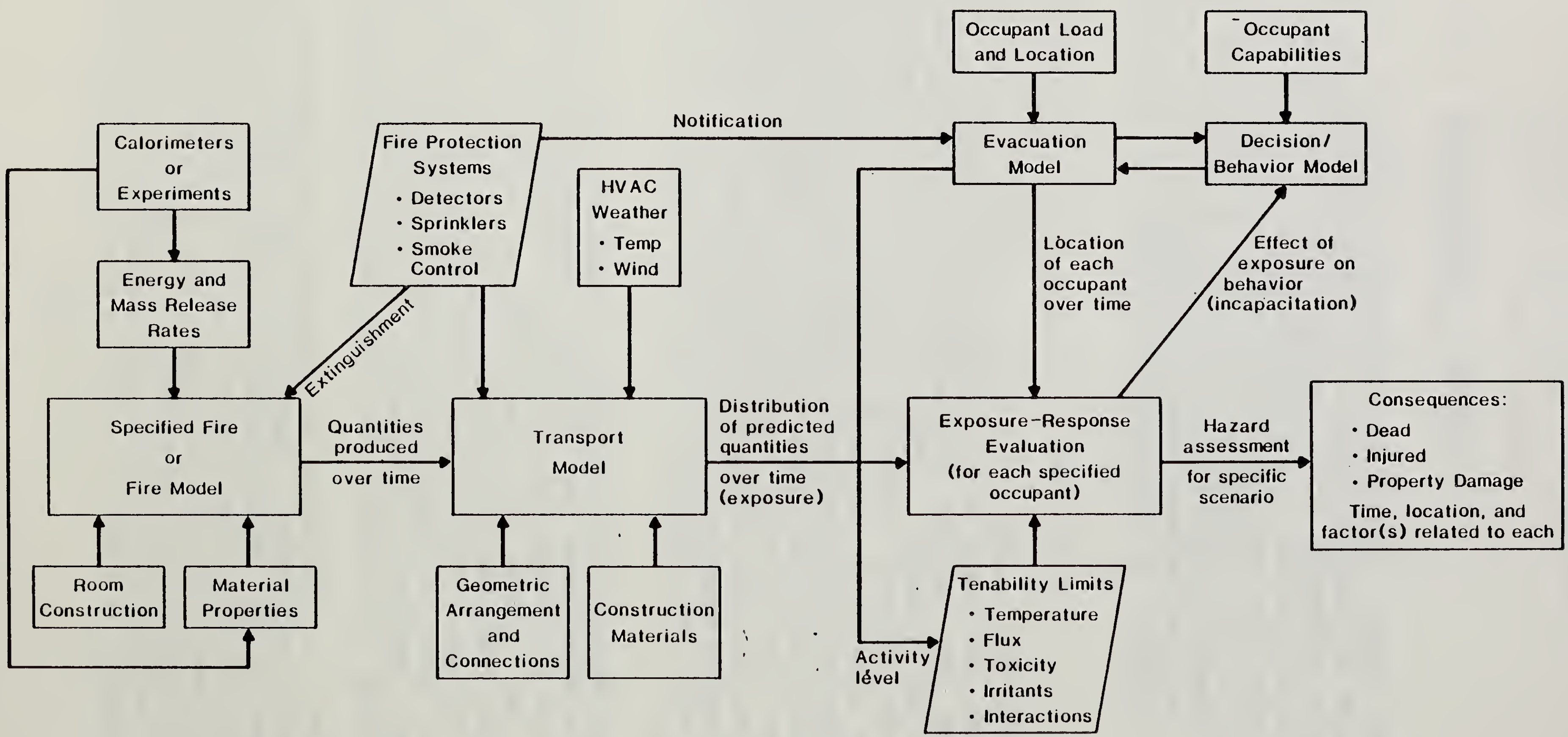
1.1 The Need For Quantitative Hazard Analysis

Public fire safety is provided through a system of fire and building codes which are based on the judgement 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.

These methods work 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. This can help to ensure the safe and rapid introduction of new technology by providing information on the likely impact on fire safety before a performance record is established through use. Similarly, these methods can be of value to product manufacturers in identifying the potential fire safety benefits of proposed design changes.

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

FIG. 1-1 INTERRELATIONSHIPS OF MAJOR COMPONENTS OF A FIRE HAZARD MODEL



physical capabilities, the decisions they make, and their susceptibility to the hazards to which they are exposed.

These tools 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 determines if the time available for egress is greater than the time required; and if not, why not. Time is the critical factor. Having three minutes for safe escape when ten minutes are needed results in human disaster. But providing thirty minutes of protection when ten are needed can lead to high costs. A hazard analysis method can help prevent both types of problem from occurring.

Quantitative hazard analysis techniques have the potential of providing significant cost-savings. Alternative protection strategies can be studied within the hazard analysis framework to give the benefit-cost relation for each. In addition, measures are evaluated as a system with their many interactions, including the impact of both structure and contents. This 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

The heart of HAZARD I is a sequence of procedures to calculate the development of hazardous conditions over time, calculate the time needed by building occupants to escape under those conditions, and estimate the resulting loss of life based on assumed occupant behavior and tenability criteria. These calculations are performed for a specified building and set of fire scenarios of concern.

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

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

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

1.3 Overview

The material contained herein encompasses the first version of the Fire Hazard Assessment Method - HAZARD I. This consists of a three volume report and a set of 5 1/4 in. disks containing the software necessary to conduct hazard analyses of products used in residential occupancies. All of the software provided will operate on any IBM[1] PC (XT or AT) or compatible MS-DOS computer with the following minimum hardware configuration:

- 512k MEMORY
- GRAPHICS CARD (IBM CGA OR EGA, OR HERCULES COMPATIBLE)
- HARD DISK DRIVE
- MATH CO-PROCESSOR (8087 OR 80287)
- PRINTER
- DBASEIII+ (REQUIRED ONLY FOR THE DATA BASE PROGRAM)

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[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 Bureau of Standards.

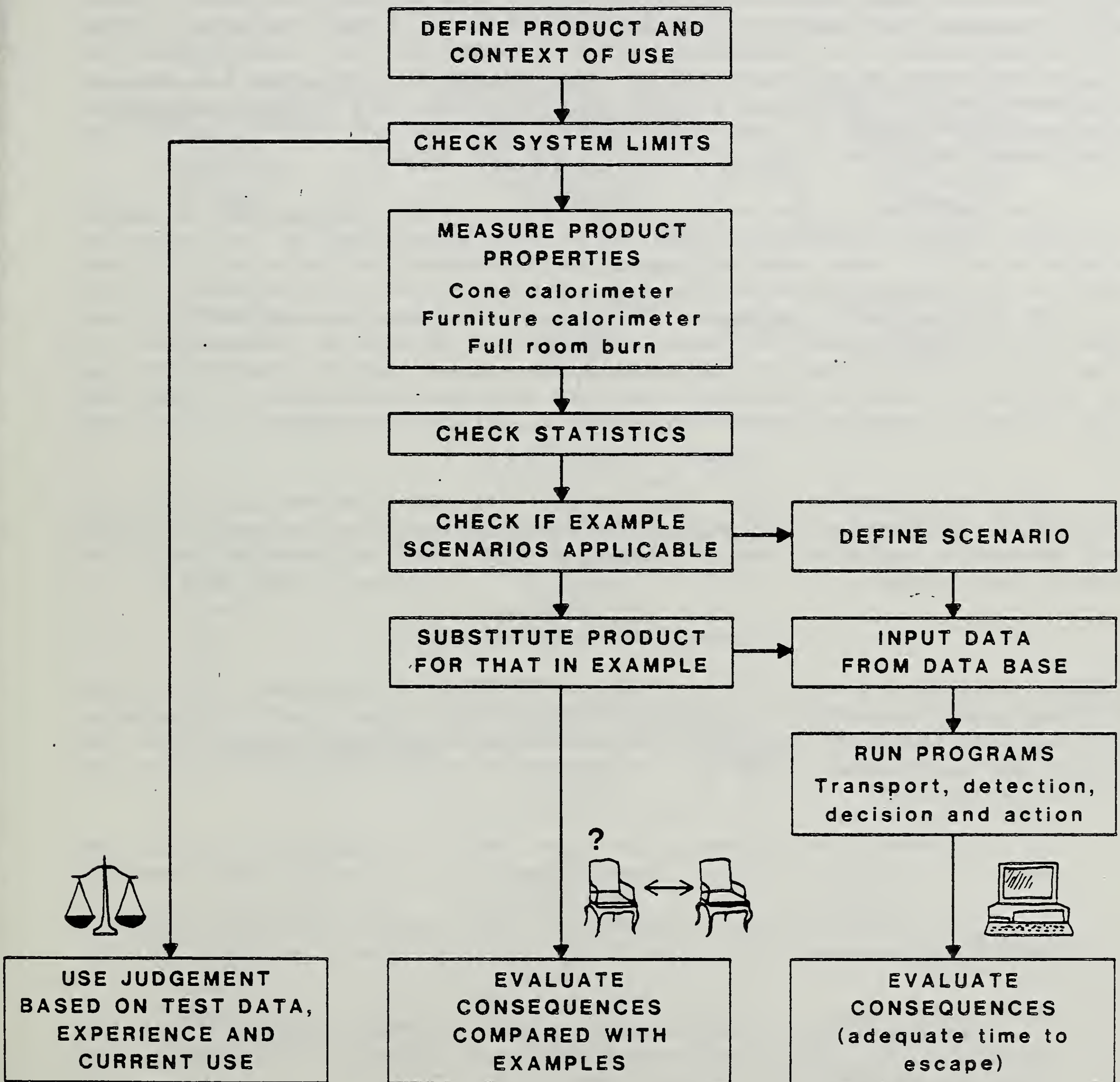


FIG. 1-2 **THE OVERALL METHOD**

The organization of the HAZARD I software package is shown in figure 1-3. It includes a utility program which provides guidance in developing scenarios (PRODUCT.ONE); an interactive program for inputing data to the fire model (FINPUT); a data base program (FIREDATA) including files of thermophysical, thermochemical, and reference toxicity data; the FAST model for multi-compartment energy and mass transport; a graphics utility for plotting data (FASTPLOT); a detector/sprinkler activation model (DETACT); an evacuation model which includes human decision/behavior (EXITT); and a tenability model (TENAB) which evaluates the impact of the predicted exposure of the occupants in terms of incapacitation or lethality from temperature or toxic gases or incapacitation by second degree burns from radiant flux exposure. A step-by-step procedure for performing a hazard analysis using this software package is presented in chapter 4, and user guides for each of these programs are contained in chapter 6.

Also included in the report is the set of eight representative example cases of typical residential fires which were established by two panels of outside experts. These examples consist of fire scenarios, selected by a panel composed of representatives of the major fire services organizations, in each of three single-family residences which were considered to represent typical homes by a panel from the model code and architectural communities. A description of the process of developing these cases and the results obtained for each is included in chapter 5, and the complete documentation (input data file listings, program outputs and graphs of selected variables) is in Volume 2.

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 extension would be made in parallel with the improvements identified through user feedback.

1.4 Assumptions and Limitations

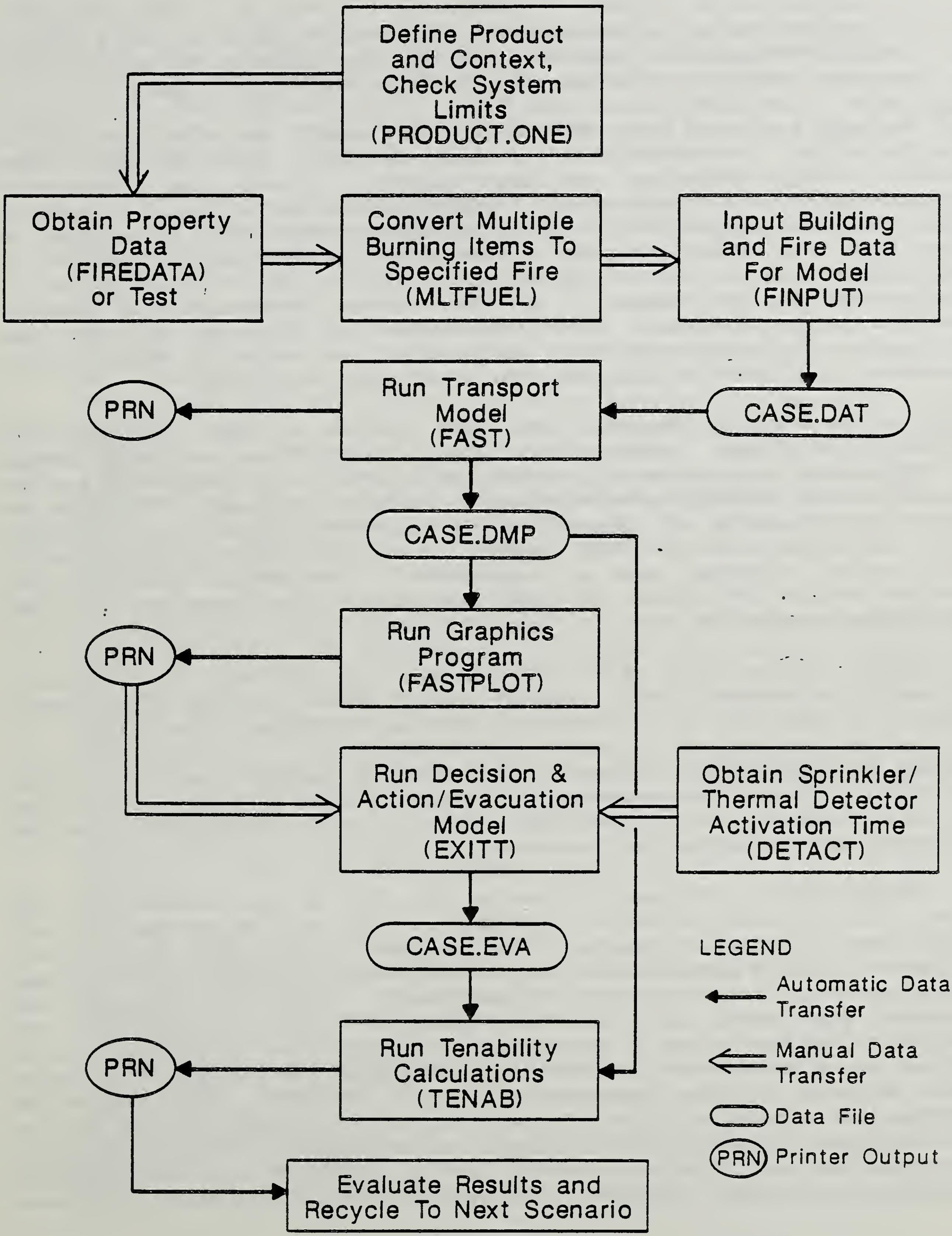
GENERAL: HAZARD I consists of a collection of data, procedures, and computer programs which are used to simulate the important time-dependant phenomena, generally as depicted in figure 1-1 (although this first version does not account for all of the phenomena listed). The major functions provided include calculation of:

1. 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,

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

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

FIG. 1-3 HAZARD I SOFTWARE



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

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

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

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

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

PROGRAMS AND PROCEDURES: Figure 1-3 presents the HAZARD I software package developed to implement the assessment of hazard as shown in figure 1-1. Of the nine programs shown, four (PRODUCT.ONE, FIREDATA, FINPUT, and FASTPLOT) perform utility and user interface functions only.

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

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

1. For the Furniture Calorimeter, a product (chair, table, bookcase, etc.) is placed under a large collection hood and ignited by a 50 kW gas burner (simulating a wastebasket) placed adjacent to the item for 120 sec. 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, the influence of the compartment on the burning behavior of the item is small. The differences obtained from the use of different ignition sources or locations of application have not been explored. These factors are discussed in reference [1].

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

3. The data and procedures provided relate directly only to burning of contents items initiated by relatively large flaming sources. Almost no data are currently available for release rates under smoldering combustion, or for the high external flux and low oxygen conditions characteristic of post-flashover burning. While the program MLTFUEL allows multiple items burning simultaneously to be converted to a single "equivalent" specified fire, it does not account for the energy interchange of such items. Thus, for other ignition scenarios, multiple items burning simultaneously (which exchange energy by radiation and convection), combustible interior finish, and post-flashover conditions, the procedures provided give estimates which are often non-conservative

(the actual release rates would be greater than estimated). At present, the only sure way to account for all of these complex phenonema 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 HARVARD V [3] or FIRST [4] which can be used as the source fire.

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

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

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

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

1. The "specified fire" input by the user is not subject to the influences of the room as discussed previously. If a large mass loss rate is entered, the model will proceed, even if there is insufficient oxygen available for that quantity of fuel to burn in the room. In this case, the model releases all of the energy in the room which will result in extremely high predicted temperatures (sometimes exceeding the adiabatic flame temperature) within the room of origin. (A message will be printed when this "ventilation limit" is reached.) Predicted temperatures for rooms away from the fire would be influenced less once this condition exists. Thereafter the input fire should be adjusted or the subsequent results carefully interpreted. No change in the fire input energy leads to a conservative result for temperature hazard. Also, if temperatures have approached 500 C in the room of origin, flashover is likely and the input fire would have to be adjusted to account for more burning items.

2. Similarly, user-specified species yields are used by the model, regardless of the predicted oxygen concentration within the room. It is known that low oxygen changes the combustion chemistry, with an attendant increase in the yields of products of incomplete combustion such as CO. However, not enough is known about these chemical processes to predict reliably such yields at the present time. Some room fire test data show that under post-flashover conditions, the production (yield) of CO increases (and CO_2 decreases) in the room. Subsequently, some of the excess CO may burn (to CO_2) in the door flame if it can entrain oxygen from the next room [5]. In such cases, the resulting concentrations may not differ substantially from the pre-flashover condition. If sufficient oxygen is not available, the high CO concentrations will remain in the doorway effluent. There are many complexities in the ways that a fire can be ventilated which will influence the production and fate of the gases of interest which need to be carefully interpreted.

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

4. In real fires, some 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). Neither of these phenomena are included in FAST, since for the former an appropriately-documented mixing coefficient is not known, and for the latter the associated theory is only now being developed. Thus, the lower layer is always free of smoke and gases, and can heat only by radiation from the upper part of the room heating the lower walls and floor, which then convect to the lower layer. This produces consistent underestimates of the lower layer temperatures and overestimates of the upper layer temperatures, the magnitudes of which will decrease with distance from the fire room. Thus, the resulting errors would tend to be conservative since the primary threat to occupants is from upper layer conditions.

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

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

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

<u>ACTIVATION OF THERMAL DEVICES:</u> The activation of heat detectors or sprinklers is handled in the program DETACT. The report (included as an appendix to this report) describes the underlying theory and assumptions used. The basic assumption is one of quasi-steady ceiling layer gas flow under an unconfined ceiling (no walls). It is based on the experimental study [7,8] done by Factory Mutual Research Corp. for the Fire Detection Institute and on which the NFPA 72E [9], Appendix C methods were developed. As such, the assumptions employed in this program are those in common use by the engineering and code communities and represent the current state-of-the-art.

TENABILITY CRITERIA: The impact of exposure to the occupants is evaluated in the program TENAB. Individual determinations are made for both incapacitation and lethality from temperature and toxicity, along with potential incapacitation from burns due to flux exposure. No interactions are currently included (e.g., temperature exposure does not change rate of uptake of toxic species). The basis for the threshold values used and the derivation of the equations on which the toxicity calculation is based are provided in 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. (It is used for temporary grafts for burn patients.) The toxicity data however, are from the combustion toxicology literature which is based entirely on animal exposures (primarily rodents). Thus, it is assumed that humans will exhibit a physiological response similar to rodents. The limiting values used are from experiments where lethality is the end point, and values for incapacitation are assumed to be half of the lethal level (see sect. 6.12).

A toxicity parameter, Ct - concentration multiplied by exposure time; which is often referred to as "exposure dose" - is used to indicate the toxic impact of the smoke without differentiating the constituent gases nor the possibility of diminished oxygen. This is a broad assumption. Another toxicity parameter, FED (the fractional effective dose) is also introduced. This represents the fraction of the lethal dose that has been accumulated by an individual over time. The FED parameter combines the effects and interactions of the gases CO, CO_2, and HCN. Again, the effect of diminished oxygen is not included at this time. The model on which the FED calculation is based, referred to as the N-Gas model [10], is under continuing development, and additional gases will be added as the data are obtained. It is expected that reduced oxygen and the first irritant gas (HCℓ) will be included in the next version.

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CHAPTER 2. BACKGROUND

2.1 Summary of Developments to Date

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

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

2.1.1 Hand Calculations

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

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

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

2.1.2 Computer Models

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

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

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

2.1.3 Measurement Systems

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

2.1.3.1 Cone Calorimeter

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

2.1.3.2 OSU Calorimeter

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

2.1.3.3 Factory Mutual Flammability Apparatus

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

2.1.3.4 Lateral Ignition and Flamespread Test (LIFT)

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

2.1.3.5 Large-Scale Calorimeters

There are a number of large-scale calorimeters using the oxygen consumption technique. By large-scale is meant that they are large enough to burn complete items (e.g., sofas, bookcases, or desks). At CFR, the furniture calorimeter has a maximum energy release rate of about 0.7 Mw. The "Large Combustion Products Collector" at Factory Mutual Research Corp. is rated about ten times higher. Other than size, their function is similar to the Cone Calorimeter.

2.1.3.6 Standard Room

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

Beyond these test methods, which focus on burning rate and combustion product release data, there are a number of other "new generation" test methods under development. The models and other predictive techniques are identifying data needs, and measurement methods are being produced to fill those needs.

2.1.4 Applications to Date

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

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

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

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

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CHAPTER 3. A SIMPLE EXAMPLE

3.1 Introduction to Overall Logic Diagram

Fire hazard analysis involves four main steps: defining the context, defining the scenario, calculating the hazard, and evaluating the consequences. The context involves the use, the building occupancy class, and the usual location of the product. The scenario defines the source of ignition, the items involved, whether doors are open, and the location and mobility of building occupants. Calculating hazard involves a comparison of the timing of the growth and spread of the fire, the involvement of fire protection devices, and the actions and response of people. Evaluation of the consequences requires an evaluation of the predicted exposure of the occupants against a set of tenability criteria for thermal hazards, toxic potency, and smoke obscuration.

Evaluating the relative contribution of a specific product to the overall hazard of smoke in a fire involves the completion of this analysis process for all the fire scenarios of concern. Not all users will want to specify complete details of the building(s) or fire scenarios used in each calculation, so a set of reference examples and a set of prototypical buildings and fire scenarios has been compiled. To assist the user through the overall analytical process, and make efficient use of the programs, documentation and procedures, particularly the identification of scenarios of concern, an overall logic diagram shown in figure 3-1 has been developed. This diagram has been translated into an interactive computer program (PRODUCT.ONE), which is described in more detail in section 6.1. Although the approach is conceptually applicable to many occupancy classes the reference examples are limited to commonly occurring scenarios in three prototypical residences, a ranch, a town house and a two story detached house.

The first step in the process is defining the context, which includes describing the product itself, and defining where, when, in what way and by whom the product is normally used. Because this initial version of the hazard analysis procedure is directed primarily at in-room, residential fires, it is first necessary to determine if the product is used in residential occupancies and if the example cases include a similar product. If this is the case, the analyst has the option of 1) estimating the hazard based on a comparison of the fire properties of the product of concern with those of the product used in the example or 2) proceeding with a hazard calculation. The hazard calculation can be based on a scenario used in the examples or on a newly created scenario.

To assist the analyst in selecting an appropriate fire scenario the program provides statistical information on residential fires, and asks a series of questions relating to the ignition source, possible other items involved, and important details of the building and its occupants. The statistical information is contained in section 6.2 of this report.

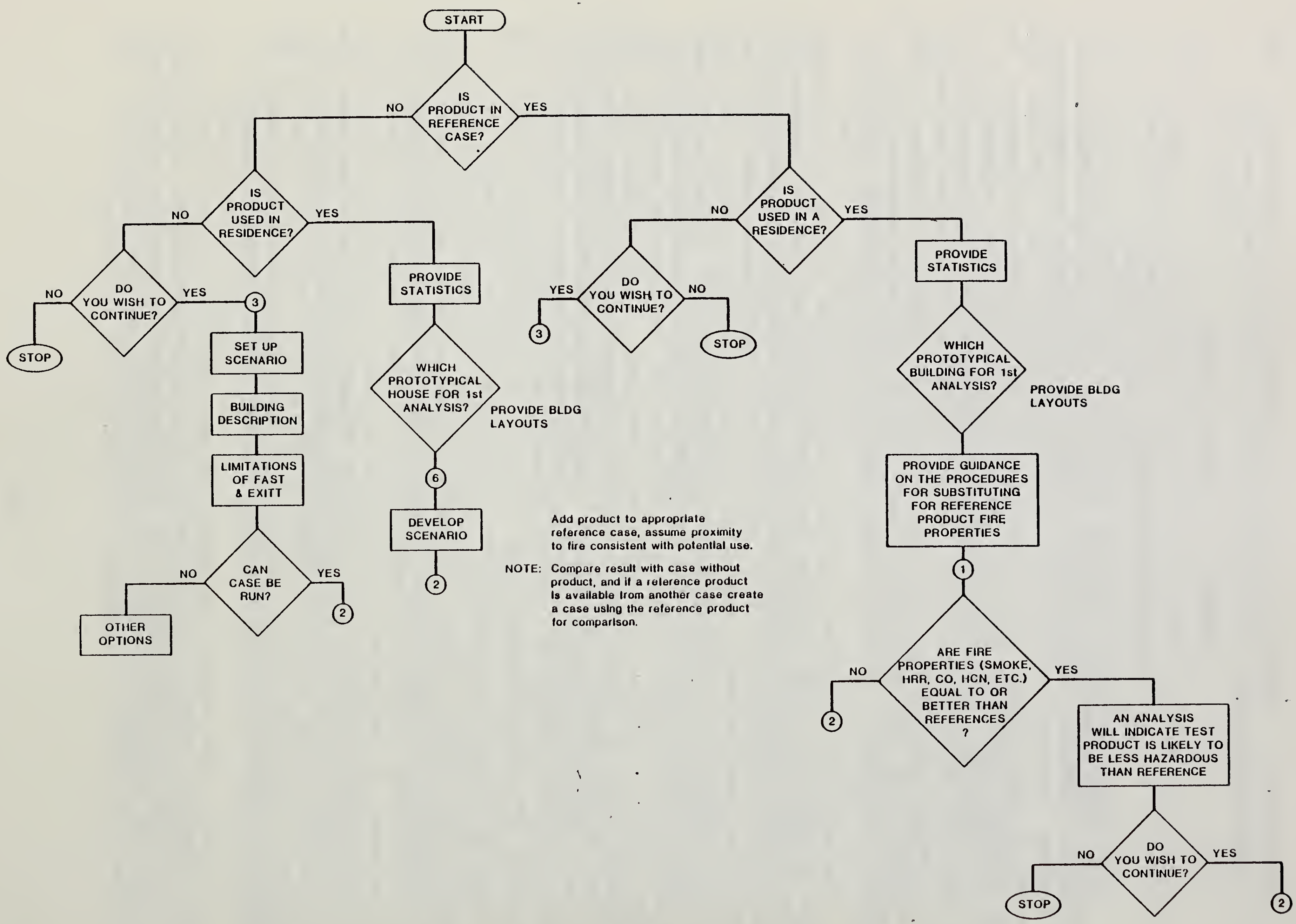
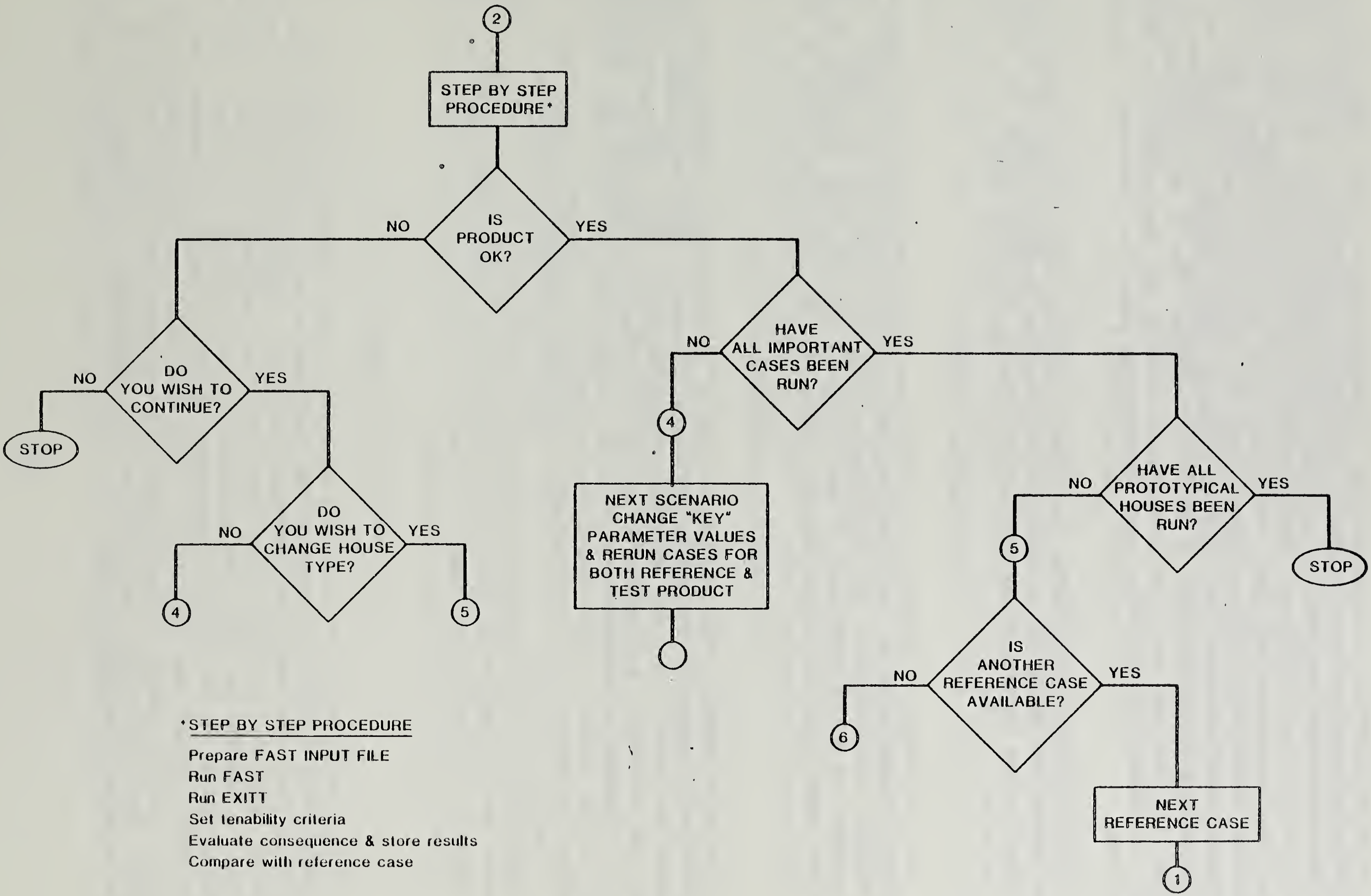


FIG. 3-1 LOGIC DIAGRAM FOR HAZARD ANALYSIS



*STEP BY STEP PROCEDURE

Prepare FAST INPUT FILE
Run FAST
Run EXITT
Set tenability criteria
Evaluate consequence & store results
Compare with reference case

FIG. 3-1 (CONTINUED)

The program now directs the user to perform the hazard calculation using the detailed step by step procedure described in section 4.2 of this report. This procedure asks the user to provide a detailed description of the building, the fire, and the occupants. The procedure specifies the input data required to run the hazard calculation. If these data are not available in the data base the user must perform the necessary laboratory measurements. The procedure also instructs the user on running three computer programs, a fire and smoke transport program, a detector program, and a decision and action program. Instructions are also given on evaluating the consequences by defining a set of tenability criteria, and determining when the hazardous conditions reach them.

Once a hazard calculation has been completed, the overall logic program asks a series of questions to check if all desired scenarios have been run. If not, the program leads the analyst back to the appropriate stage.

3.2 Example Problem

The following is intended to demonstrate how a user might work through a relatively simple problem involving upholstered furniture in a residence, using the HAZARD I software. The perspective for the example is that of the manufacturer of a specific chair, who wishes to estimate the potential hazard from this chair when it is involved in a specific fire incident.

3.2.1 Defining the Context of Use

For this example, the context of use of this product is straightforward. The user has a specific chair and residence in mind. Thus, the layout of the residence is known. If the user were interested in the performance of his product in residences in general, then he would need to specify the layout for a set of typical or representative houses of the sort in which his product is likely to be found. (The pre-worked examples in chapter 5 include three different residences.) In this example, the ranch house will be used.

The user must also specify the location of the chair (e.g, in the living room) and its placement relative to the room walls, other furniture, etc. For this example, it is assumed that the chair is placed away from the walls and not in direct contact with other furniture.

3.2.2 Defining the Scenario

The scenario selection involves describing the fire to be simulated. The chair manufacturer wants to examine the performance of his chair for a fire of interest in the, now specified, physical setting. Assuming that this involves a flaming ignition (perhaps since the chair is designed to resist cigarette ignition), a wastebasket ignition adjacent to the chair will be used. To have a scenario which is not totally dependent on "his" chair, he assumes that the burning chair causes the ignition of a loveseat which is close enough so as to ignite by radiant energy. The methods for obtaining the required inputs for the model for this fire specification are presented in chapter 6, in the section on Multiple Burning Items.

The next step in the scenario selection is to specify the occupant characteristics. The number of persons, their sex, age, and other attributes (heavy sleepers, drunk/drugged, handicapped, etc.) are selected and taken into account within the evacuation/behavior simulation EXITT. For the sake of simplicity in this example, it will be assumed that there is one person in each room of the house and that they do not evacuate. This precludes the need to run the evacuation model, and is a helpful technique when one desires to obtain "quick" results on the development of hazard in the building regardless of the occupant actions.

3.2.3 Calculating the Hazard

Following the Step-by Step Procedure in chapter 4, the FIREDATA is used to search the data bases for the appropriate data. The items and materials are selected as appropriate to the example case cited above, and the program MLTFUEL is used to produce the specified fire to be input to the model (the data for this case is presented in the Multiple Items Burning section of chapter 6).

Next, the program FINPUT is used interactively to produce the input data file. Since we are using the ranch house from the example cases, we can edit one of the data files for an example case in the ranch house provided on the disks to avoid having to re-enter the building data. (The procedure for doing this is explained in the section on FINPUT.) After entering the specified fire data, the file (Table 3-1)* is produced.

The program FAST is now executed with this file, producing the printer output shown in Table 3-2*, and a "dump" file to be used with subsequent programs. This dump file contains detailed data on the environmental conditions in each room over the simulated fire time (e.g., temperatures, smoke densities, gas concentrations, etc.) for use in subsequent programs.

The graphing program FASTPLOT is used next to produce the data plots of selected variables as shown in figures 3-2 to 3-10. (The curve numbers on the figures refer to the room numbers as shown on figure 3-1.) This allows the user to examine the results of the fire simulation in an easily understandable format.

* For an explanation of the FAST input and output format, see the User's Guide for FAST in Appendix A of this report.

The next step of doing the evacuation simulation is not required in this example since we assumed that the occupants did not try to escape. If this were not the case, the smoke data from the FAST dump file would be listed to the printer with FASTPLOT, and input (from the keyboard) into the EXITT model using the procedures described in chapter 6. If the scenario involved heat detectors or sprinklers, the program DETACT would be used prior to the EXITT run to provide the detector/sprinkler activation time.

Lastly, the program TENAB is used to determine the consequences of the exposure of the occupants to the predicted environment produced by FAST. The results of this run for this example case are presented in Table 3-3. These consequences, in terms of lethality or incapacitation, represent the hazard of this specific scenario. Any change in any parameter can potentially change the outcome. Subsequently, the user will want to evaluate all additional scenarios of concern and, from the total results, decide on the hazard which might or might not exist with respect to the product in question; in this case, his chair.

In this example scenario, conditions deteriorate significantly throughout the house beginning around 9 minutes, about a minute prior to the peak burning rate (Figure 3.2A) for the specified fire. Note from Figure 3-3 that the upper layer temperatures in all of the rooms climb together (all of the interior doors are open) while only the lower layer temperature (Figure 3-4) in the fire room increases significantly (due to radiant heating of the floor). Also of importance is the position of the interface (between the layers as shown in Figure 3-5) which determines to which layer the occupants are exposed. Figure 3-6 gives the upper layer smoke density in each room and Figures 3-7 through 3-9 shows the presentation of CO and CO_2 data both as concentration and dose. While these are not all of the parameters which can be obtained, they (along with oxygen) represent the most important to examine for most cases. Finally, note that the fatal insult is from temperature for all occupants (Table 3.2D) whereas lethal Ct does not accumulate during the simulation. Figure 3.2C shows incapacitating Ct (450 g-min/m^3 from Table 3.2D) occurring around 16 minutes.

3.2.4 Evaluating the Consequences

Once the consequences of the specified scenario have been calculated, the user must interpret the results. This is the last step in the overall process. Depending on the application, the user typically will run additional cases/scenarios and compare results. For example, calculated consequences may be compared with previously worked or representative cases. Alternatively, the user may run scenarios with and without the product in question to quantify the difference in consequences/loss. Finally, variations in product properties may be assessed in successive calculations.

NOTE: After reading the remainder of this volume, the user should try to apply the procedures and programs provided to this example problem before attempting a problem of his or her own. The output of each of the programs used are provided in the following tables and graphs or elsewhere in this document as described, so that direct comparisons of results can easily be made.

TABLE 3-1 FAST INPUT FILE

```
VERSN   17SIMPLE EXAMPLE IN RANCH HOUSE
TIMES   1200 100  10
NROOM      7
NMXOP      1
TAMB   300.
HI/F    0.0  0.0  0.0  0.0  0.0  0.0  0.0
WIDTH   3.6  3.6  3.4  4.5  2.7  2.7  0.9
DEPTH   3.8  3.0  3.0  8.1  3.8  3.8  7.6
HEIGH   2.3  2.3  2.3  2.3  2.3  2.3  2.3
HVENT   1  7   1.1   2.1   0.0
HVENT   1  8   1.1   0.2   0.0
HVENT   2  7   1.1   2.1   0.0
HVENT   3  7   1.1   2.1   0.0
HVENT   4  5   1.1   2.1   0.0
HVENT   4  7   1.1   2.1   0.0
HVENT   5  7   1.1   2.1   0.0
HVENT   6  7   1.1   2.1   0.0
CEILI
COND   0.00018 0.00018 0.00018 0.00018 0.00018 0.00018 0.00018
SPHT      0.90    0.90    0.90    0.90    0.90    0.90    0.90
DNSTY    790.0   790.0   790.0   790.0   790.0   790.0   790.0
THICK   0.0160  0.0160  0.0160  0.0160  0.0160  0.0160  0.0160
EMISS  0.90000 0.90000 0.90000 0.90000 0.90000 0.90000 0.90000
WALLS
COND   0.00012 0.00012 0.00012 0.00012 0.00012 0.00012 0.00012
SPHT      2.50    2.50    2.50    2.50    2.50    2.50    2.50
DNSTY    540.0   540.0   540.0   540.0   540.0   540.0   540.0
THICK   0.0160  0.0160  0.0160  0.0160  0.0160  0.0160  0.0160
EMISS  0.80000 0.80000 0.80000 0.80000 0.80000 0.80000 0.80000
FLOOR
COND   0.00012 0.00012 0.00012 0.00012 0.00012 0.00012 0.00012
SPHT      2.50    2.50    2.50    2.50    2.50    2.50    2.50
DNSTY    540.0   540.0   540.0   540.0   540.0   540.0   540.0
THICK   0.0160  0.0160  0.0160  0.0160  0.0160  0.0160  0.0160
EMISS  0.80000 0.80000 0.80000 0.80000 0.80000 0.80000 0.80000
CHEMI 1.0 0.0 0.0 0.0 0.0          17933. 300.
LFBO   4
LFBT   1
LFPOS  1
LFMAX 10
FMASS  0.0000 0.0001 0.0008 0.0058 0.0280 0.1456 0.0792 0.0887 0.0208 0.0051 0.0000
FHIGH    0.50   0.50   0.50   0.50   0.50   0.50   0.50   0.50   0.50   0.50   0.50
FTIME   240.0  110.0  100.0   50.0   60.0   65.0  125.0  270.0   49.0  131.0
O2      -1.37  -1.37  -1.37  -1.37  -1.37  -1.37  -1.37  -1.37  -1.37  -1.37  -1.37
CO2     0.00   0.05   0.05   0.59   0.75   1.10   1.43   1.85   1.23   0.74   0.00
CO      0.00   0.01   0.01   0.03   0.02   0.02   0.02   0.03   0.02   0.02   0.00
OD      0.00   0.01   0.01   0.01   0.01   0.02   0.02   0.02   0.01   0.00   0.00
CT      1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00
DUMPR   C:SIMEXAM.DMP
```

TABLE 3-2 PRINTER OUTPUT FROM FAST

FAST 17 REVISION 2P

SIMPLE EXAMPLE IN RANCH HOUSE

TOTAL COMPARTMENTS = 7

MAXIMUM OPENINGS PER PAIR = 1

FLOOR PLAN

WIDTH	3.6	3.6	3.4	4.5	2.7	2.7	0.9
DEPTH	3.8	3.0	3.0	8.1	3.8	3.8	7.6
HEIGHT	2.3	2.3	2.3	2.3	2.3	2.3	2.3
AREA	13.7	10.8	10.2	36.4	10.3	10.3	6.8
VOLUME	31.5	24.8	23.5	83.8	23.6	23.6	15.7
CEILING	2.3	2.3	2.3	2.3	2.3	2.3	2.3
FLOOR	0.0	0.0	0.0	0.0	0.0	0.0	0.0

CONNECTIONS

1 (1)	BW=	0.0	0.0	0.0	0.0	0.0	0.0	1.1	1.1
	HH=	0.0	0.0	0.0	0.0	0.0	0.0	2.1	0.2
	HL=	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	HHP=	0.0	0.0	0.0	0.0	0.0	0.0	2.1	0.2
	HLP=	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2 (1)	BW=	0.0	0.0	0.0	0.0	0.0	0.0	1.1	0.0
	HH=	0.0	0.0	0.0	0.0	0.0	0.0	2.1	0.0
	HL=	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	HHP=	0.0	0.0	0.0	0.0	0.0	0.0	2.1	0.0
	HLP=	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3 (1)	BW=	0.0	0.0	0.0	0.0	0.0	0.0	1.1	0.0
	HH=	0.0	0.0	0.0	0.0	0.0	0.0	2.1	0.0
	HL=	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	HHP=	0.0	0.0	0.0	0.0	0.0	0.0	2.1	0.0
	HLP=	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4 (1)	BW=	0.0	0.0	0.0	0.0	1.1	0.0	1.1	0.0
	HH=	0.0	0.0	0.0	0.0	2.1	0.0	2.1	0.0
	HL=	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	HHP=	0.0	0.0	0.0	0.0	2.1	0.0	2.1	0.0
	HLP=	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5 (1)	BW=	0.0	0.0	0.0	1.1	0.0	0.0	1.1	0.0
	HH=	0.0	0.0	0.0	2.1	0.0	0.0	2.1	0.0
	HL=	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	HHP=	0.0	0.0	0.0	2.1	0.0	0.0	2.1	0.0
	HLP=	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6 (1)	BW=	0.0	0.0	0.0	0.0	0.0	0.0	1.1	0.0
	HH=	0.0	0.0	0.0	0.0	0.0	0.0	2.1	0.0
	HL=	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	HHP=	0.0	0.0	0.0	0.0	0.0	0.0	2.1	0.0
	HLP=	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7 (1)	BW=	1.1	1.1	1.1	1.1	1.1	1.1	0.0	0.0
	HH=	2.1	2.1	2.1	2.1	2.1	2.1	0.0	0.0
	HL=	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	HHP=	2.1	2.1	2.1	2.1	2.1	2.1	0.0	0.0
	HLP=	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

```
 CEILING
COND =      1.800E-04   1.800E-04   1.800E-04   1.800E-04   1.800E-04   1.800E-04   1.800E-04
SPHT =      9.000E-01   9.000E-01   9.000E-01   9.000E-01   9.000E-01   9.000E-01   9.000E-01
DNSTY=      7.900E+02   7.900E+02   7.900E+02   7.900E+02   7.900E+02   7.900E+02   7.900E+02
THICK=      1.600E-02   1.600E-02   1.600E-02   1.600E-02   1.600E-02   1.600E-02   1.600E-02
EMISS=      9.000E-01   9.000E-01   9.000E-01   9.000E-01   9.000E-01   9.000E-01   9.000E-01
 FLOOR
COND =      1.200E-04   1.200E-04   1.200E-04   1.200E-04   1.200E-04   1.200E-04   1.200E-04
SPHT =      2.500E+00   2.500E+00   2.500E+00   2.500E+00   2.500E+00   2.500E+00   2.500E+00
DNSTY=      5.400E+02   5.400E+02   5.400E+02   5.400E+02   5.400E+02   5.400E+02   5.400E+02
THICK=      1.600E-02   1.600E-02   1.600E-02   1.600E-02   1.600E-02   1.600E-02   1.600E-02
EMISS=      8.000E-01   8.000E-01   8.000E-01   8.000E-01   8.000E-01   8.000E-01   8.000E-01
 UPPER WALL
COND =      1.200E-04   1.200E-04   1.200E-04   1.200E-04   1.200E-04   1.200E-04   1.200E-04
SPHT =      2.500E+00   2.500E+00   2.500E+00   2.500E+00   2.500E+00   2.500E+00   2.500E+00
DNSTY=      5.400E+02   5.400E+02   5.400E+02   5.400E+02   5.400E+02   5.400E+02   5.400E+02
THICK=      1.600E-02   1.600E-02   1.600E-02   1.600E-02   1.600E-02   1.600E-02   1.600E-02
EMISS=      8.000E-01   8.000E-01   8.000E-01   8.000E-01   8.000E-01   8.000E-01   8.000E-01
 LOWER WALL
COND =      1.200E-04   1.200E-04   1.200E-04   1.200E-04   1.200E-04   1.200E-04   1.200E-04
SPHT =      2.500E+00   2.500E+00   2.500E+00   2.500E+00   2.500E+00   2.500E+00   2.500E+00
DNSTY=      5.400E+02   5.400E+02   5.400E+02   5.400E+02   5.400E+02   5.400E+02   5.400E+02
THICK=      1.600E-02   1.600E-02   1.600E-02   1.600E-02   1.600E-02   1.600E-02   1.600E-02
EMISS=      8.000E-01   8.000E-01   8.000E-01   8.000E-01   8.000E-01   8.000E-01   8.000E-01
FIRE ROOM NUMBER IS     4
TIME STEP IS  1.00 SECONDS
PRINT EVERY 100 TIME STEPS
NUMBER OF FIRE INTERVALS =     10
TOTAL TIME INTERVAL = 1200
FIRE SOURCE =    1
FIRE TYPE = SPECIFIED
INITIAL FUEL TEMPERATURE (K) =                300.
AMBIENT AIR TEMPERATURE (K) =                 300.
AMBIENT REFERENCE PRESSURE (kPa) =          101.30
EFFECTIVE HEAT OF COMBUSTION (KJ/KG) =      17933.

FMASS=   0.00       1.00E-04   8.00E-04   5.80E-03   2.80E-02   0.15       7.92E-02   8.87E-02   2.08E-02   5.10E-03   0.00
FHIGH=   0.50       0.50       0.50       0.50       0.50       0.50       0.50       0.50       0.50       0.50       0.50
   O2=   -1.4       -1.4       -1.4       -1.4       -1.4       -1.4       -1.4       -1.4       -1.4       -1.4       -1.4
  CO2=   0.00       5.00E-02   5.00E-02   0.59       0.75       1.1        1.4        1.9        1.2        0.74       0.00
   CO=   0.00       1.00E-02   1.00E-02   3.00E-02   2.00E-02   2.00E-02   2.00E-02   3.00E-02   2.00E-02   2.00E-02   0.00
   OD=   0.00       1.00E-02   1.00E-02   1.00E-02   1.00E-02   2.00E-02   2.00E-02   2.00E-02   1.00E-02   0.00       0.00
   CT=    1.0        1.0        1.0        1.0        1.0        1.0        1.0        1.0        1.0        1.0        1.0
FTIME=   2.40E+02   1.10E+02   1.00E+02   50.        60.        65.        1.25E+02   2.70E+02   49.        1.31E+02
```

TIME = 0.0 SECONDS.

U.TEMP.	300.0	300.0	300.0	300.0	300.0	300.0	300.0
L.TEMP.	300.0	300.0	300.0	300.0	300.0	300.0	300.0
U.VOLUM	0.0	0.0	0.0	0.1	0.0	0.0	0.0
U.DEPTH	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CE.TEMP	300.0	300.0	300.0	300.0	300.0	300.0	300.0
UW.TEMP	300.0	300.0	300.0	300.0	300.0	300.0	300.0
LW.TEMP	300.0	300.0	300.0	300.0	300.0	300.0	300.0
FL.TEMP	300.0	300.0	300.0	300.0	300.0	300.0	300.0
EMS(I)=	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
EMP(I)=	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
QF(I)=	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
QR(I)=	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
QC(I)=	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	0.000E+00	0.000E+00
Pres(kpa)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00

Upper layer species concentration

O2 MASS	9.287E-03	7.332E-03	6.925E-03	2.475E-02	6.965E-03	6.965E-03	4.644E-03
PPM	2.300E+05	2.300E+05	2.300E+05	2.300E+05	2.300E+05	2.300E+05	2.300E+05
CO2 MASS	0.000	0.000	0.000	0.000	0.000	0.000	0.000
PPM	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CO MASS	0.000	0.000	0.000	0.000	0.000	0.000	0.000
PPM	0.000	0.000	0.000	0.000	0.000	0.000	0.000
OD MASS	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1/M	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CT mg-m/l	0.000	0.000	0.000	0.000	0.000	0.000	0.000

TIME = 100.0 SECONDS.

U.TEMP.	300.0	300.0	300.0	301.4	300.8	300.0	302.1
L.TEMP.	301.2	301.7	301.8	300.2	303.3	301.8	350.1
U.VOLUM	0.0	0.0	0.0	17.9	0.5	0.0	0.0
U.DEPTH	0.0	0.0	0.0	0.5	0.0	0.0	0.0
CE.TEMP	300.0	300.0	300.0	300.0	300.0	300.0	300.8
UW.TEMP	300.0	300.0	300.0	300.0	300.0	300.0	300.6
LW.TEMP	300.0	300.0	300.0	300.0	300.1	300.0	307.1
FL.TEMP	300.0	300.0	300.0	300.0	300.1	300.0	307.1
EMS(I)=	0.000E+00	0.000E+00	0.000E+00	1.928E-01	0.000E+00	0.000E+00	0.000E+00
EMP(I)=	0.000E+00	0.000E+00	0.000E+00	4.167E-05	0.000E+00	0.000E+00	0.000E+00
QF(I)=	0.000E+00	0.000E+00	0.000E+00	7.472E-01	0.000E+00	0.000E+00	0.000E+00
QR(I)=	-7.404E-05	-2.517E-05	-1.048E-05	-7.102E-02	-9.488E-03	-1.800E-05	1.927E-02
QC(I)=	-4.833E-05	-1.081E-05	-1.158E-05	-2.003E-01	-2.209E-02	-1.452E-05	-2.489E-02
	-8.858E-02	-1.175E-01	-1.285E-01	-1.204E-02	-2.751E-01	-1.276E-01	-1.046E+01
Pres(kpa)	-9.444E-02	-1.317E-01	-1.407E-01	-4.622E-02	-2.206E-01	-1.392E-01	-1.743E+00

Upper layer species concentration

O2 MASS	9.287E-03	7.332E-03	6.925E-03	4.84	8.447E-02	6.965E-03	4.650E-03
PPM	2.070E+05	2.070E+05	2.070E+05	1.909E+05	1.289E+05	2.070E+05	2.089E+05
CO2 MASS	0.000	0.000	0.000	2.909E-05	2.834E-07	0.000	3.354E-11
PPM	0.000	0.000	0.000	0.835	0.315	0.000	1.096E-03
CO MASS	0.000	0.000	0.000	5.818E-06	5.668E-08	0.000	6.708E-12
PPM	0.000	0.000	0.000	0.262	9.887E-02	0.000	3.444E-04
OD MASS	0.000	0.000	0.000	5.818E-06	5.668E-08	0.000	6.708E-12
1/M	0.000	0.000	0.000	1.141E-03	4.307E-04	0.000	1.494E-06
CT mg-m/l	0.000	0.000	0.000	9.935E-02	4.309E-02	0.000	2.662E-05

TIME = 200.0 SECONDS.

U.TEMP.	303.1	303.6	303.7	302.9	302.7	303.7	316.5
L.TEMP.	301.1	301.5	301.6	300.2	302.9	301.6	334.3
U.VOLUM	0.4	0.4	0.4	29.3	4.5	0.4	1.5
U.DEPTH	0.0	0.0	0.0	0.8	0.4	0.0	0.2
CE.TEMP	300.2	300.2	300.2	300.2	300.1	300.2	302.7
UW.TEMP	300.1	300.2	300.2	300.1	300.1	300.2	302.1
LW.TEMP	300.0	300.0	300.0	300.0	300.1	300.0	306.5
FL.TEMP	300.0	300.0	300.0	300.0	300.1	300.0	306.5
EMS(I)=	0.000E+00	0.000E+00	0.000E+00	1.359E-01	0.000E+00	0.000E+00	0.000E+00
EMP(I)=	0.000E+00	0.000E+00	0.000E+00	8.333E-05	0.000E+00	0.000E+00	0.000E+00
QF(I)=	0.000E+00	0.000E+00	0.000E+00	1.494E+00	0.000E+00	0.000E+00	0.000E+00
QR(I)=	-5.124E-02	-4.715E-02	-4.610E-02	-1.569E-01	-4.198E-02	-4.621E-02	-1.408E-01
QC(I)=	-1.738E-01	-1.673E-01	-1.653E-01	-5.552E-01	-1.480E-01	-1.655E-01	-8.955E-01
	-7.838E-02	-1.021E-01	-1.091E-01	-1.047E-02	-1.949E-01	-1.093E-01	-5.467E+00
Pres(kpa)	-8.981E-02	-1.320E-01	-1.414E-01	-3.235E-02	-2.295E-01	-1.402E-01	-8.219E-01

Upper layer species concentration

O2 MASS	5.041E-02	4.816E-02	4.757E-02	7.86	0.533	4.764E-02	0.170
PPM	8.570E+04	8.377E+04	8.339E+04	1.902E+05	8.459E+04	8.342E+04	8.619E+04
CO2 MASS	8.110E-07	8.049E-07	8.012E-07	2.160E-04	1.018E-05	8.017E-07	3.799E-06
PPM	1.00	1.02	1.02	3.80	1.17	1.02	1.40
CO MASS	1.622E-07	1.610E-07	1.602E-07	4.320E-05	2.036E-06	1.603E-07	7.598E-07
PPM	0.315	0.320	0.321	1.19	0.369	0.321	0.441
OD MASS	1.622E-07	1.610E-07	1.602E-07	4.320E-05	2.036E-06	1.603E-07	7.598E-07
1/M	1.362E-03	1.381E-03	1.385E-03	5.166E-03	1.598E-03	1.384E-03	1.824E-03
CT mg-m/l	2.897E-02	3.005E-02	3.029E-02	0.412	0.146	3.027E-02	7.117E-02

TIME = 300.0 SECONDS.

U.TEMP.	307.4	308.0	308.2	308.4	305.9	308.2	321.3
L.TEMP.	301.1	301.5	301.6	300.2	302.9	301.6	332.9
U.VOLUM	3.3	3.3	3.3	38.2	9.0	3.3	1.8
U.DEPTH	0.2	0.3	0.3	1.0	0.9	0.3	0.3
CE.TEMP	300.7	300.8	300.8	300.7	300.5	300.8	304.5
UW.TEMP	300.5	300.6	300.6	300.6	300.4	300.6	303.7
LW.TEMP	300.0	300.0	300.0	300.0	300.1	300.0	307.0
FL.TEMP	300.0	300.0	300.0	300.0	300.1	300.0	307.0
EMS(I)=	0.000E+00	0.000E+00	0.000E+00	1.220E-01	0.000E+00	0.000E+00	0.000E+00
EMP(I)=	0.000E+00	0.000E+00	0.000E+00	4.818E-04	0.000E+00	0.000E+00	0.000E+00
QF(I)=	0.000E+00	0.000E+00	0.000E+00	8.640E+00	0.000E+00	0.000E+00	0.000E+00
QR(I)=	-1.358E-01	-1.219E-01	-1.188E-01	-4.932E-01	-1.104E-01	-1.193E-01	-1.971E-01
QC(I)=	-5.980E-01	-5.556E-01	-5.458E-01	-2.396E+00	-5.032E-01	-5.477E-01	-1.224E+00
	-7.192E-02	-8.827E-02	-9.272E-02	-6.558E-03	-1.497E-01	-9.475E-02	-4.891E+00
Pres(kpa)	-7.204E-02	-1.079E-01	-1.157E-01	-6.329E-02	-2.108E-01	-1.157E-01	-9.055E-01

Upper layer species concentration

O2 MASS	0.311	0.307	0.305	9.12	1.43	0.305	0.135
PPM	6.693E+04	6.672E+04	6.670E+04	1.722E+05	1.140E+05	6.670E+04	5.736E+04
CO2 MASS	1.458E-05	1.448E-05	1.441E-05	1.115E-03	9.888E-05	1.442E-05	1.284E-05
PPM	2.28	2.29	2.29	15.3	5.72	2.29	3.95
CO MASS	2.917E-06	2.896E-06	2.883E-06	2.230E-04	1.978E-05	2.884E-06	2.569E-06
PPM	0.718	0.719	0.720	4.81	1.80	0.720	1.24
OD MASS	2.917E-06	2.896E-06	2.883E-06	2.230E-04	1.978E-05	2.884E-06	2.569E-06
1/M	3.059E-03	3.060E-03	3.060E-03	2.045E-02	7.704E-03	3.060E-03	5.066E-03
CT mg-m/l	0.195	0.197	0.198	1.07	0.422	0.198	0.285

TIME = 400.0 SECONDS.

U.TEMP.	315.2	315.7	315.9	334.5	319.4	315.8	323.3
L.TEMP.	301.2	301.5	301.6	300.2	302.8	301.6	329.9
U.VOLUM	19.2	15.9	15.1	49.4	16.0	15.2	7.6
U.DEPTH	1.4	1.5	1.5	1.4	1.6	1.5	1.1
CE.TEMP	302.0	302.2	302.2	304.4	302.2	302.2	305.8
UW.TEMP	301.6	301.7	301.7	303.5	301.7	301.7	304.8
LW.TEMP	300.1	300.1	300.1	300.3	300.2	300.1	306.9
FL.TEMP	300.1	300.1	300.1	300.3	300.2	300.1	306.9
EMS(I)=	0.000E+00	0.000E+00	0.000E+00	1.674E-01	0.000E+00	0.000E+00	0.000E+00
EMP(I)=	0.000E+00	0.000E+00	0.000E+00	3.300E-03	0.000E+00	0.000E+00	0.000E+00
QF(I)=	0.000E+00	0.000E+00	0.000E+00	5.918E+01	0.000E+00	0.000E+00	0.000E+00
QR(I)=	-4.300E-01	-3.788E-01	-3.679E-01	-2.437E+00	-4.826E-01	-3.707E-01	-3.909E-01
QC(I)=	-2.494E+00	-2.245E+00	-2.191E+00	-1.569E+01	-3.053E+00	-2.209E+00	-2.601E+00
	-3.012E-02	-3.473E-02	-3.635E-02	7.800E-03	-7.113E-02	-3.695E-02	-2.457E+00
Pres(kpa)	4.054E-02	5.890E-03	-7.568E-03	-6.746E-02	-1.172E-01	-6.210E-03	-5.004E-01

Upper layer species concentration

O2 MASS	1.24	1.03	0.981	9.02	2.11	0.986	0.509
PPM	4.746E+04	4.781E+04	4.786E+04	1.428E+05	9.812E+04	4.785E+04	5.066E+04
CO2 MASS	4.844E-04	4.232E-04	4.109E-04	2.107E-02	1.838E-03	4.122E-04	5.457E-04
PPM	13.5	14.3	14.6	243.	62.2	14.6	39.5
CO MASS	6.295E-05	5.426E-05	5.242E-05	1.774E-03	1.996E-04	5.262E-05	5.375E-05
PPM	2.76	2.88	2.92	32.1	10.6	2.92	6.11
OD MASS	5.524E-05	4.735E-05	4.566E-05	1.220E-03	1.614E-04	4.584E-05	4.117E-05
1/M	1.008E-02	1.043E-02	1.056E-02	8.649E-02	3.520E-02	1.055E-02	1.896E-02
CT mg-m/l	0.508	0.512	0.513	3.34	1.38	0.513	0.771

TIME = 500.0 SECONDS.

U.TEMP.	343.5	343.5	344.2	455.9	383.9	344.1	370.6
L.TEMP.	306.0	308.0	308.1	306.5	308.6	308.1	340.0
U.VOLUM	31.4	24.3	23.0	73.0	23.0	23.1	15.3
U.DEPTH	2.3	2.3	2.3	2.0	2.2	2.3	2.2
CE.TEMP	305.8	306.0	306.1	324.2	311.1	306.1	311.2
UW.TEMP	304.7	304.8	304.9	320.1	309.1	304.9	309.2
LW.TEMP	300.7	300.7	300.7	302.8	301.3	300.7	306.9
FL.TEMP	300.7	300.7	300.7	302.8	301.3	300.7	306.9
EMS(I)=	0.000E+00	0.000E+00	0.000E+00	2.800E-02	0.000E+00	0.000E+00	0.000E+00
EMP(I)=	0.000E+00	0.000E+00	0.000E+00	2.800E-02	0.000E+00	0.000E+00	0.000E+00
QF(I)=	0.000E+00	0.000E+00	0.000E+00	5.021E+02	0.000E+00	0.000E+00	0.000E+00
QR(I)=	-1.810E+00	-1.512E+00	-1.479E+00	-2.256E+01	-3.484E+00	-1.491E+00	-2.701E+00
QC(I)=	-1.283E+01	-1.077E+01	-1.056E+01	-1.115E+02	-2.368E+01	-1.066E+01	-1.965E+01
	-1.987E-02	-3.872E-02	-3.702E-02	-1.107E-01	-3.989E-02	-3.737E-02	-2.823E-01
Pres(kpa)	8.612E+00	8.970E+00	8.943E+00	7.612E+00	7.986E+00	8.948E+00	8.699E+00

Upper layer species concentration

O2 MASS	3.01	2.36	2.24	5.15	2.21	2.25	1.39
PPM	7.689E+04	7.794E+04	7.832E+04	7.514E+04	8.609E+04	7.828E+04	7.835E+04
CO2 MASS	4.648E-02	3.659E-02	3.554E-02	0.431	8.257E-02	3.566E-02	4.298E-02
PPM	865.	878.	904.	4.574E+03	2.339E+03	901.	1.768E+03
CO MASS	2.191E-03	1.731E-03	1.675E-03	1.542E-02	3.390E-03	1.681E-03	1.767E-03
PPM	64.1	65.3	67.0	257.	151.	66.8	114.
OD MASS	9.704E-04	7.660E-04	7.397E-04	6.746E-03	1.444E-03	7.425E-04	7.665E-04
1/M	0.108	0.110	0.113	0.324	0.219	0.112	0.175
CT mg-m/l	2.41	2.53	2.58	11.3	5.83	2.57	4.05

TIME = 600.0 SECONDS.

U.TEMP.	538.2	513.7	516.6	1064.8	709.5	516.0	615.2
L.TEMP.	308.6	306.6	306.7	371.8	322.9	306.7	348.2
U.VOLUM	31.3	24.6	23.2	65.2	21.0	23.4	14.7
U.DEPTH	2.3	2.3	2.3	1.8	2.0	2.3	2.2
CE.TEMP	351.4	345.3	346.1	583.6	406.7	345.9	376.4
UW.TEMP	343.6	338.4	339.0	543.3	391.1	338.9	365.2
LW.TEMP	310.1	308.5	308.7	435.7	328.6	308.7	321.6
FL.TEMP	310.1	308.5	308.7	435.7	328.6	308.7	321.6
EMS(I)=	0.000E+00	0.000E+00	0.000E+00	2.869E-01	0.000E+00	0.000E+00	0.000E+00
EMP(I)=	0.000E+00	0.000E+00	0.000E+00	1.047E-01	0.000E+00	0.000E+00	0.000E+00
QF(I)=	0.000E+00	0.000E+00	0.000E+00	1.878E+03	0.000E+00	0.000E+00	0.000E+00
QR(I)=	-2.382E+01	-1.626E+01	-1.600E+01	-7.833E+02	-6.023E+01	-1.608E+01	-3.436E+01
QC(I)=	-8.375E+01	-6.390E+01	-6.221E+01	-3.528E+02	-1.042E+02	-6.279E+01	-9.190E+01
	6.830E-02	7.021E-02	7.161E-02	2.848E+01	3.486E-01	7.094E-02	-4.012E-01
Pres(kpa)	4.576E+01	4.697E+01	4.693E+01	4.658E+01	4.660E+01	4.694E+01	4.719E+01

Upper layer species concentration

O2 MASS	0.771	0.723	0.663	9.481E-02	0.161	0.669	0.235
PPM	3.100E+04	3.527E+04	3.445E+04	3.619E+03	1.270E+04	3.453E+04	2.298E+04
CO2 MASS	1.30	0.980	0.936	3.14	1.06	0.941	0.640
PPM	3.797E+04	3.474E+04	3.536E+04	8.711E+04	6.081E+04	3.530E+04	4.546E+04
CO MASS	2.565E-02	1.966E-02	1.872E-02	5.441E-02	1.938E-02	1.883E-02	1.206E-02
PPM	1.179E+03	1.095E+03	1.112E+03	2.373E+03	1.753E+03	1.110E+03	1.347E+03
OD MASS	2.199E-02	1.659E-02	1.584E-02	5.159E-02	1.775E-02	1.593E-02	1.074E-02
1/M	2.46	2.36	2.39	2.77	2.96	2.39	2.55
CT mg-m/l	34.5	33.2	33.7	55.7	48.5	33.7	41.0

TIME = 700.0 SECONDS.

U.TEMP.	535.6	517.2	519.5	987.5	690.2	518.9	609.7
L.TEMP.	319.4	315.7	315.9	445.9	337.3	315.8	356.8
U.VOLUM	31.4	24.6	23.2	65.4	21.8	23.4	15.0
U.DEPTH	2.3	2.3	2.3	1.8	2.1	2.3	2.2
CE.TEMP	372.8	365.6	366.4	608.9	436.5	366.2	401.4
UW.TEMP	363.0	356.7	357.5	569.8	418.7	357.3	388.2
LW.TEMP	320.1	316.9	317.2	487.9	347.2	317.1	333.4
FL.TEMP	320.1	316.9	317.2	487.9	347.2	317.1	333.4
EMS(I)=	0.000E+00	0.000E+00	0.000E+00	1.492E-01	0.000E+00	0.000E+00	0.000E+00
EMP(I)=	0.000E+00	0.000E+00	0.000E+00	8.490E-02	0.000E+00	0.000E+00	0.000E+00
QF(I)=	0.000E+00	0.000E+00	0.000E+00	1.523E+03	0.000E+00	0.000E+00	0.000E+00
QR(I)=	-2.208E+01	-1.587E+01	-1.554E+01	-5.504E+02	-5.236E+01	-1.563E+01	-3.223E+01
QC(I)=	-7.038E+01	-5.563E+01	-5.400E+01	-2.693E+02	-8.632E+01	-5.453E+01	-7.931E+01
	2.062E-02	4.082E-02	4.096E-02	1.449E+01	6.743E-01	4.058E-02	-2.505E-01
Pres(kpa)	3.087E+01	3.187E+01	3.184E+01	3.083E+01	3.107E+01	3.185E+01	3.140E+01

Upper layer species concentration

O2 MASS	0.222	0.201	0.185	0.000	4.594E-02	0.186	6.791E-02
PPM	8.853E+03	9.886E+03	9.645E+03	0.000	3.395E+03	9.668E+03	6.434E+03
CO2 MASS	2.19	1.74	1.64	3.79	1.47	1.65	0.989
PPM	6.352E+04	6.206E+04	6.244E+04	9.732E+04	7.892E+04	6.240E+04	6.814E+04
CO MASS	3.509E-02	2.804E-02	2.647E-02	5.878E-02	2.296E-02	2.665E-02	1.569E-02
PPM	1.601E+03	1.574E+03	1.581E+03	2.370E+03	1.939E+03	1.580E+03	1.699E+03
OD MASS	3.177E-02	2.544E-02	2.401E-02	4.990E-02	2.020E-02	2.417E-02	1.395E-02
1/M	3.55	3.62	3.62	2.67	3.24	3.62	3.24
CT mg-m/l	115.	114.	115.	121.	126.	115.	116.

TIME = 800.0 SECONDS.

U.TEMP.	551.8	534.9	537.3	985.0	706.7	536.6	628.0
L.TEMP.	329.6	324.8	325.2	516.3	363.4	325.1	370.3
U.VOLUM	31.4	24.7	23.3	66.2	22.6	23.5	15.3
U.DEPTH	2.3	2.3	2.3	1.8	2.2	2.3	2.2
CE.TEMP	389.9	381.9	382.9	653.5	464.6	382.6	424.1
UW.TEMP	378.7	371.6	372.5	612.4	444.7	372.2	409.1
LW.TEMP	330.2	325.8	326.3	553.8	371.6	326.2	348.5
FL.TEMP	330.2	325.8	326.3	553.8	371.6	326.2	348.5
EMS(I)=	0.000E+00	0.000E+00	0.000E+00	7.613E-02	0.000E+00	0.000E+00	0.000E+00
EMP(I)=	0.000E+00	0.000E+00	0.000E+00	7.613E-02	0.000E+00	0.000E+00	0.000E+00
QF(I)=	0.000E+00	0.000E+00	0.000E+00	1.365E+03	0.000E+00	0.000E+00	0.000E+00
QR(I)=	-2.451E+01	-1.801E+01	-1.762E+01	-5.182E+02	-5.692E+01	-1.772E+01	-3.602E+01
QC(I)=	-6.882E+01	-5.546E+01	-5.380E+01	-2.276E+02	-8.186E+01	-5.433E+01	-7.723E+01
	1.500E-02	3.107E-02	3.084E-02	1.124E+01	4.768E-01	3.058E-02	-1.547E-01
Pres(kpa)	2.257E+01	2.338E+01	2.335E+01	2.201E+01	2.225E+01	2.336E+01	2.273E+01

Upper layer species concentration

O2 MASS	4.268E-02	3.841E-02	3.513E-02	0.000	9.293E-03	3.547E-02	1.350E-02
PPM	1.753E+03	1.943E+03	1.890E+03	0.000	680.	1.895E+03	1.293E+03
CO2 MASS	2.95	2.36	2.23	4.48	1.90	2.24	1.32
PPM	8.809E+04	8.690E+04	8.725E+04	1.131E+05	1.011E+05	8.722E+04	9.167E+04
CO MASS	4.706E-02	3.767E-02	3.556E-02	7.202E-02	3.048E-02	3.580E-02	2.104E-02
PPM	2.209E+03	2.178E+03	2.187E+03	2.861E+03	2.549E+03	2.186E+03	2.304E+03
OD MASS	3.603E-02	2.904E-02	2.736E-02	5.064E-02	2.221E-02	2.755E-02	1.573E-02
1/M	4.02	4.11	4.10	2.68	3.44	4.11	3.59
CT mg-m/l	209.	210.	211.	187.	209.	211.	201.

TIME = 900.0 SECONDS.

U.TEMP.	527.2	522.0	524.2	875.0	665.4	523.6	599.0
L.TEMP.	337.2	332.8	333.4	560.2	389.6	333.2	367.6
U.VOLUM	31.5	24.8	23.5	80.3	23.6	23.6	15.7
U.DEPTH	2.3	2.3	2.3	2.2	2.3	2.3	2.3
CE.TEMP	395.4	389.2	390.3	634.2	470.2	390.0	431.3
UW.TEMP	385.0	379.3	380.3	602.6	452.6	380.0	417.7
LW.TEMP	337.3	332.9	333.5	570.8	390.0	333.4	361.0
FL.TEMP	337.3	332.9	333.5	570.8	390.0	333.4	361.0
EMS(I)=	0.000E+00	0.000E+00	0.000E+00	5.098E-02	0.000E+00	0.000E+00	0.000E+00
EMP(I)=	0.000E+00	0.000E+00	0.000E+00	5.098E-02	0.000E+00	0.000E+00	0.000E+00
QF(I)=	0.000E+00	0.000E+00	0.000E+00	9.142E+02	0.000E+00	0.000E+00	0.000E+00
QR(I)=	-1.883E+01	-1.541E+01	-1.505E+01	-3.132E+02	-4.257E+01	-1.514E+01	-2.821E+01
QC(I)=	-5.402E+01	-4.680E+01	-4.536E+01	-1.765E+02	-6.565E+01	-4.582E+01	-6.271E+01
	3.647E-04	1.846E-03	1.806E-03	1.719E+00	8.129E-03	1.770E-03	-1.121E-02
Pres(kpa)	2.342E+00	2.609E+00	2.577E+00	6.554E-02	1.095E+00	2.585E+00	1.863E+00

Upper layer species concentration

O2 MASS	1.007E-02	8.208E-03	7.542E-03	0.000	2.371E-03	7.611E-03	3.248E-03
PPM	395.	403.	394.	0.000	156.	395.	289.
CO2 MASS	3.06	2.44	2.30	5.42	1.95	2.31	1.40
PPM	8.719E+04	8.708E+04	8.728E+04	1.004E+05	9.347E+04	8.726E+04	9.046E+04
CO MASS	4.924E-02	3.920E-02	3.696E-02	8.751E-02	3.141E-02	3.721E-02	2.248E-02
PPM	2.205E+03	2.202E+03	2.207E+03	2.548E+03	2.368E+03	2.206E+03	2.290E+03
OD MASS	3.434E-02	2.736E-02	2.577E-02	5.795E-02	2.127E-02	2.594E-02	1.546E-02
1/M	3.82	3.86	3.85	2.53	3.16	3.85	3.44
CT mg-m/l	307.	310.	311.	253.	292.	311.	290.

TIME = 1000.0 SECONDS.

U.TEMP.	487.5	493.0	494.4	741.1	598.0	494.0	544.1
L.TEMP.	338.2	336.3	336.9	565.9	393.7	336.7	384.8
U.VOLUM	29.7	24.8	23.4	81.7	23.4	23.5	15.5
U.DEPTH	2.2	2.3	2.3	2.2	2.3	2.3	2.3
CE.TEMP	389.3	387.4	388.3	591.2	457.8	388.0	422.9
UW.TEMP	381.9	379.7	380.6	574.6	446.0	380.3	413.5
LW.TEMP	338.3	336.4	337.0	552.9	393.2	336.8	363.4
FL.TEMP	338.3	336.4	337.0	552.9	393.2	336.8	363.4
EMS(I)=	0.000E+00	0.000E+00	0.000E+00	2.583E-02	0.000E+00	0.000E+00	0.000E+00
EMP(I)=	0.000E+00	0.000E+00	0.000E+00	2.583E-02	0.000E+00	0.000E+00	0.000E+00
QF(I)=	0.000E+00	0.000E+00	0.000E+00	4.632E+02	0.000E+00	0.000E+00	0.000E+00
QR(I)=	-1.179E+01	-1.107E+01	-1.075E+01	-1.344E+02	-2.446E+01	-1.083E+01	-1.667E+01
QC(I)=	-3.668E+01	-3.545E+01	-3.424E+01	-1.032E+02	-4.444E+01	-3.461E+01	-4.231E+01
	9.719E-04	1.135E-03	1.026E-03	-1.581E-01	-7.459E-04	1.033E-03	-1.057E-01
Pres(kpa)	-7.286E-01	-1.304E+00	-1.326E+00	-3.811E+00	-2.629E+00	-1.319E+00	-1.740E+00

Upper layer species concentration

O2 MASS	3.766E-03	2.865E-03	2.647E-03	0.000	9.583E-04	2.670E-03	1.205E-03
PPM	144.	133.	131.	0.000	57.3	131.	98.9
CO2 MASS	3.53	2.96	2.79	7.36	2.47	2.81	1.71
PPM	9.857E+04	9.993E+04	1.001E+05	1.134E+05	1.075E+05	1.001E+05	1.021E+05
CO MASS	5.699E-02	4.768E-02	4.498E-02	0.119	3.994E-02	4.528E-02	2.759E-02
PPM	2.499E+03	2.534E+03	2.539E+03	2.879E+03	2.728E+03	2.538E+03	2.588E+03
OD MASS	3.796E-02	3.167E-02	2.986E-02	7.636E-02	2.605E-02	3.006E-02	1.817E-02
1/M	4.47	4.47	4.47	3.27	3.90	4.47	4.10
CT mg-m/l	418.	422.	422.	338.	391.	423.	393.

TIME = 1100.0 SECONDS.

U.TEMP.	439.5	443.7	444.5	551.4	495.6	444.2	467.0
L.TEMP.	337.0	336.9	337.5	542.8	390.9	337.3	383.3
U.VOLUM	27.1	24.5	23.1	78.9	23.0	23.3	15.1
U.DEPTH	2.0	2.3	2.3	2.2	2.2	2.3	2.2
CE.TEMP	377.5	377.3	378.0	522.6	429.7	377.7	403.3
UW.TEMP	374.4	373.5	374.2	525.8	426.7	374.0	400.4
LW.TEMP	336.1	336.1	336.7	509.1	385.0	336.5	359.1
FL.TEMP	336.1	336.1	336.7	509.1	385.0	336.5	359.1
EMS(I)=	0.000E+00	0.000E+00	0.000E+00	3.893E-03	0.000E+00	0.000E+00	0.000E+00
EMP(I)=	0.000E+00	0.000E+00	0.000E+00	3.893E-03	0.000E+00	0.000E+00	0.000E+00
QF(I)=	0.000E+00	0.000E+00	0.000E+00	6.982E+01	0.000E+00	0.000E+00	0.000E+00
QR(I)=	-5.907E+00	-5.714E+00	-5.515E+00	-1.397E+01	-7.878E+00	-5.558E+00	-6.338E+00
QC(I)=	-1.953E+01	-1.988E+01	-1.912E+01	-1.151E+01	-1.732E+01	-1.933E+01	-1.851E+01
	-9.087E-03	-1.604E-03	-1.605E-03	-8.583E-01	-2.665E-02	-1.617E-03	-2.445E-01
Pres(kpa)	-2.399E+00	-3.324E+00	-3.336E+00	-5.110E+00	-4.216E+00	-3.331E+00	-3.409E+00

Upper layer species concentration

O2 MASS |	1.487E-03	1.204E-03	1.111E-03	0.000	4.568E-04	1.121E-03	5.176E-04
PPM |	56.4	50.9	49.9	0.000	23.0	50.0	37.5
CO2 MASS |	3.49	3.14	2.96	7.96	2.62	2.98	1.78
PPM |	9.622E+04	9.671E+04	9.664E+04	9.462E+04	9.626E+04	9.665E+04	9.403E+04
CO MASS |	5.655E-02	5.095E-02	4.795E-02	0.130	4.274E-02	4.828E-02	2.900E-02
PPM |	2.449E+03	2.463E+03	2.462E+03	2.433E+03	2.463E+03	2.462E+03	2.400E+03
OD MASS |	3.657E-02	3.286E-02	3.091E-02	8.149E-02	2.713E-02	3.113E-02	1.857E-02
1/M |	4.72	4.69	4.68	3.62	4.13	4.68	4.31
CT mg-m/l |	552.	556.	556.	444.	511.	556.	517.

TIME = 1200.0 SECONDS.

U.TEMP.	409.6	412.9	413.4	472.4	442.9	413.2	427.1
L.TEMP.	337.2	336.9	337.5	512.7	384.5	337.3	378.6
U.VOLUM	27.6	24.4	23.0	79.5	23.1	23.1	15.1
U.DEPTH	2.0	2.3	2.3	2.2	2.3	2.3	2.2
CE.TEMP	365.0	365.4	365.9	472.4	403.6	365.8	384.3
UW.TEMP	366.4	365.9	366.5	492.6	409.3	366.3	387.8
LW.TEMP	333.4	333.9	334.4	474.8	375.1	334.2	353.5
FL.TEMP	333.4	333.9	334.4	474.8	375.1	334.2	353.5
EMS(I)=	0.000E+00	0.000E+00	0.000E+00	3.893E-05	0.000E+00	0.000E+00	0.000E+00
EMP(I)=	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
QF(I)=	0.000E+00	0.000E+00	0.000E+00	6.982E-01	0.000E+00	0.000E+00	0.000E+00
QR(I)=	-3.699E+00	-3.512E+00	-3.380E+00	1.870E-01	-3.674E+00	-3.410E+00	-3.408E+00
QC(I)=	-1.246E+01	-1.250E+01	-1.199E+01	4.188E+00	-7.948E+00	-1.213E+01	-9.800E+00
	-5.510E-02	-1.090E-02	-1.120E-02	-9.777E-01	-4.490E-02	-1.098E-02	-2.319E-01
Pres(kpa)	-1.480E+00	-2.112E+00	-2.124E+00	-3.455E+00	-2.806E+00	-2.120E+00	-1.938E+00

Upper layer species concentration

O2 MASS	6.932E-04	5.650E-04	5.223E-04	2.672E-04	2.513E-04	5.269E-04	2.598E-04
PPM	24.0	22.4	22.0	3.71	11.3	22.0	17.1
CO2 MASS	3.46	3.08	2.90	8.23	2.65	2.92	1.79
PPM	8.723E+04	8.865E+04	8.851E+04	8.321E+04	8.615E+04	8.852E+04	8.580E+04
CO MASS	5.629E-02	5.011E-02	4.715E-02	0.134	4.314E-02	4.747E-02	2.913E-02
PPM	2.231E+03	2.268E+03	2.265E+03	2.134E+03	2.208E+03	2.265E+03	2.197E+03
OD MASS	3.585E-02	3.188E-02	2.999E-02	8.490E-02	2.732E-02	3.019E-02	1.850E-02
1/M	4.55	4.58	4.56	3.74	4.14	4.57	4.28
CT mg-m/l	690.	694.	694.	556.	637.	695.	647.

TABLE 3-3 PRINTER OUTOUT FROM TENAB

INPUT FAST FILE : C:SIMEXAM.DMP
INPUT EXITT FILE : C:SIMEXAM.EVA
TENABS OUTPUT FILE: C:SIMEXAM.TEN

OCCUPANT 1	ROOM NUMBER 1	ENTER TIME (S) 0
OCCUPANT 2	ROOM NUMBER 2	ENTER TIME (S) 0
OCCUPANT 3	ROOM NUMBER 3	ENTER TIME (S) 0
OCCUPANT 4	ROOM NUMBER 4	ENTER TIME (S) 0
OCCUPANT 5	ROOM NUMBER 5	ENTER TIME (S) 0
OCCUPANT 6	ROOM NUMBER 6	ENTER TIME (S) 0
OCCUPANT 7	ROOM NUMBER 7	ENTER TIME (S) 0

FACTORS	INCAPACITATION LEVEL	LETHAL LEVEL
FED	0.5	1.0
CT (G-MIN/M3)	450.0	900.0
TEMP (C)	65.0	100.0

PERSON 1

TIME (MIN)	ROOM	CONDITION	CAUSE	TEMP (C)	FLUX (KW-MIN/M2)	FED	CT (G-MIN/M3)
9.	1	INCAPACITATED	TEMP	69.4	0.0	0.00	3.
10.	1	DEAD	TEMP	121.2	0.1	0.00	7.
18.	1	INCAPACITATED	CT	199.7	1.9	0.08	483.
21.	1	FINAL TIME		144.4	1.9	0.12	690.

PERSON 2

TIME (MIN)	ROOM	CONDITION	CAUSE	TEMP (C)	FLUX (KW-MIN/M2)	FED	CT (G-MIN/M3)
9.	2	INCAPACITATED	TEMP	69.4	0.0	0.00	3.
10.	2	DEAD	TEMP	115.5	0.1	0.00	7.
18.	2	INCAPACITATED	CT	204.9	1.7	0.08	487.
21.	2	FINAL TIME		147.9	1.8	0.12	694.

PERSON 3

TIME (MIN)	ROOM	CONDITION	CAUSE	TEMP (C)	FLUX (KW-MIN/M2)	FED	CT (G-MIN/M3)
9.	3	INCAPACITATED	TEMP	70.0	0.0	0.00	3.
10.	3	DEAD	TEMP	117.0	0.1	0.00	7.
18.	3	INCAPACITATED	CT	206.1	1.8	0.08	487.
21.	3	FINAL TIME		148.6	1.9	0.12	694.

PERSON 4

TIME (MIN)	ROOM	CONDITION	CAUSE	TEMP (C)	FLUX (KW-MIN/M2)	FED	CT (G-MIN/M3)
8.	4	INCAPACITATED	TEMP	75.9	0.0	0.00	5.
9.	4	DEAD	TEMP	106.2	0.1	0.00	7.
19.	4	INCAPACITATED	CT	286.2	23.2	0.20	454.
21.	4	FINAL TIME		220.6	23.2	0.22	555.

PERSON 5

TIME (MIN)	ROOM	CONDITION	CAUSE	TEMP (C)	FLUX (KW-MIN/M2)	FED	CT (G-MIN/M3)
9.	5	INCAPACITATED	TEMP	69.4	0.0	0.00	4.
9.	5	DEAD	TEMP	108.3	0.1	0.00	7.
19.	5	INCAPACITATED	CT	258.5	6.3	0.13	486.
21.	5	FINAL TIME		183.8	6.4	0.16	637.

PERSON 6

TIME (MIN)	ROOM	CONDITION	CAUSE	TEMP (C)	FLUX (KW-MIN/M2)	FED	CT (G-MIN/M3)
9.	6	INCAPACITATED	TEMP	69.9	0.0	0.00	3.
10.	6	DEAD	TEMP	116.8	0.1	0.00	7.
18.	6	INCAPACITATED	CT	205.7	1.8	0.08	487.
21.	6	FINAL TIME		148.3	1.9	0.12	694.

PERSON 7

TIME (MIN)	ROOM	CONDITION	CAUSE	TEMP (C)	FLUX (KW-MIN/M2)	FED	CT (G-MIN/M3)
2.	7	INCAPACITATED	TEMP	94.3	0.0	0.00	0.
10.	7	DEAD	TEMP	182.5	0.3	0.00	10.
18.	7	INCAPACITATED	CT	246.3	4.3	0.09	453.
21.	7	FINAL TIME		164.5	4.4	0.13	646.

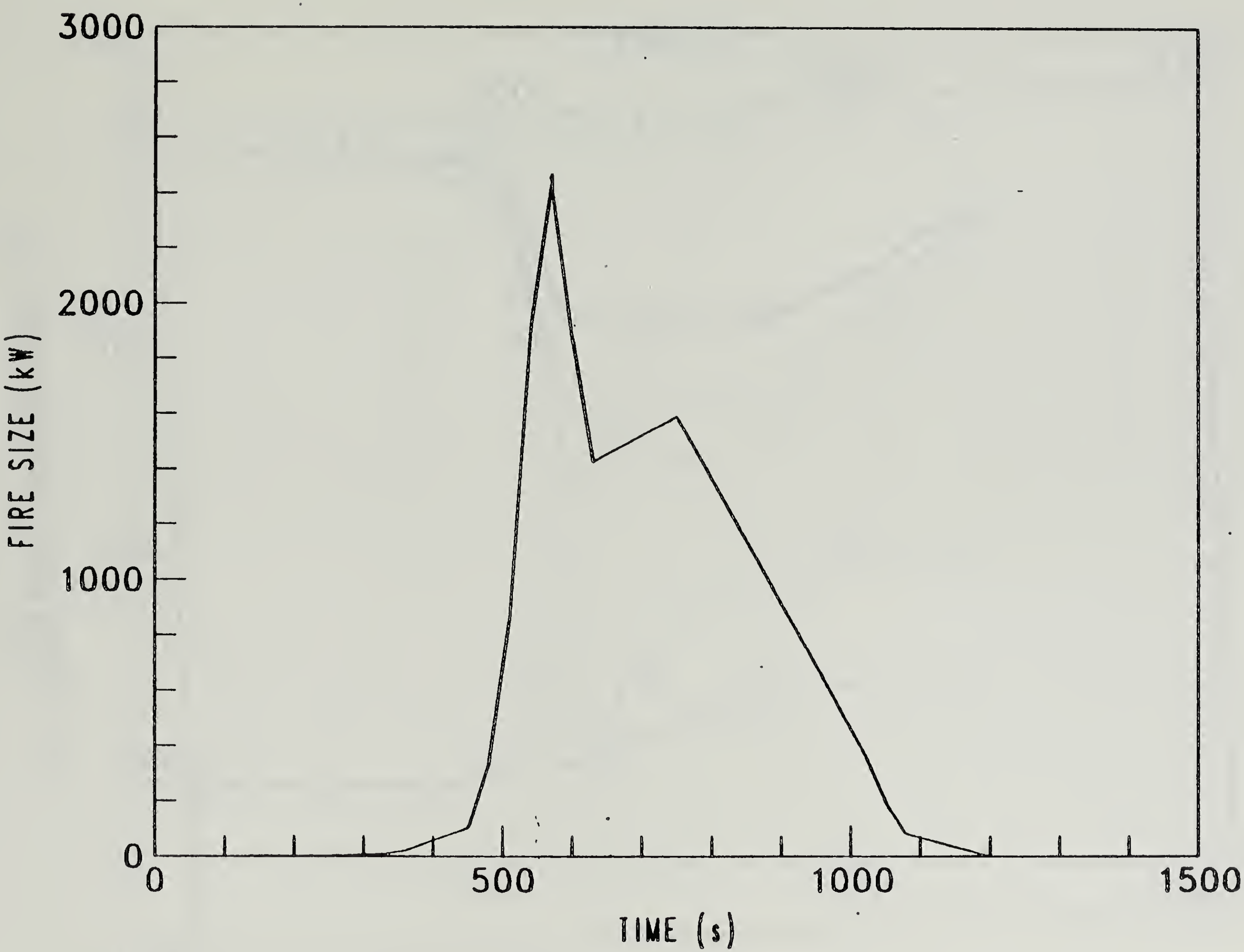


FIG. 3-2 COMPOSITE RATE OF HEAT RELEASE OF SPECIFIED FIRE

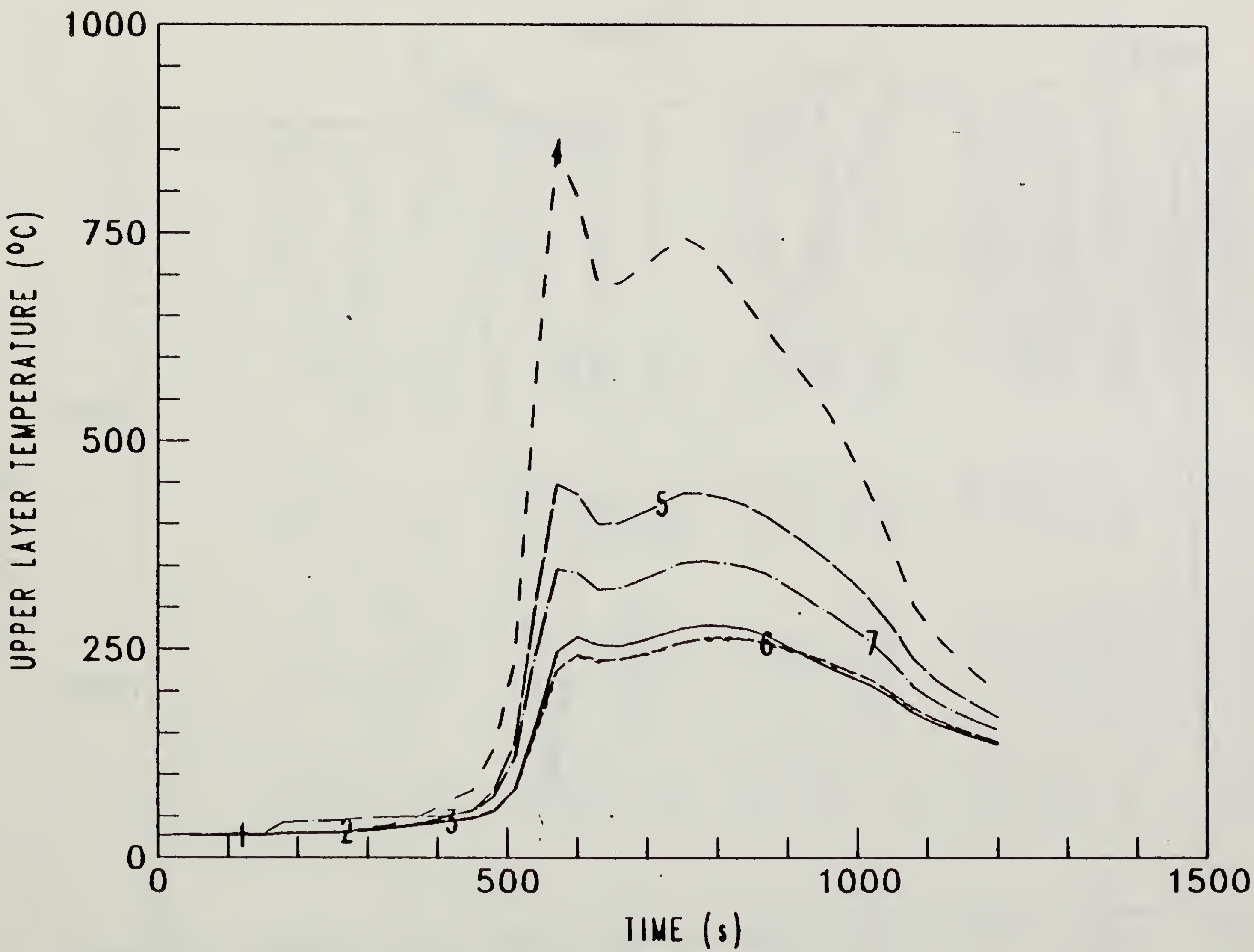


FIG. 3-3 UPPER LAYER TEMPERATURES FOR EACH ROOM

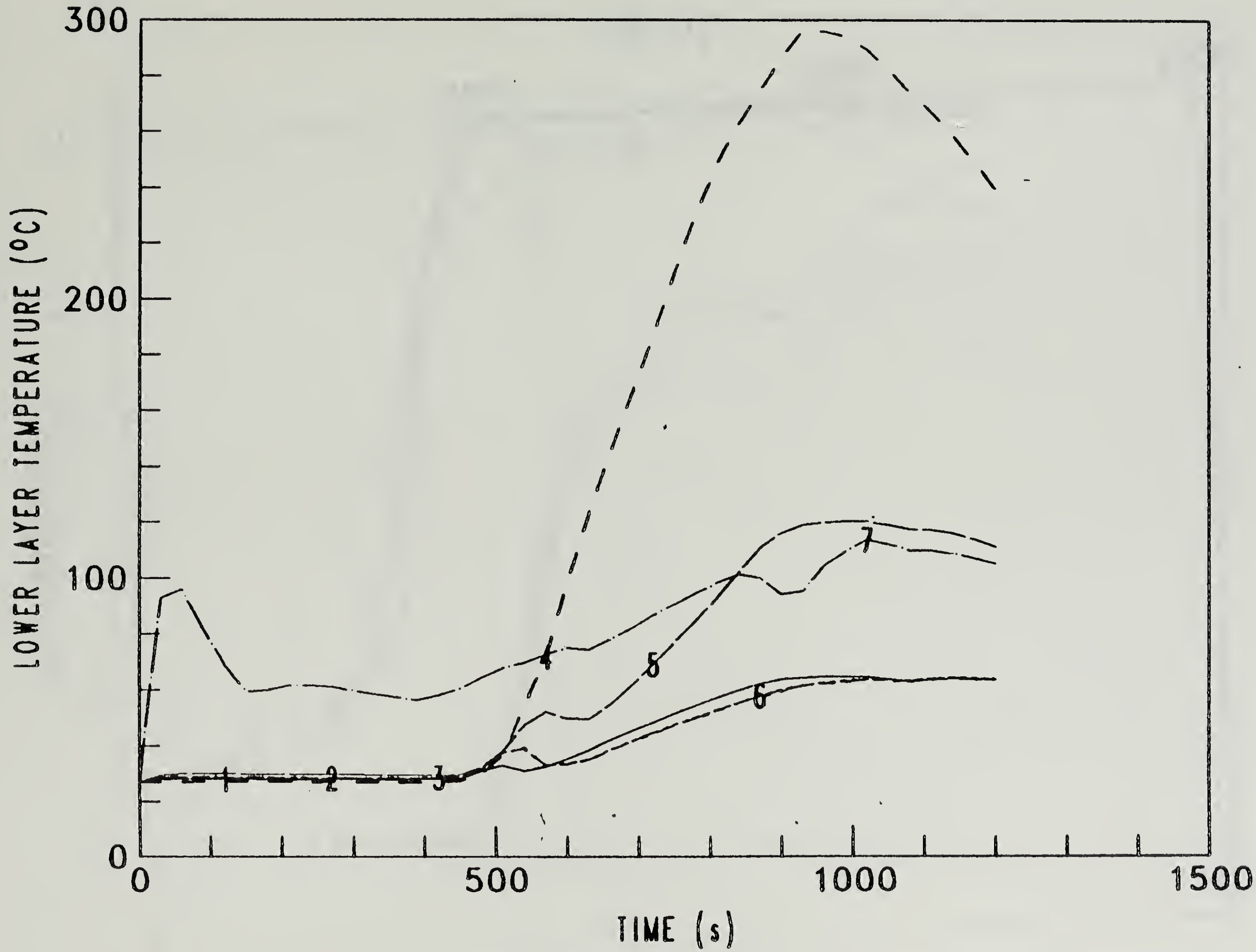


FIG. 3-4 LOWER LAYER TEMPERATURES FOR EACH ROOM

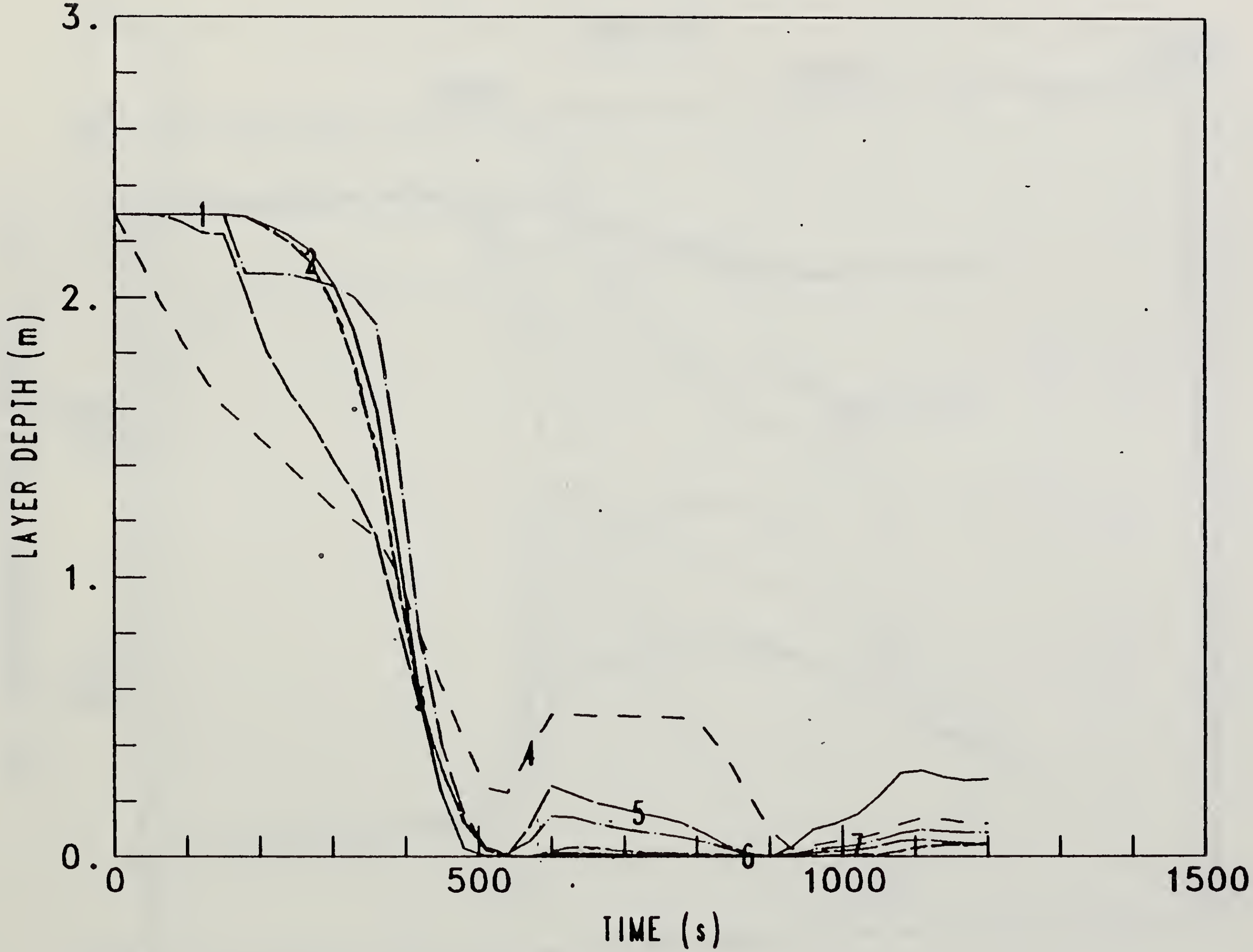


FIG. 3-5 INTERFACE HEIGHT FOR EACH ROOM

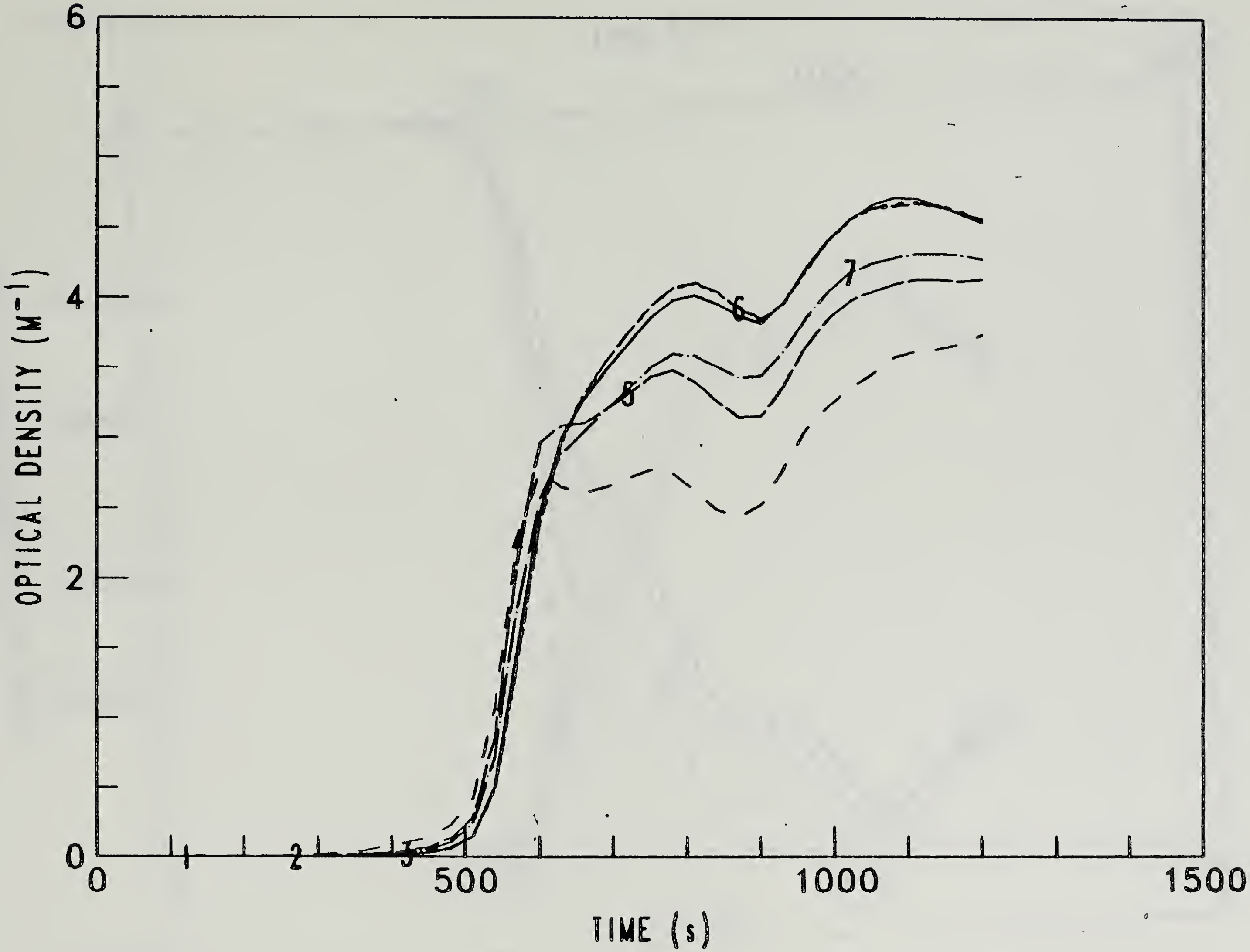


FIG. 3-6 SMOKE OPTICAL DENSITY FOR EACH ROOM

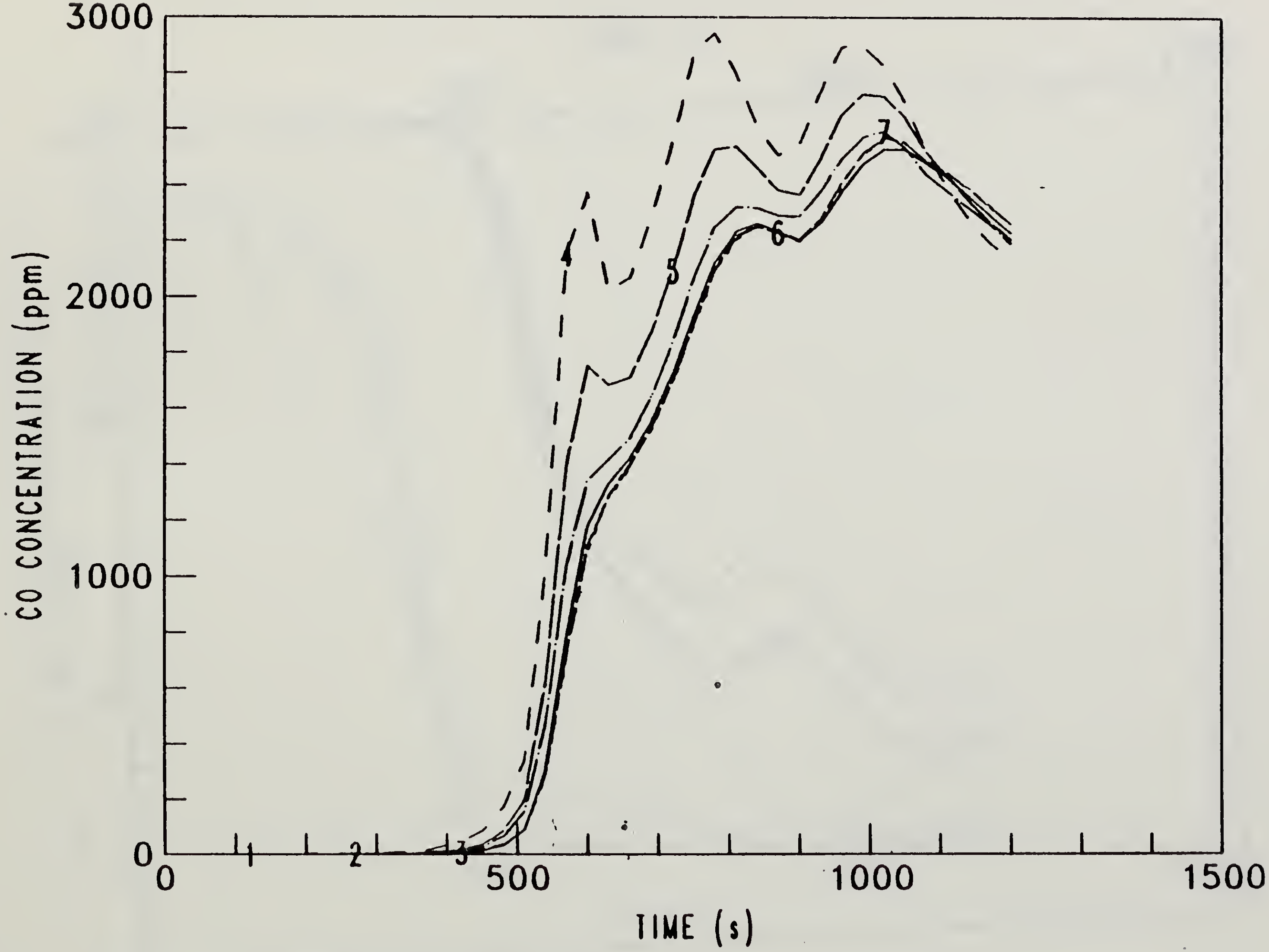


FIG. 3-7 CARBON MONOXIDE CONCENTRATION FOR EACH ROOM

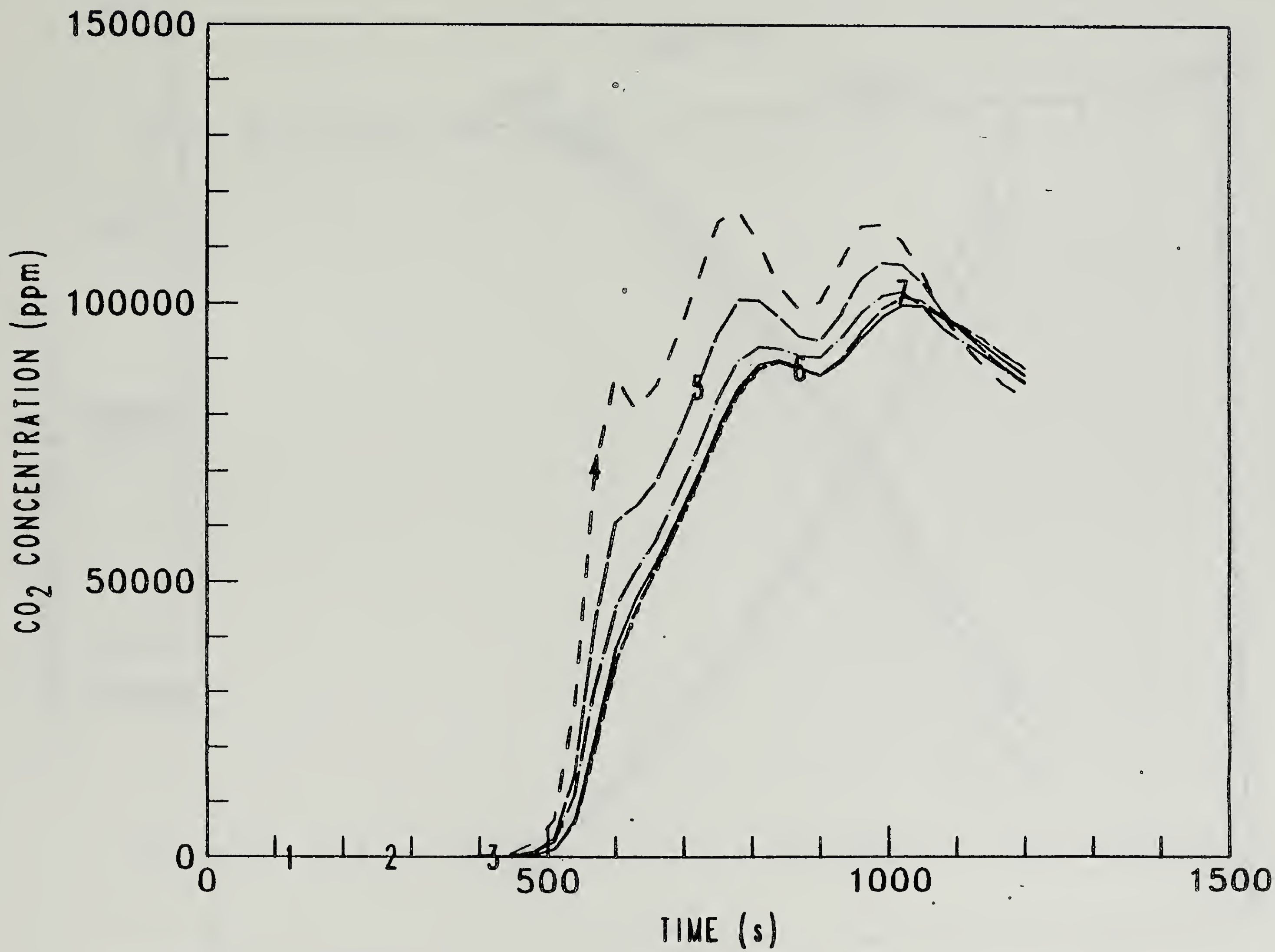


FIG. 3-8 CARBON DIOXIDE CONCENTRATION FOR EACH ROOM

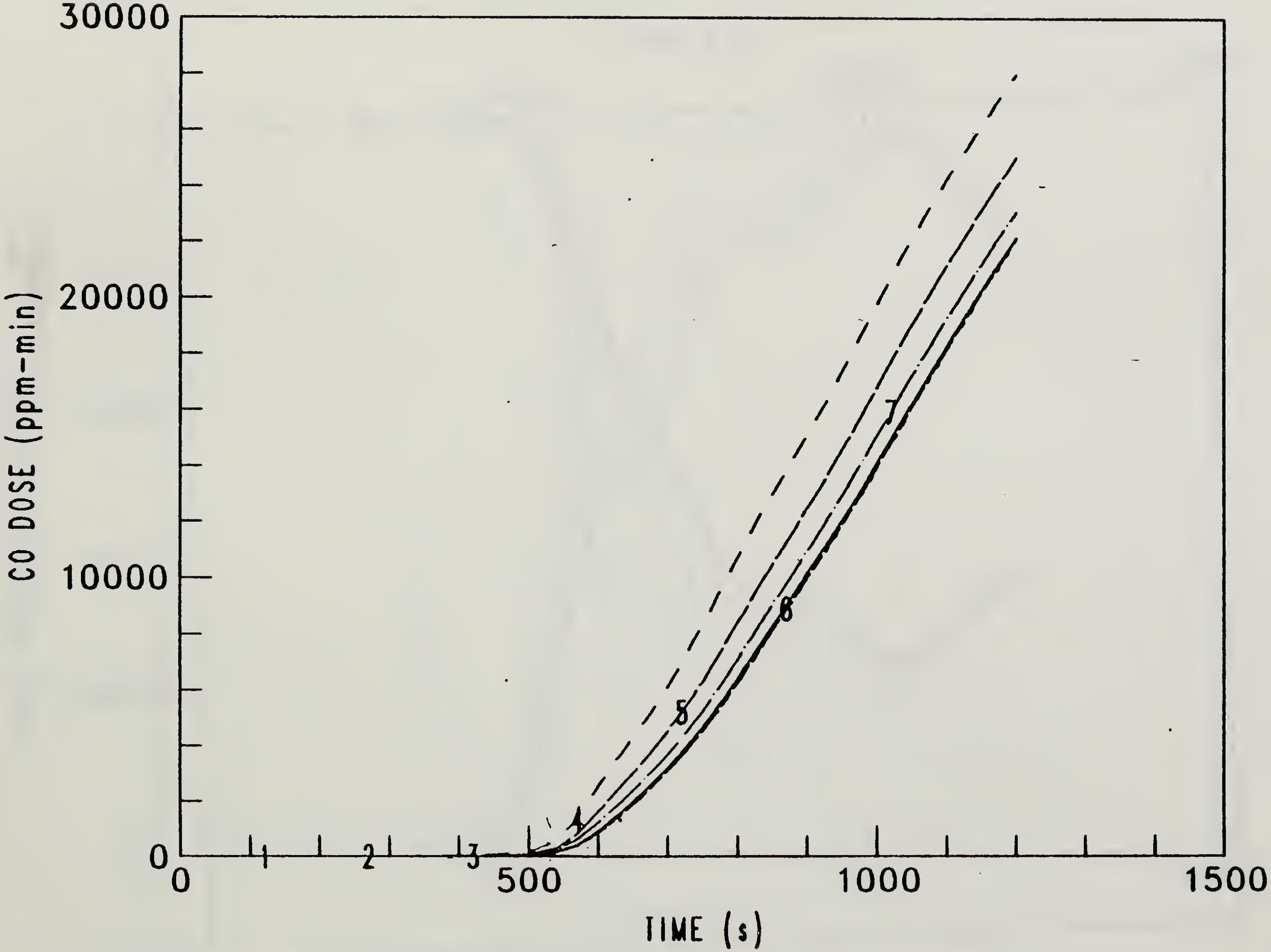


FIG. 3-9 CARBON MONOXIDE EXPOSURE-DOSE FOR EACH ROOM

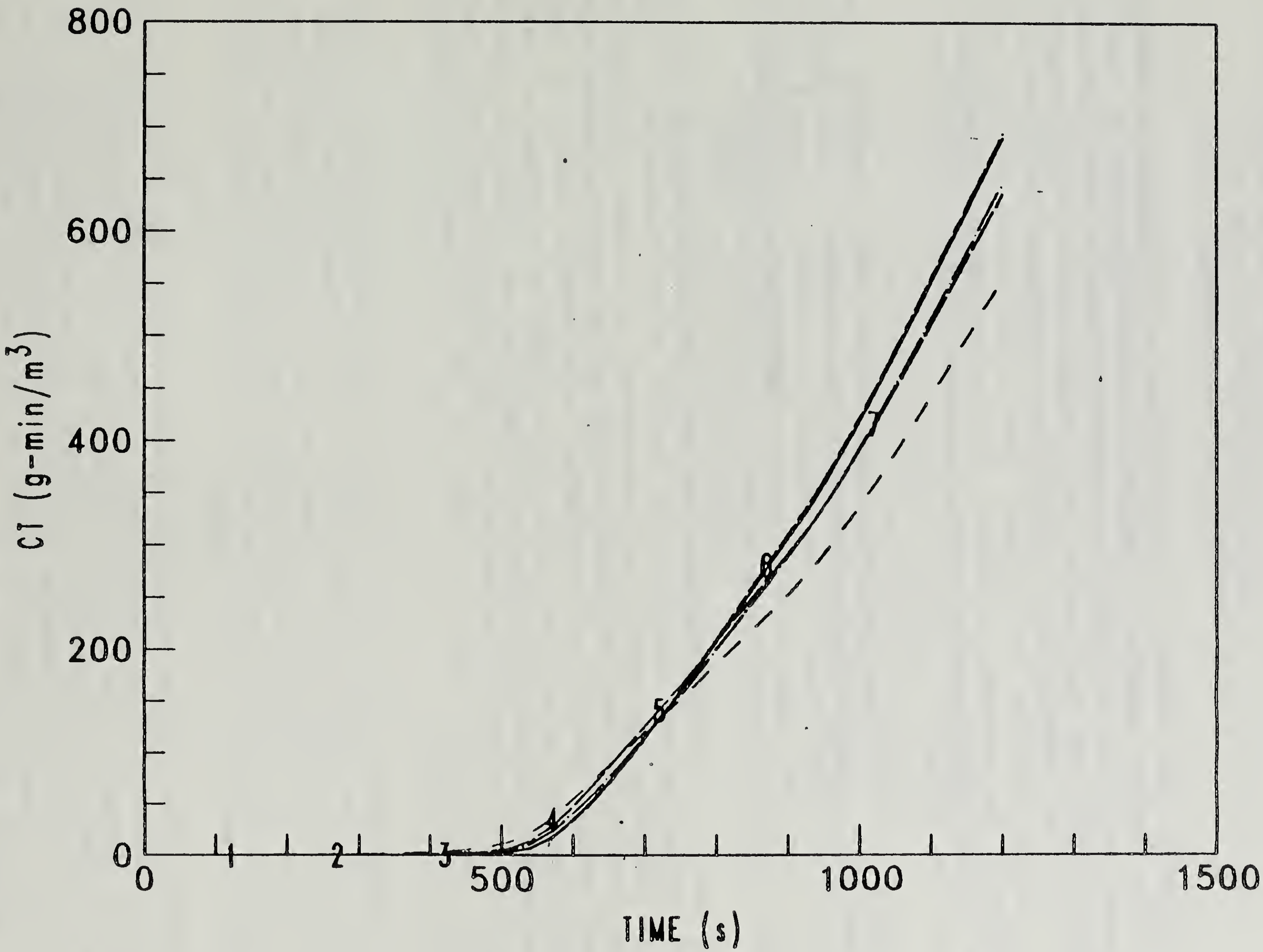


FIG. 3-10 SPECIES Ct (CONCENTRATION-TIME PRODUCT)

CHAPTER 4. STEP-BY-STEP PROCEDURE FOR CONDUCTING A HAZARD ANALYSIS

4.1 The Logic of the Procedure

Initially, the context of use and scenario(s) of concern (steps one and two of the hazard analysis process) 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 models, supporting programs and data that constitute HAZARD I.

Figure 4-1 outlines the four steps in the hazard analysis procedure. These steps will be discussed in detail in the remainder of this chapter. The relationship of these steps to the package of software provided is shown in figure 4-2, with the names of the programs associated with the steps given in parentheses within the appropriate blocks.

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

When proceeding with a hazard analysis, the user should try to understand the process and the reasons for each step. The representative examples should be referred to as a guide to the process and as a data base 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, the user may find it helpful to refer to the representative example case studies and to the section (6.2) of this report on scenario data from the NFIRS system. In this section, the NFIRS data base information is presented, arranged by product identified as first item ignited. That is, for example, the section on upholstered furniture lists the major data elements (form of heat of combustion, equipment involved, material, and area of origin, as well as extent of flame and smoke spread, etc.) by frequency for residential fires, deaths, injuries, and dollar loss. These data can help in establishing frequent scenarios or details to include in one's own scenarios of concern.

FIGURE 4-1 HAZARD ANALYSIS PROCEDURE

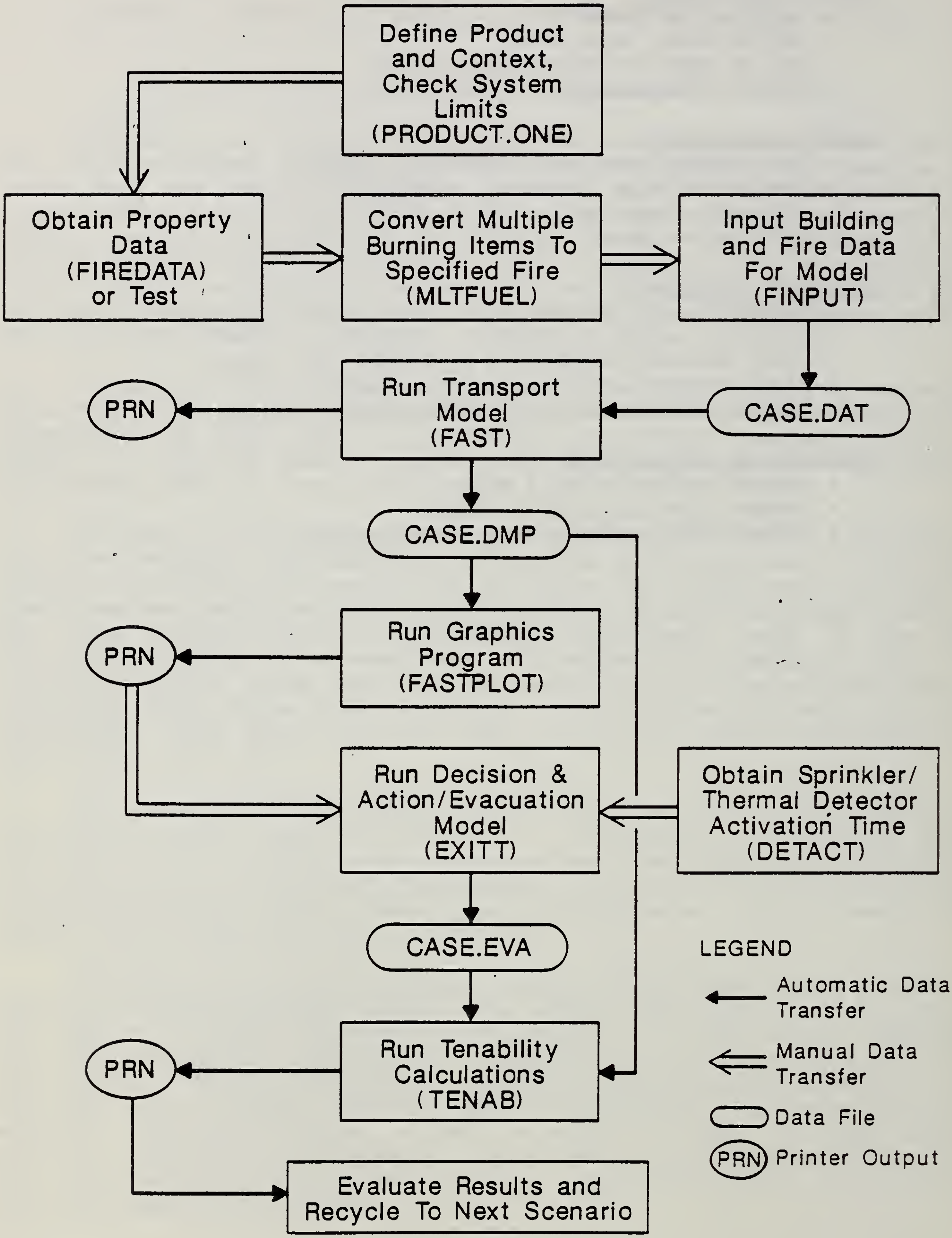
1. <u>DEFINE THE CONTEXT</u>
   - DESCRIBE THE PRODUCT.
   - DEFINE WHERE, WHEN, HOW,
     AND BY WHOM THE PRODUCT MAY BE USED.
   - EXECUTE PRODUCT.ONE.

2. <u>DEFINE THE SCENARIO</u>
   - BUILDING DESCRIPTION, CONDITIONS, STATUS.
   - FIRE DESCRIPTION (FIREDATA, MLTFUEL).
   - OCCUPANT DESCRIPTION.
   - INPUT DATA (FINPUT).

3. <u>CALCULATE THE HAZARD</u>
   - PREDICT CONDITIONS OVER TIME IN EACH ROOM (FAST).
   - PLOT/LIST VALUES OF INTEREST (FASTPLOT).
   - INPUT OCCUPANT DESCRIPTION AND SMOKE DATA (EXITT).
   - SPECIFY DETECTOR(S)/SPRINKLERS (DETACT).
   - SELECT CRITERIA AND OBTAIN CONSEQUENCES (TENAB).

4. <u>EVALUATE THE CONSEQUENCES</u>
   - COMPARE AGAINST EXAMPLE CASES.
   - COMPARE WITH AND WITHOUT PRODUCT.
   - COMPARE WITH MODIFIED PRODUCT PROPERTIES.

FIG. 4-2 HAZARD I SOFTWARE



4.2 Defining the Context

Defining the context requires that a description of the product and the details of its use within the occupancy of interest be developed. This initial step should include running the program PRODUCT.ONE (written in BASIC). This is an interactive program which asks a series of multiple choice questions regarding the product in question and its context of use. The responses to these questions will result in references to various sections of the report where further information (e.g., descriptions of any example case involving that product, statistical data, building floorplans) can be found. Certain responses may result in a message that the problem is outside the scope of the HAZARD I system. (In addition, the program will ask the user if all of the scenarios of concern have been analyzed and, if not, will re-cycle.)

4.3 Defining the Scenario

The next step is developing the detailed scenario to be analyzed. An outline of the items which need to be specified is given in figure 4-3. Detailed discussion of the inputs required is contained in Chapter 6. The entire scenario should be developed before data input is begun. If there is more than one scenario of concern, they can all be developed initially, or taken one at a time. Studies of the sensitivity of the results to variations in one or more parameters of the scenario specification are recommended, but these should be decided upon after seeing the results of the first analysis for the baseline scenario.

4.3.1 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 FINPUT and change the non-building inputs. In any case, a complete set of floor plan drawings for the building used in the analysis should be made. These drawings will be used extensively throughout the process to locate doors and windows, contents, people, dimensions and distances, etc. For multi-story buildings, a sectioned elevation drawing should also be prepared to locate the elevation of building elements above some reference 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.

FIGURE 4-3

SCENARIO DESCRIPTION
FOR A
HAZARD ANALYSIS

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.

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 data base section of this report. 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.

4.3.2 Fire Description

The fire description begins with the ignition source (known in NFIRS as the "form of heat of combustion") and first item ignited. Once these have been decided upon, the arrangement and 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 decide on the desired (pre-flashover) fire spread based on the NFIRS data or other considerations and adjust the arrangement of the other items in the room to obtain this condition.

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 fire model, this 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 models are all 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.

The fire is specified in terms of heat of combustion, mass loss 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. The heat of combustion is a single value for the entire fire but the mass loss and species yields can vary over user-defined time intervals. The data base section (6.2) of this report contains furniture calorimeter data on the burning of specific full-scale items by CFR. If an item in this section is acceptable for the scenario being studied (i.e., similar to the item of interest), the data required is provided in a form directly ready for inclusion.

If none of the items are acceptable or the item needed is not provided, the data base section 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 6.4 of this report titled "Determining The Rate Of Heat Release".

If the required data are not provided, it may be necessary to have the item or material tested. This would particularly be the case if one is analyzing the performance of a specific item. Large scale oxygen consumption calorimeters are available at many fire research and testing laboratories. Cone calorimeters are being produced commercially and will soon be operating in many testing laboratories in a number of countries, initially as an ASTM draft procedure and eventually as a standard test method.

Spread to the next item occurs when there is contact by the flame from the first item or by radiant ignition. (Note: Data on radiant ignition of materials is often given for piloted and non-piloted conditions. The piloted case would yield the more conservative result.) This latter case is discussed in section 6.5. 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.

At this time, the user must make adjustments in the input data to allow for changes in the burning which result from the restricted ventilation. There are three possible ways to proceed:

1. Continuing with the specified free-burning fire will likely result in an over-estimate of the pyrolysis rate (and resulting fire room temperatures) and an under-estimate of the CO yield. Since this approach accounts for all of the energy which potentially can be released, it represents the most conservative of the three.

2. Holding the mass loss rate constant at the value which just causes the ventilation limit to be reached should reduce the over estimates of pyrolysis rate and temperature in the fire room. But this may result in underestimates of the temperatures in other rooms, because it does not account for the potential energy released by fuel due to excess pyrolyzate caused by high heat transfer conditions.

3. Limiting the fuel that burns to that which can burn with the oxygen flowing into the room is a third choice. The mass flow rate of oxygen is 23% of the mass flow rate of air into the room through the vent (obtained with FASTPLOT in the variable VENT). The maximum energy release is 13,100 kW times the mass flow rate of oxygen (in kg/sec). Dividing this by the heat of combustion for the specified fuel gives the associated maximum mass loss rate. This method also does not account for energy release from fuel which burns beyond the fire room.

Regardless of which method is used, subsequent results must be interpreted accordingly; and it should be noted that no general theory exists to deal precisely with the ventilation limited or post-flashover condition. However, all of this may not be necessary for every case. If the occupants all escape or the lethality criterion is exceeded in all rooms before the fire spreads from the first item, the rest of the fire need not be calculated since the hazard to the occupants will not be affected. This may often be the case for smaller residences.

As was stated earlier, the model requires a single heat of combustion and one series of mass loss 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 (see section 6.6). The program asks for the number of fuel items and the number of intervals and then the data for each fuel and interval are entered in order. Where yields of more than one species are to be used, the effective yield of the first species is calculated in the initial sequence of questions and additional species are calculated one at a time without the need to re-enter the mass loss data.

4.3.3 Occupant Description

The data required for the occupant description are used in the evacuation/behavior model and not in the fire model. Thus a detailed discussion of the data inputs will be made later in this section. The general detail as shown in figure 4-3 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, which will influence the results of the fire model.

4.4 Calculate the Hazard

4.4.1 Input Program

Once the detailed problem has been defined, the interactive input program (FINPUT) is run. This program creates the input file necessary to run the transport model, FAST. It can be used to read in an existing file, which can then be modified in sections to create a new file, or it can create a file from "scratch". 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.

The program 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. These are accessed by typing HELP (or simply ?) or HELP <keyword>. This <keyword> is a specific item for which help is desired (e.g., HELP THERMAL CONDUCTIVITY will bring up a brief description of thermal conductivity). Additional details on the input program operation are provided in section 6.7.

4.4.2 FAST Model and its Output

The transport model (FAST Version 17.5) is run as a "batch" program rather than interactively as are the other programs in HAZARD I. The program will prompt for the name of an input file which is usually the name of the input program created in the previous step. 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 (as shown in table 3-2) at time intervals selected by the user in the input program. These tabulated data can be directed to the screen, to a printer (this is preferred in order to provide a permanent record), or to a file for later printing. A more detailed (frequent) output is sent to a plot file (called a dump file), also at intervals specified by the user in the input program. It should be noted that this is a very large file; 20.5k 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 which can be used with commercial plotting software for fancier graphs. The possible graphs which the user should find the most useful include upper and lower layer temperature (C), interface position (the boundary between the layers), smoke optical density (1/m), concentration (ppm) and dose (the time integral of concentration in ppm-min) of any species computed, and Ct (the concentration time product as described in Chapter 6, in g-min/m^3), for each room.

4.4.3 Decision/Behavior Evacuation Model

After obtaining the results of the FAST calculation, the evacuation model EXITT is run. This is a BASIC program which must be run with BASICA on a PC. On other machines, it should run under GW BASIC, although the graphics output is specific to the PC.

The detailed inputs are discussed in section 6.11. They are entered interactively in response to questions. The physical dimensions are taken from the drawings and the occupant descriptions from the data decided upon in the first step. In addition, the model asks for data from FAST on the interface position and smoke density in the upper layer of each room at each timestep. This is currently entered manually, but in the next version will be automatically read from the FAST dump file. For convenience, it is helpful if the dump interval specified for FAST (in the input program) is the same as the timestep interval to be used in the evacuation program. Then, the data required will be available without the need to interpolate.

The evacuation model will calculate the activation time of any smoke detectors specified from the smoke data (smoke density and layer thickness) entered. For heat detector or sprinkler head activation times the model DETACT-QS is provided. The instructions for running it are provided in section 6.10. 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-QS 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 judgement of the user.

4.4.4 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.

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 this report 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 such interactions.

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

Toxicity is considered in two ways (in TENAB): (1) using the concentration-time product parameter (Ct), and (2) by the FED method which considers the exposure to hydrogen cyanide and carbon monoxide, accounting for the impact of the simultaneous exposure to carbon dioxide. (Note: For a thorough discussion of Ct and FED, and response to other fire products, see section 6.12 on tenability limits.) 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)" nor an "unusual toxicological response (UTR)". These terms are defined in the glossary of this report. 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 represents the first version of a toxicity evaluation technique referred to as the "N-Gas Model" (see section 6.12). The equations used by TENAB to make this evaluation are discussed in the section on Tenability Limits. When the computed value for FED reaches 1, lethality is assumed to occur; at a value of 0.5, incapacitation is assumed.

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

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.

4.5 Evaluate the Consequences

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 effect the validity of the result can be minimized by evaluating the <u>relative</u> difference of two calculations. Thus, the system should only be 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, the user should recognize that many of the inputs specified are assumptions 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.

CHAPTER 5. MATRIX OF EXAMPLE CASES

5.1 Purpose

The example cases provided within HAZARD I 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 can be used as representative of that occupancy for other types of analyses and purposes such as education, firefighter training, evaluating the potential impact of code changes, etc.

5.2 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 US, this responsibility is shared by the Fire Services and Building Code Officials through the fire and building codes, respectively.

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

Tables 5-1 and 5-2 list the panel participants and the organizations represented for the first set of meetings. Their first exercise was limited to the development of cases for residential (one- and two-family) occupancies.

Table 5-3 gives the detail to which the panels were asked to describe the cases. The Building Configuration Panel supplied the items under building description and the Fire Services Panel covered the items under both fire description and occupant description. The furnishings selected for the three houses are tabulated in Tables 5-4 to 5-6, and the floorplans are shown in Figures 5-1 to 5-4. The results of the calculations, in terms of the predicted impact on the occupants are summarized in Tables 5-7 to 5-14. And the complete documentation of the calculations is included in Volume 2 of this report.

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

QUESTIONS TO BE RESOLVED

THE PURPOSE OF THE GENERIC FIRES AND BUILDING DESCRIPTIONS IS TO PROVIDE A BASELINE AGAINST WHICH TO COMPARE THE CHANGE IN HAZARD TO THE BUILDING OCCUPANTS RESULTING FROM THE USE OF NEW OR MODIFIED PRODUCTS. SINCE NEITHER THE MANUFACTURERS OF SUCH PRODUCTS NOR THE CODE AUTHORITIES ASKED TO RULE ON THE PRODUCT ACCEPTABILITY KNOW THE SPECIFIC CHARACTERISTICS OF THE BUILDING INTO WHICH THE PRODUCT WILL BE PLACED, THESE GENERIC SCENARIOS ARE NEEDED TO PERFORM AN ANALYSIS OF THE POTENTIAL BENEFITS OF NEW TECHNOLOGY.

WITH THIS IN MIND, THERE ARE SOME QUESTIONS WHICH NEED TO BE RESOLVED:

1. SHOULD THE BUILDING DESCRIBED REPRESENT THE TYPICAL HOME OR THE TYPICAL HOME WHICH WILL EXPERIENCE A (REPORTED) FIRE?

2. SHOULD EITHER OF THE ABOVE BE TYPICAL AT ALL, OR RATHER BE "MARGINALLY" CODE COMPLIANT?

3. SHOULD THE FIRES REPRESENT THE MOST COMMON FIRES (REPORTED OR UNREPORTED), OR MOST COMMON FATAL FIRES? SHOULD THEY BE MATCHED TO THE MATERIAL OR PRODUCT?

4. SHOULD THE FIRES COME ONLY FROM FREQUENCY OF OCCURRENCE OR SHOULD THEY ATTEMPT TO INCLUDE LOW FREQUENCY, HIGH RISK CASES?

5. SHOULD THE OCCUPANTS REPRESENT THE TYPICAL FAMILY, TYPICAL FAMILY WHO WILL HAVE A (REPORTED) FIRE, OR INCLUDE PERSONS KNOWN TO BE AT HIGHER RISK, SUCH AS THE VERY YOUNG AND OLD?

ALL OF THESE QUESTIONS ARE REALLY THE SAME. NO ONE EXPECTS TO ELIMINATE FIRE LOSSES. THE OBJECT IS TO IMPROVE SAFETY OR AT LEAST MAINTAIN THE STATUS QUO AT REDUCED COST. THUS, WHEN ATTEMPTING TO MEASURE THE LEVEL OF SAFETY PROVIDED, IS IT BETTER TO DO SO FOR A TYPICAL CASE OR A MINIMUM ACCEPTABLE CASE?

While initially unsure of a response, in their work the groups settled on <u>typical</u> 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.

5.3 Other Occupancies to be Added

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

1. Other Residential (Apartment, Hotel/Motel)

2. Health Care

3. Assembly and Educational

4. Business and Mercantile

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

5.4 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.

5.5 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.

5.6 Impact on Occupants

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

Of the eight fire scenarios, five experienced ventilation controlled burning conditions (fires #1, 2, 6, 7 and 8). As a result, the free burn data from the data base for the sofa in scenarios 1, 6, and 7 was used without modification, only up to the point of ventilation-controlled burning. In cases 2 and 8, some of the required data were not directly available in the data base, so estimated values were used. For fire #2, data for the kitchen cabinets were estimated from data from the wardrobe cabinet, and in fire #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 cases 1, 2, and 8, the data were adjusted, beginning at the point of ventilation control, by holding the mass loss rate constant at that which will just burn with the oxygen available. Such adjustments were not made in scenarios 6 and 7 to illustrate the excessive predicted temperatures which result.

Two scenarios (fires #3 and 4) were ventilation controlled because the door to the fire room was closed. Here, the input data was adjusted to account for the severely limited oxygen availability by stopping the fire when the oxygen in the room fell to zero. There was an insufficient oxygen inflow through the undercut of the door to continue burning. (See discussion of these procedures in section 4.3.2.)

One scenario (fire #5) contained insufficient fuel to reach ventilation control for the specified room and door opening. Here, the data for the christmas tree and beanbag chair could be used directly as presented in the data base.

Tables 5-7 through 5-14 summarize the predicted impact on the occupants in the eight fire scenarios. With the exception of scenario #1, all occupants safely exited the buildings. This can be attributed to the fact that all scenarios were specified with working smoke detectors which provided timely warning before conditions reached dangerous levels. This, coupled with the fact that all of the occupants were physically capable of escaping (except for the intoxicated person in scenario #1), led to the results obtained. The result obtained for the single fatality would change as a function of the assumed degree of intoxication.

TABLE 5-1
BUILDING CONFIGURATION PANEL

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

Mr. J. Vicars*
American Institute of Architects
1735 New York Av. N.W.
Washington, DC 20004

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

Mr. C. McGarity JR (AIA/NFPA)*
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Spartanburg, S.C. 129304

Mr. Jim Dowling
National Association of Home Builders
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Mr. Paul K. Heilstedt
BOCA
17926 Heilstedt Road
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Mr. Richard Vognelt
SBCCl
900 Montclair Road
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Mr. Frank Drake
International Conference of Building Officials
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Whittier, California 90601

* indicates attendees at first meeting

TABLE 5-2
FIRE SERVICE PANEL

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

Mr. Bob McCarthy*
USFA/FEMA

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

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

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

Chief Bill Roberts*
Austin Fire Department
1621 Festive Beach
Austin, Texas 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, D.C.

Roger Lanahan*
USFA/FEMA

* indicates attendees at first meeting

TABLE 5-3
SCENARIO DESCRIPTION
FOR A
HAZARD ANALYSIS

<u>BUILDING DESCRIPTION</u>

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

<u>FIRE DESCRIPTION</u>

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

<u>OCCUPANT DESCRIPTION</u>

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

*CURRENT VERSION REQUIRES THAT PRE-FLASHOVER FIRE SPREAD BE SPECIFIED BY THE USER. <u>NFIRS</u> DATA ON EXTENT OF FIRE SPREAD BY MATERIAL AND PRODUCT WILL BE PROVIDED FOR GUIDANCE. TIME TO FLASHOVER IS SCENARIO DEPENDANT 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.

TABLE 5-4
CONSENSUS ON RANCH HOUSE FURNISHING

RANCH HOUSE:

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
Small Bedroom:	bunk beds - wood (maple) - 2 cotton mattresses chair & desk dresser - wood
2nd Bedroom:	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, throwrugs throughout (consensus)

TABLE 5-5
CONSENSUS ON TOWNHOUSE FURNISHINGS

Living Room:	sofa chairs - 2 coffee table - wood stereo - large and 21" TV end table - wood buffet - wood large bookcase with books - wood large bean bag chair
Family Area:	dinette table - chrome and vinyl chairs - 4 - chrome and vinyl high chair - chrome and vinyl side board - wood
Kitchen:	laminated pressed board cabinets formica counter tops
Master Bedroom:	queen waterbed dresser chest of drawers chairs 13" TV
Bedroom #2:	single bed chest of drawers toy box - wood
Bedroom #3:	crib - wood changing table chest of drawers - wood
Smoke detectors -	not connected - photo electric 85 decibels downstairs - middle of hall between door to toilet and door to laundry upstairs - between top of stairs and door to bathroom
Closet under stairs:	hot water heater household cleaning materials - broom plastic bucket, paper, rags, etc.

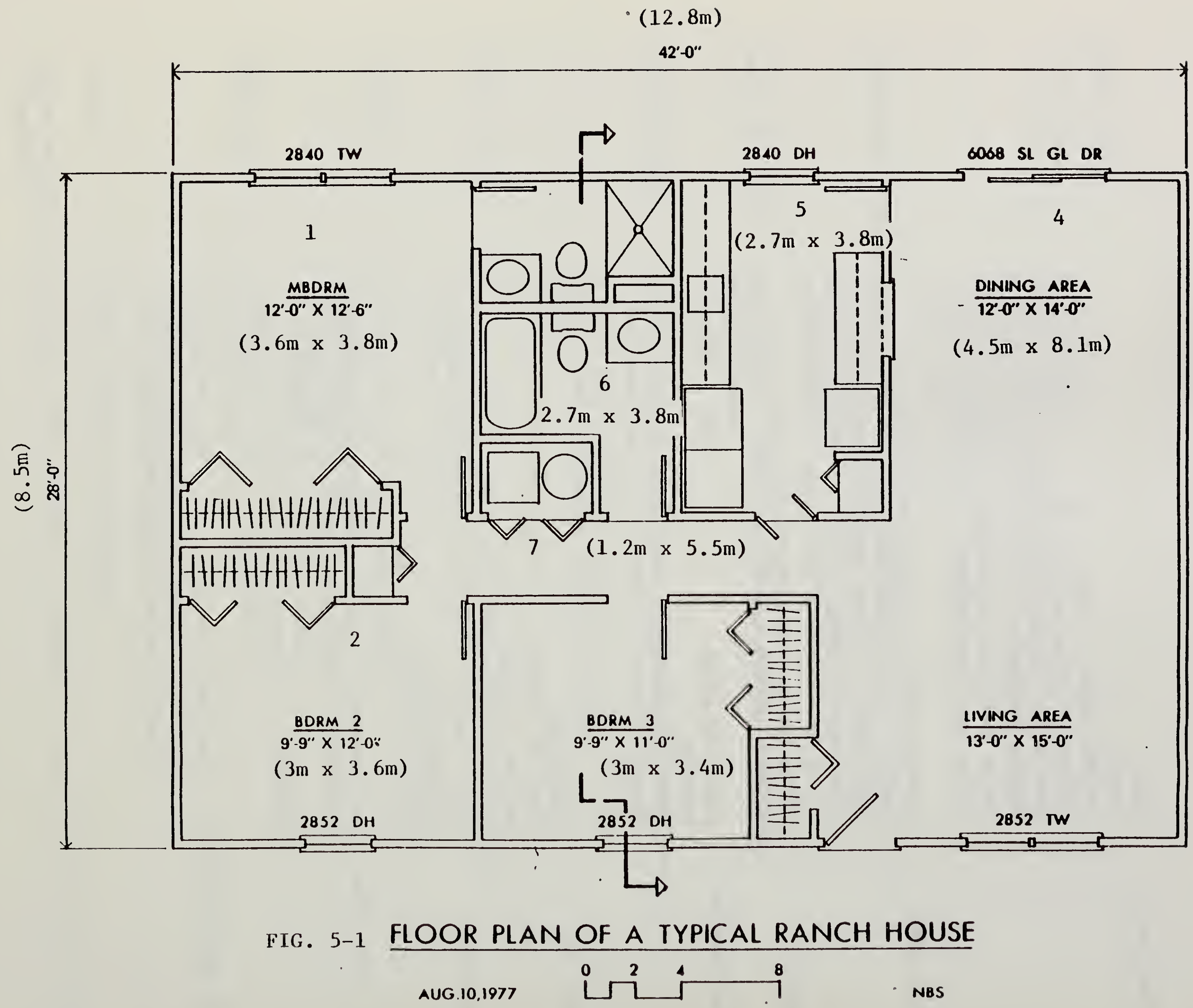
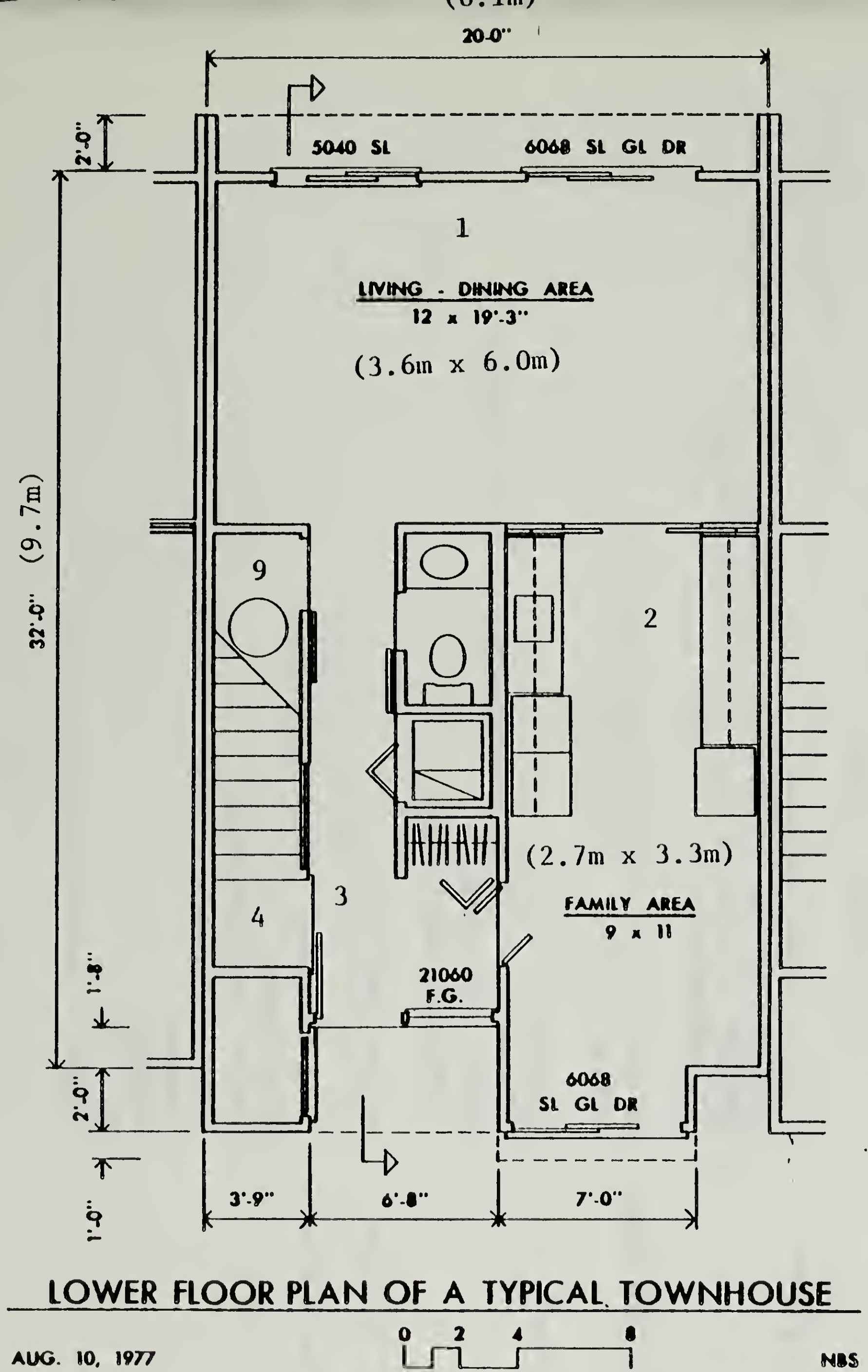
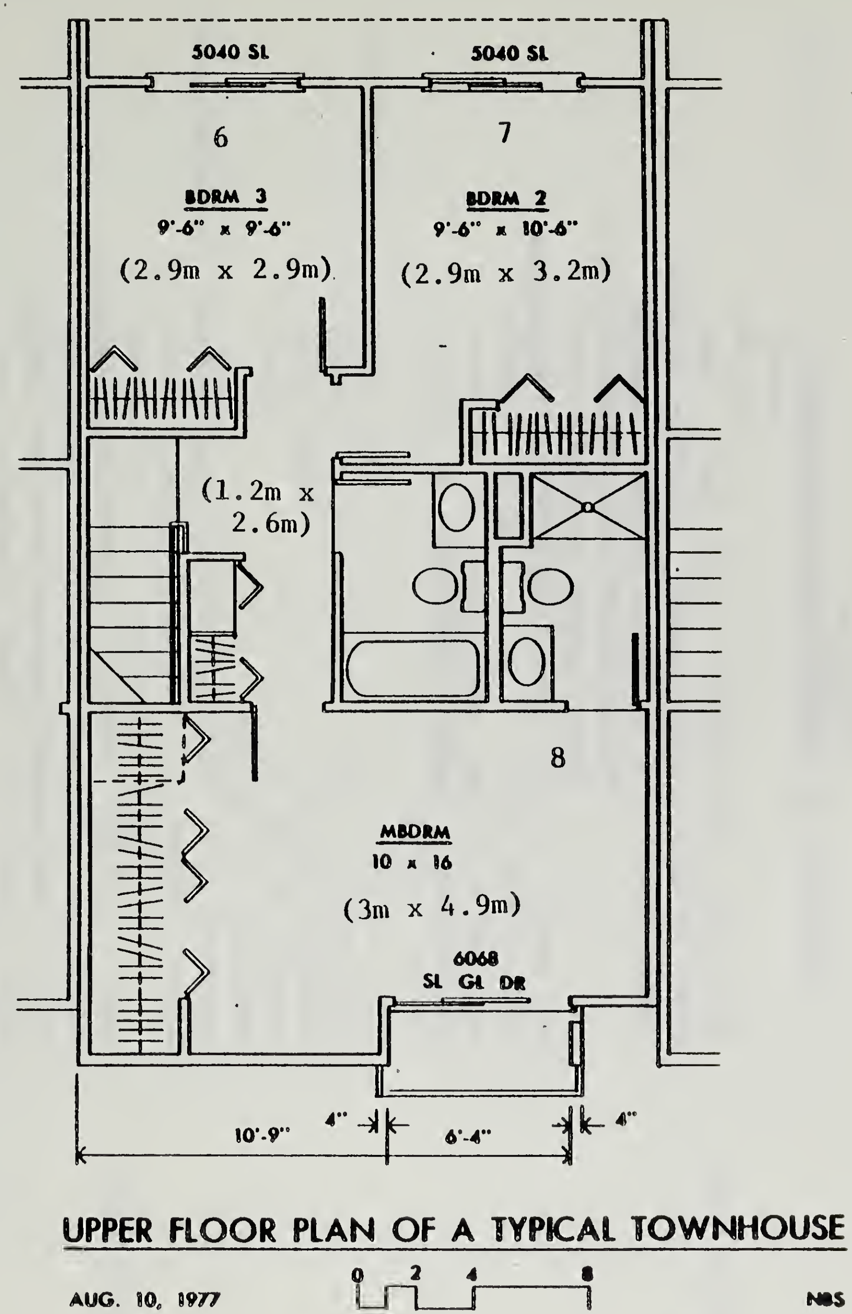


FIG. 5-1 FLOOR PLAN OF A TYPICAL RANCH HOUSE



LOWER FLOOR PLAN OF A TYPICAL TOWNHOUSE

AUG. 10, 1977 NBS



UPPER FLOOR PLAN OF A TYPICAL TOWNHOUSE

AUG. 10, 1977 NBS

FIG. 5-2

TABLE 5-6
CONSENSUS ON 2-STORY HOUSE FURNISHING

Family Room:	wood panel over drywall - 1/8" luan
	couch 90 inch - velour cover, urethane interior
	coffee table - 24 lbs wood, 29 lbs books and magazines on lower shelf, 2 five 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"
	closet - contains 267 lbs clothes

Bedroom #2:	trundle bed with bedspread dresser bureau desk end table stereo receiver - 12 lbs speakers - 12 lbs total bookcase books - 108 lbs chair - 10 lbs records - 30 lbs clothes in closet - 136 lbs
Bedroom #3:	double bed wicker basket cedar chest dresser
Bedroom #4:	office desk - wood chair - 40 lbs - executive type typewriter table typewriter bookcases - 3 five shelf units, 258 lbs stereo receiver - small TV - 13" portable

Did not furnish basement

Smoke Detectors - not connected - ionization - 85 decibels
opposite front door, left of door to passageway
middle of hall, near door to bedroom #4

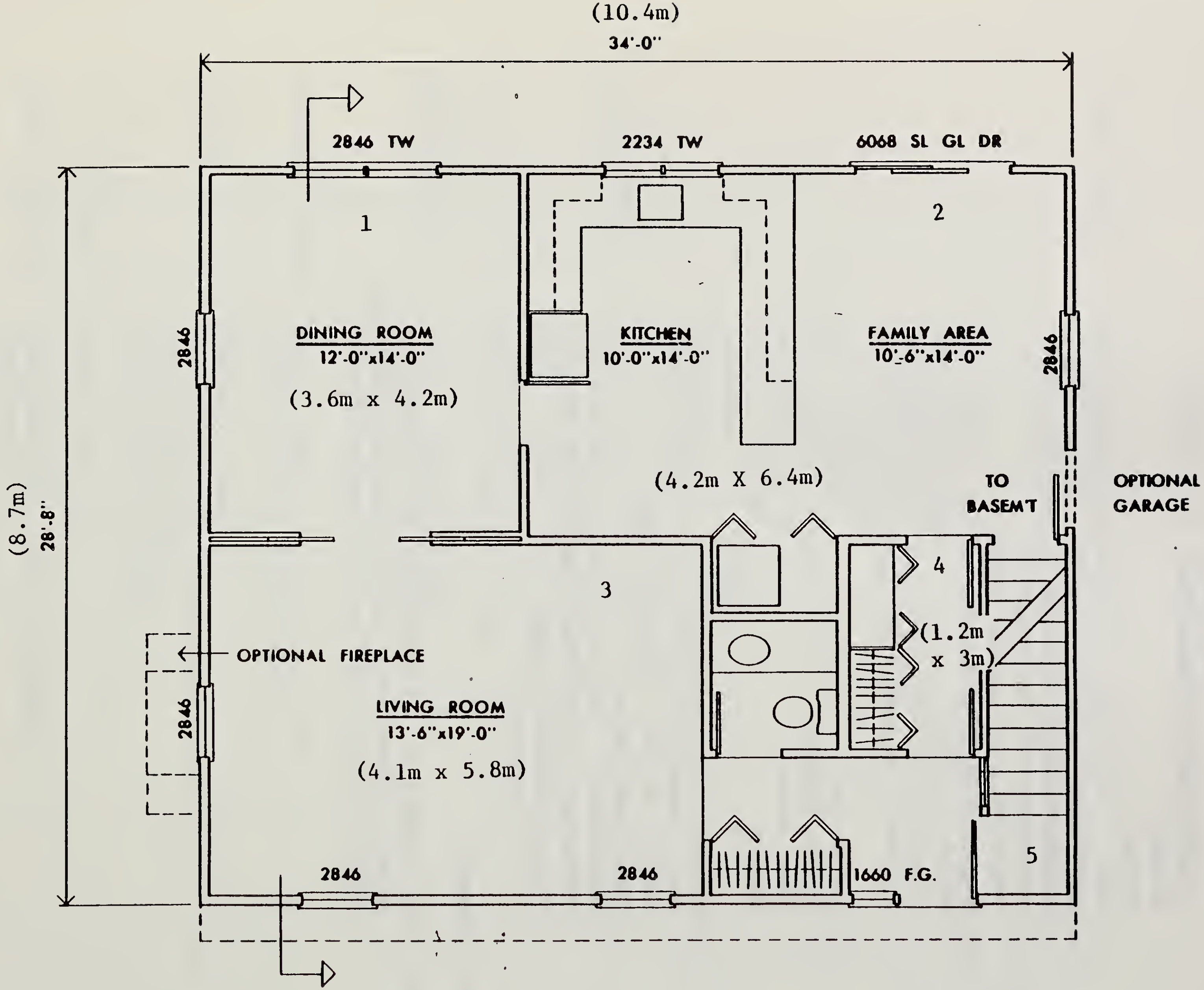


FIG. 5-3 LOWER FLOOR PLAN OF A TYPICAL 2-STORY HOUSE

AUG. 10,1977

NBS

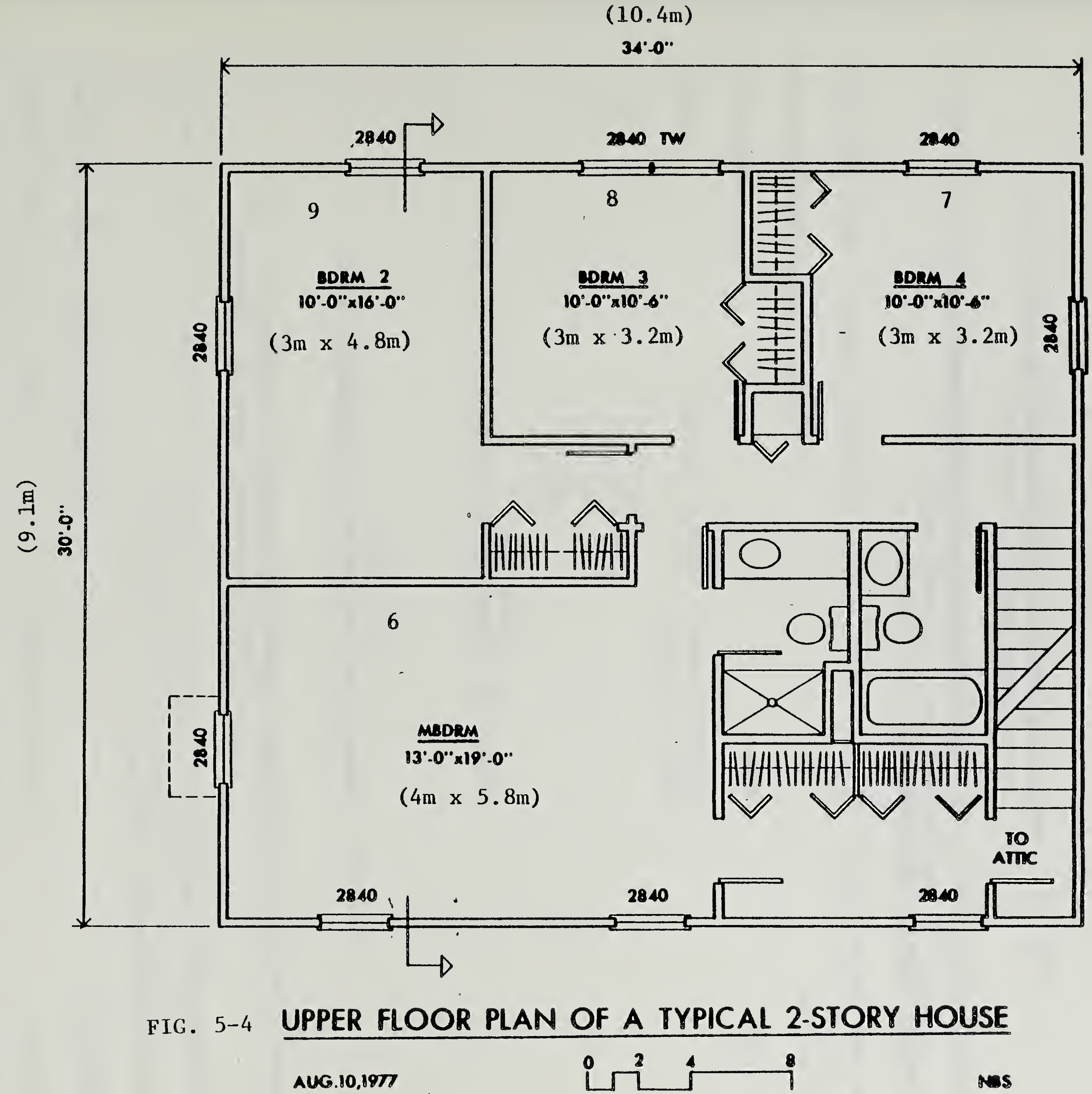


FIG. 5-4 UPPER FLOOR PLAN OF A TYPICAL 2-STORY HOUSE

TABLE 5-7
IMPACT ON OCCUPANTS FOR FIRE #1

Fire #1 - Smoldering Sofa in Living Room of the Ranch house

Assumed properties of product: Material code UPS001 (sofa)

Flashover time: 50 minutes

Maximum temperature: 720°C

Evacuation

Occupant	Time
1	Incapacitated - 45 min Dead - 48 min

TABLE 5-8
IMPACT ON OCCUPANTS FOR FIRE #2

Fire #2 - Grease Fire in Kitchen of the Ranch house

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

Flashover time: 12 min

Maximum temperature: 800°C

Evacuation

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

TABLE 5-9
IMPACT ON OCCUPANTS FOR FIRE #3

Fire #3 - Mattress and Bed Linen
in bedroom 2 of the Ranch house

Assumed properties of product: Material code BED002
Mass loss rate was reduced due to limited availability of oxygen within a closed room.

Flashover time: did not flashover

Maximum temperature: 260°C

Evacuation

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

TABLE 5-10
IMPACT ON OCCUPANTS FOR FIRE #4

Fire #4 - Trash and Cleaning Materials
in a closet in the Townhouse

Assumed properties of product: Material code TRB001 (bag of paper trash)
Mass loss rate was reduced due to limited availability of oxygen in a closed room.

Flashover time: did not flashover

Maximum temperature: 260°C

Evacuation

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

TABLE 5-11
IMPACT ON OCCUPANTS FOR FIRE #5

Fire #5 - Christmas Tree and Bean Bag chair in the Living room of the Townhouse

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

Flashover time: did not flashover

Maximum temperature: 270°C

Evacuation

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

TABLE 5-12
IMPACT ON OCCUPANTS FOR FIRE #6

Fire #6 - Couch and Paneling in the family room of the Two-story

Assumed properties of product: Material code UPS001 (sofa)

Flashover time: 4 min

Maximum temperature: 2000°C (This is recognized as an unachievable temperature due to vitiation which is not currently included in the model)

Evacuation

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

TABLE 5-13
IMPACT ON OCCUPANTS FOR FIRE #7

Fire #7 - repeat of Fire #6 with
different room doors closed

Assumed properties of product: Material code UPS001 (sofa)

Flashover time: 4 min

Maximum temperature: 2000°C (see comment on fire #6)

Evacuation

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

TABLE 5-14
IMPACT ON OCCUPANTS FOR FIRE #8

Fire #8 - Trash, Drapes and Desk in the
upstairs office/bedroom of the Two-story

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

Flashover time: 12 min

Maximum temperature: 700°C

Evacuation

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

CHAPTER 6. DESCRIPTION OF SYSTEM COMPONENTS

6.1 System Logic

To assist the user through the overall analytical process, and to make efficient use of the programs, documentation, and procedures, particularly the identification of scenarios of concern, an overall logic diagram, shown in detail in figure 6-1 has been developed. The process has also been translated into a short, interactive BASIC computer program named PRODUCT.ONE.

The program asks a series of multiple choice questions, and depending on the answers, guides the user to the specific parts of this report containing information on fire statistics, the reference examples, or the step by step procedure used for the computation process. (In future versions of this program some of this information will be contained in the program.) After returning from the step by step procedure the program asks further questions to check if additional scenarios need to be run.

The first two questions in the program "What is your product?" and "Where is the product to be used?" are to determine (a) if the product of concern is one that is used in one of the example cases, and (b) if it is a product for which fire statistics are available. The next questions check if the user wants to see fire statistics on residences in general or on the product, and if so directs the user to this information in the next section (6.2) of this report.

If the product is used in one or more of the examples, the user is asked if he would like to see the schematic layout of the prototypical house(s). If so, the user is directed to the appropriate page and to section 6.4 for a description of the procedure to be used in the determination of the fire properties of the test product. The user is then asked to check if all listed fire properties are equal to or better than those of the reference product. If so, the product is likely to be less hazardous than the reference product. If not, the user is directed to section 4.2 of this report for the step by step procedure for the hazard computation process. After the computation the user is given the option of modifying the scenario by changing the key parameter values and rerunning the case for both the reference product and the test product. If another example case includes the product the user is then given the option of repeating the process for the other case(s) until all important cases have been run.

If the product is not used in any of the example cases, or the user wishes to define a specific fire scenario, it is necessary to stipulate the specific conditions for each fire. Included in the specification are the layout of the building, the condition and location of the occupants, the output of the fire generated by the product of concern and other products expected to be involved. The following questions are displayed to assist the user to better define the scenario(s) for analysis:

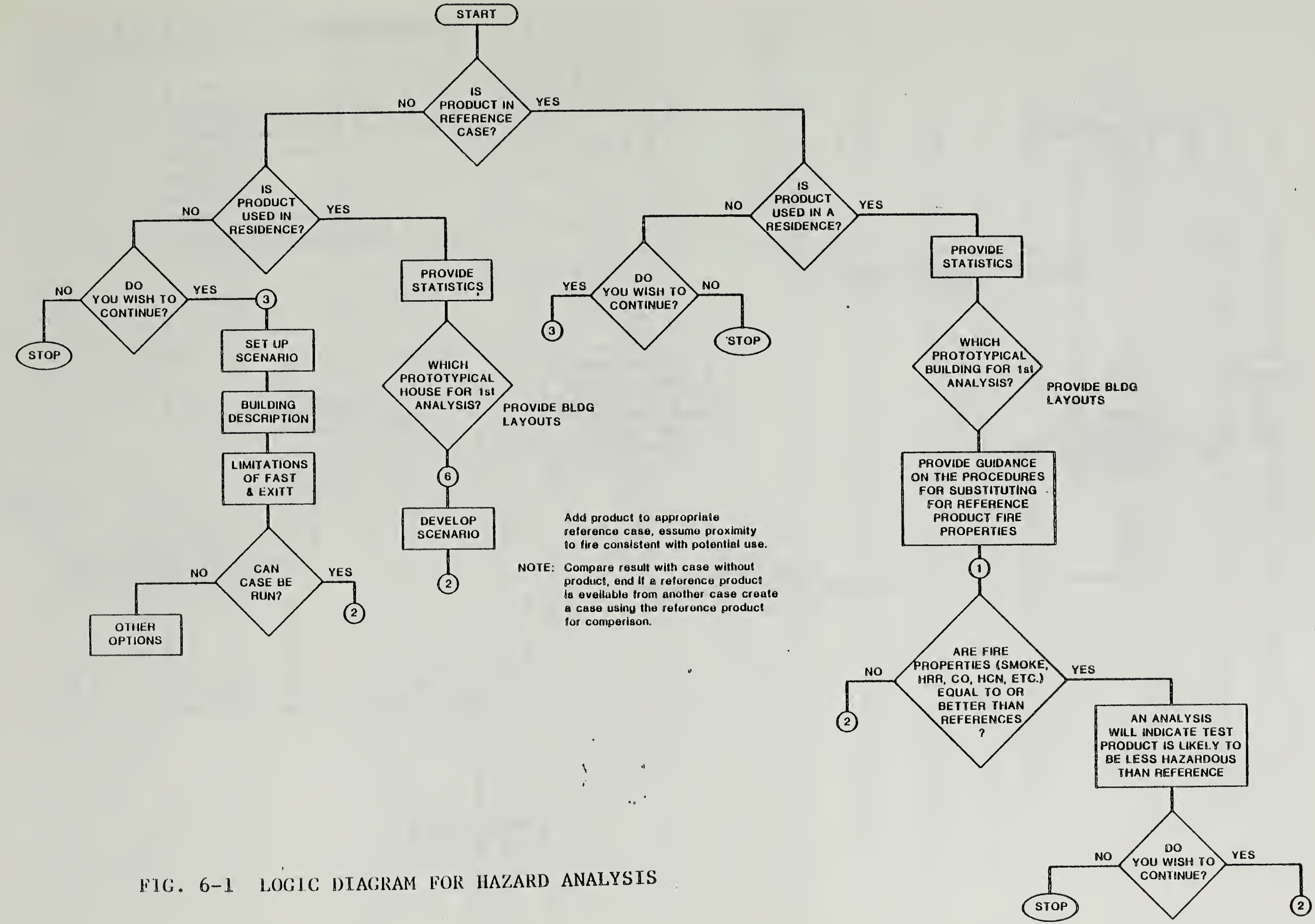


FIG. 6-1 LOGIC DIAGRAM FOR HAZARD ANALYSIS

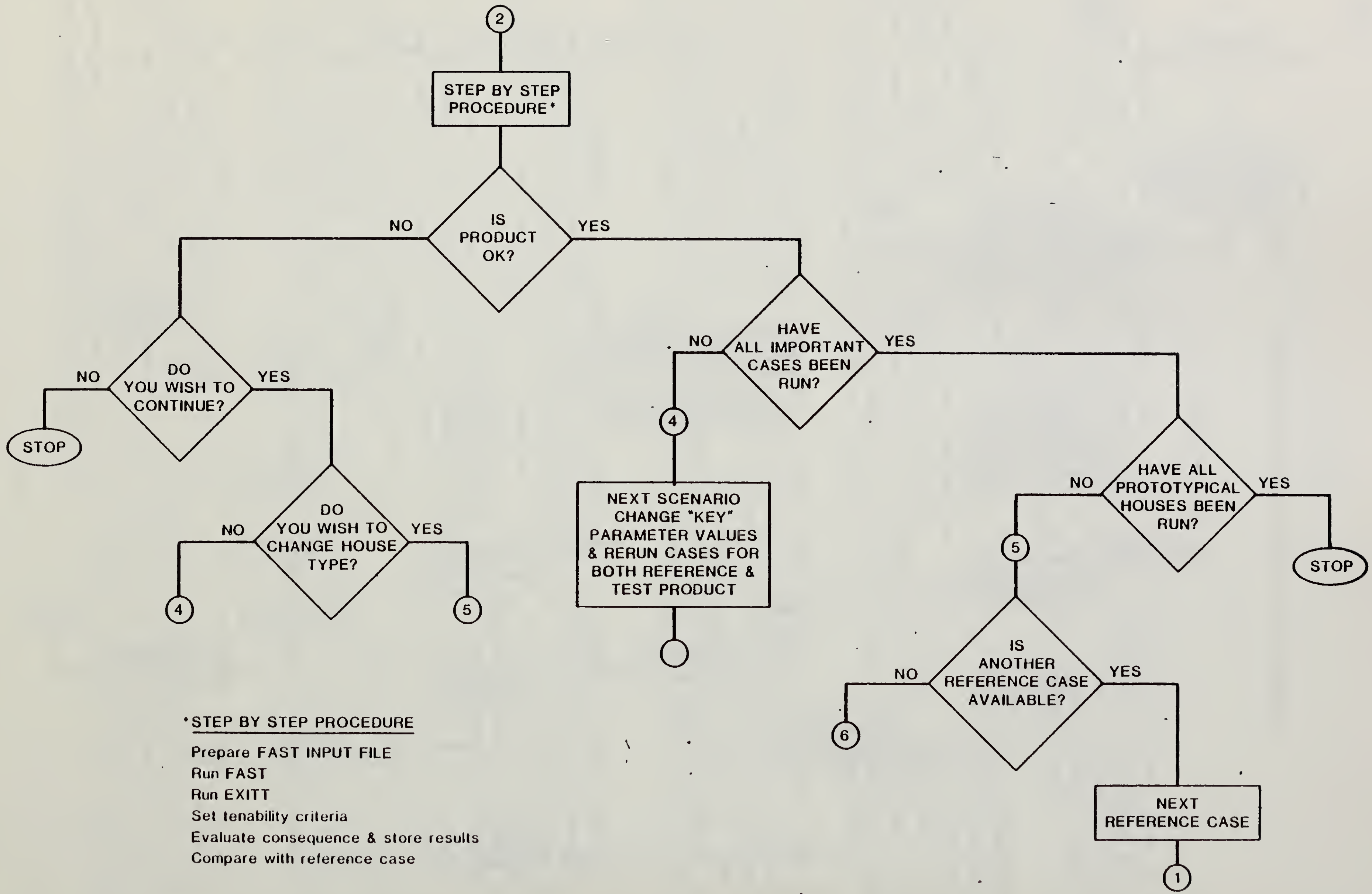


FIG. 6-1 (CONTINUED)

- Where is the product located within the facility?
- How can the product contribute to a fire (ignition source, fuel source)?
- What are the characteristics of ignition and burning (smoldering, low or high energy flaming)?
- Is this the first item ignited?
- What other items could be involved once the fire spreads?
- What other items may spread the fire to the product of concern?
- Where are the occupants, and what is their mental and physical condition?
- What are the important building features that will influence the fire spread?

The program then directs the user to the step by step procedure for the computation process.

6.2 Scenario Selection/Data

The fire hazard modeling system described in the step by step procedure is deterministic. This means that results obtained are uniquely related to the specific set of conditions provided as input to the analysis. Figure 4-1 provides the information needed to initiate a hazard analysis. This information can be based in part upon a fire scenario. Each scenario provides a description of the chain of events leading from the time, place and environment of the ignition through to the consequences (loss of life, injury or property damage) [1]. The scenario description also includes the influence of the ignition source, the characteristics of the product or products, the agents contributing to (or inhibiting) fire growth, the actions of human occupants and automatic protective devices. Selecting the relevant or important conditions which prevail most frequently in fires, particularly fatal fires, can be aided by analysis of the fire loss statistics. Often analysis of the statistics may indicate that there are a few predominant scenarios which occur more frequently than all the others.

6.2.1 United States Fire Statistics

To provide a perspective on the overall fire problem and the residential fire problem in particular, selected information follows, taken from several significant studies which have made use of fire statistics collected over the past several years. If more in-depth information or a fuller understanding is required the user is encouraged to refer to the original works. There are two main sources of fire statistics, the National Fire Protection Association (NFPA) and the United States Fire Administration (USFA). NFPA's fire loss statistics have been developed using a stratified weighting by community size through fire departments responding to an annual survey conducted by the

National Fire Protection Association. These statistics provide a measure of the size of the problem but lack the detail needed to relate cause. Table 6-1 shows the distribution of fires, civilian deaths and injuries by occupancy for 1984 [2]. As Table 6-1 indicates, residential fires in 1984 only represented about 25 percent of the total fires contributed to over 80 percent of the civilian deaths. One- and two-family dwelling fires alone accounted for over 60 percent of the total. This proportion has remained fairly constant over the past several years [3].

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

Table 6-2 relates the causes for fires and losses in one- and two-family dwellings. Obviously, some fires result in worse consequences than others. Smoking, while only involved in 4.6 percent of the fires, causes 18.9 percent of the deaths; whereas heating which has contributed to over one-third of the total fires has a proportionately lower death rate, but still is attributed with a very significant 15 percent of the deaths in one- and two-family dwellings.

Clearly the fire risk is not equally divided among all persons. An analysis of the NFIRS data from 1978-1982, shown in table 6-3, indicates the very young (5 and under) and the elderly (75 and over) have death rates of about three and four times, respectively, greater than the rate experienced by young and middle aged adults. Children under the age of 10 and adults 65 and over account for 47 percent of all fire deaths in residences but represent only 26 percent of the nation's population [3]. From the standpoint of the fire victim, table 6-3 presents by age group the cause of fire, the location at ignition and the condition before injury [4]. Figures 6-2 and 6-3 differentiate the location at ignition and the physical conditions expected for victims of different age groups. Such information is of direct use in locating the occupants relative to the fire and establishing their capabilities for escape and rescue.

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

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

TABLE 6-1

Estimates of Reported Fires, Civilian Fire Deaths and Injuries by Occupancy, 1984

Occupancy	Fires		Civilian Deaths		Civilian Injuries	
	Estimate	Percent of All Fires	Estimate	Percent of All Civilian Deaths	Estimate	Percent of All Civilian Injuries
Residential (total):	623,000	26.6	4,240	80.9	19,275	68.5
One- and two-family dwellings	506,000	21.6	3,290	62.7	15,100	53.7
Apartments	99,500	4.2	785	15.0	3,650	13.0
Hotels and motels	9,000	0.4	120	2.3	300	1.0
Other residential	8,500	0.4	45	0.9	225	0.8
Non-residential structures	225,000	9.6	285	5.5	3,750	13.3
Highway vehicles	437,000	18.7	530	10.1	3,250	11.6
Other vehicles	17,500	0.1	100	1.9	350	1.3
All others*	1,040,500	44.4	85	1.6	1,500	5.3
TOTAL	2,343,000		5,240		28,125	

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

Source: NFPA Survey of Fire Departments [2].

TABLE 6-2

Cause Analysis
One- and Two-Family Dwellings
(mobile homes not included)

	Fatalities	Injuries	Property Damage	Fires
Smoking	18.9%	12.8%	4.7%	4.6%
Heating	15.0	16.0	18.1	34.4
Incendiary/Suspicious	10.2	7.0	16.1	8.5
Electrical Distribution	6.2	6.0	10.5	7.2
Children Playing	5.2	8.2	3.4	3.9
Cooking	5.2	20.1	6.4	13.6
Other Equipment	4.1	6.2	5.9	5.7
Open Flame	3.3	5.2	3.7	4.7
Appliances, Air Conditioning	2.4	5.6	5.0	5.8
Other Heat	1.4	1.6	1.3	1.0
Exposure	0.3	0.8	2.5	2.2
Natural	0.0	0.7	2.1	1.5
Unknown	27.8	9.8	20.4	7.1

Source: 1983 NFIRS.

TABLE 6-3

Cause and Fatality Rate by Age in Residences
(1978-82 average)

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

Source: 1978-1982 NFIRS, U.S. Bureau of Census [4].

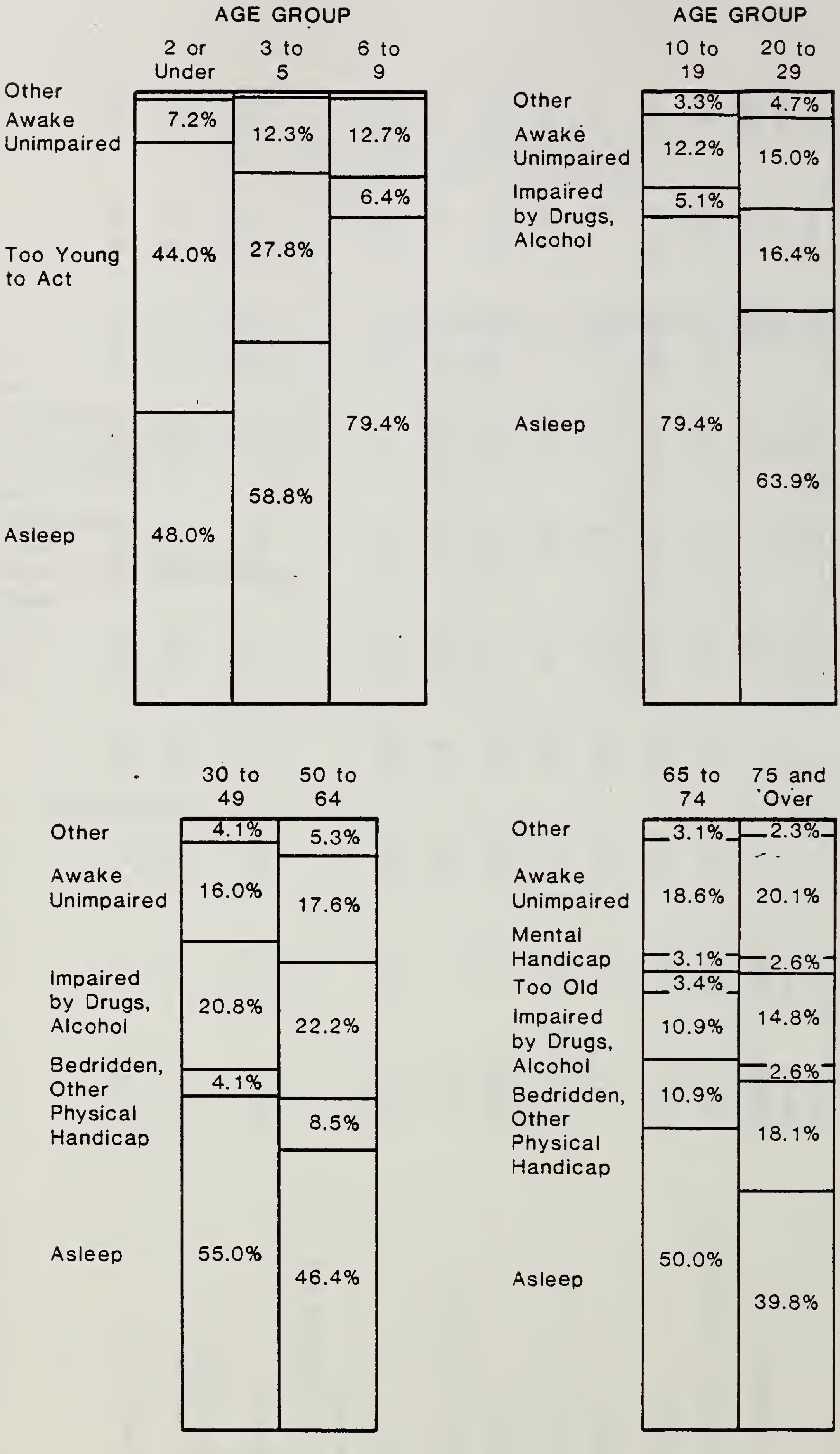


FIG. 6-2 CIVILIAN FIRE DEATHS IN RESIDENCES BY CONDITION BEFORE INJURY AND AGE OF VICTIM, 1978-82, SOURCE: NFIRS [4]

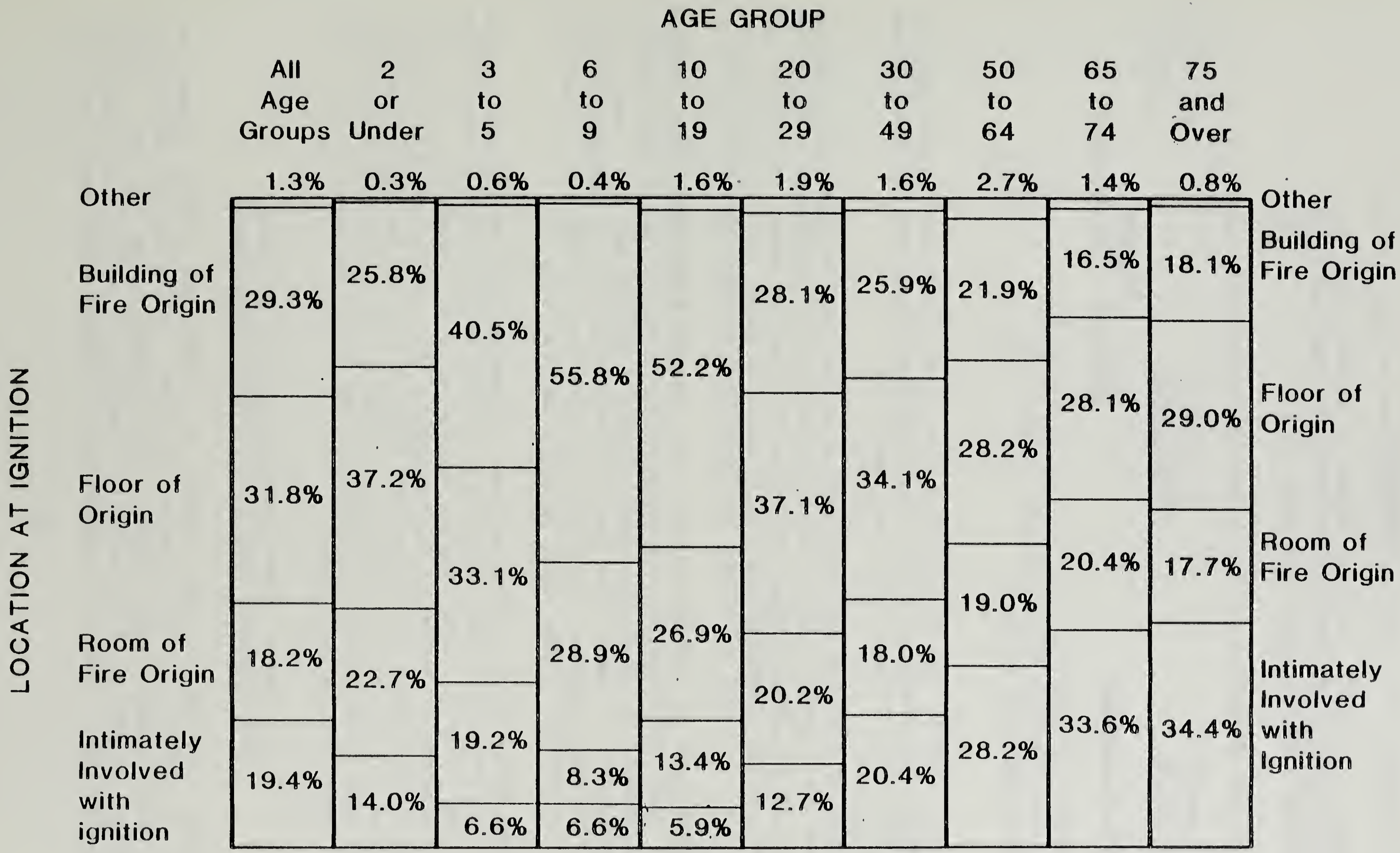


FIG. 6-3 CIVILIAN FIRE DEATHS IN RESIDENCES BY LOCATION AND AGE OF VICTIM 1978-82, SOURCE: NFIRS [4]

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

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

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

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

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

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

The distribution of fatalities for one- and two-family dwellings (table 6-4) indicates that the majority of fatal fires involve one or two deaths. While the occurrence of multiple death fires (defined as 3 or more) in residences represents a small fraction of the total; 87.3 percent of the multiple death fires reported in 1985 occurred in residential properties resulting in 79.7 percent of the total multiple deaths [7].

One of the major fire safety devices introduced into residences in the past ten years has been the smoke detector. It has been estimated, based upon a 1985 Louis Harris poll, that three-fourths of U.S. households now have detectors. Unfortunately, evidence also suggests that the households that do not have detectors are those which have the highest risk of having a fire [8]. As Table 6-5 shows, of the fires reported to NFIRS in 1981, 1982 and 1983 where detector status was known, over 75 percent of the fires occurred in one- and two-family dwellings without detectors.

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

Information relating to 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

TABLE 6-4

Distribution of Deaths in Fatal Fires:
One- and Two-Family Dwellings, 1981

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

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

Source: 1981 NFIRS Data Base.

TABLE 6-5

Fires and Loss per Fire by Detector Status for
One- and Two-Family Dwellings (mobile homes not included)
Based upon Average of 1981, 1982 and 1983 National Estimates

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

Source: 1981, 1982, and 1983 NFIRS.

dominant scenarios. Tables 6-6 through 6-9 provide an analysis of the 1982 NFIRS data [9]. Flame and smoke spread relate directly to the physics of fire development in buildings which are directly usable in the fire models.

6.2.3 Scenario Development

A study in 1976 by Clarke and Ottoson looked at fire death scenarios defined by occupancy, ignition agent and ignition source [10]. Their analysis indicated that about two-thirds of the fatalities could be accounted for by fourteen general scenarios. Residential furnishings alone accounted for 36 percent of the total deaths for all occupancies.

A study, based upon the 1982 NFIRS data, used this same approach to examine the leading ignition scenarios in residential structure fires [3]. Because of the potential influence of climatic and construction differences an analysis was performed for the north east, north central, southern and western regions of the United States (see table 6-10 to 6-13). Smoking materials dominated all four regions as the leading ignition source for civilian fire deaths (23.2 to 40.5 percent) for a small portion of the fires (3.6 to 5.1 percent). In the colder regions (north east and north central) the use of auxiliary heating devices (fireplaces and woodstoves) caused chimney fires to be the most common cause of fire. In the south and west, cooking fires using gas or electric stoves constituted the most common scenario.

6.2.4 Product-Specific Scenario Data

The same source of data (NFIRS) which provided the causal factors for residential fires and fatalities can also be queried from the viewpoint of a particular product. This is, however, significantly limited to the cases where the product is either the first material ignited or the product is equipment involved in ignition. Therefore, for fires where a product's main contribution is as an additional fuel source, the best source of data for hazard analysis is the list of general residential scenarios shown in tables 6-10 to 6-13.

Tables 6-14 through 6-17 contain analyses of fires involving contents and furnishings which were performed by the NFPA Fire Analysis Division for use by one of the NFPA Committees [11]. The 1980, 1981 and 1982 NFIRS data were used in the process of selecting the major contributors (upholstered furniture; mattresses and pillows; bedding, blankets, sheets and comforters; and curtains, blinds, draperies and tapestries). The information contained in tables 6-14 to 6-17 can be used as a resource in generating the product specific scenarios needed to perform relevant hazard analysis in one- and two-family dwellings. Three data elements are presented for each category of contents and furnishings. These elements were form of heat of ignition, equipment involved in ignition, and area of fire origin.

TABLE 6-6

Extent of Flame and Smoke Damage at Extinguishment

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

Source: 1982 NFIRS [9].

TABLE 6-7

Extent of Flame versus Detector Status

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

Source: 1982 NFIRS [9].

TABLE 6-8

Extent of Flame Versus Victim Condition and Activity
Death (Percentage)

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

Source: 1982 NFIRS [9].

TABLE 6-9

Extent of Flame Versus Time of Day

Extent of Flame	Day (7 a.m. - 5 p.m.)		Evening (5 p.m. - 1 a.m.)		Night (1 a.m. - 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 [9].

TABLE 6-10

Leading Accidental Ignition Scenarios in
Residential Structure Fires in the Northeast, 1982

Form of Heat of Ignition	Form of Material Ignited	Area of Origin	% of Incidents	% of Civilian Deaths
Solid Fueled Equipment	Residue, Soot	Chimney	16.8	.9
Properly Operating Electrical Equipment	Cooking Material	Kitchen	3.6	0
Gas Fueled Equipment	Cooking Material	Kitchen	3.0	0
Solid Fueled Equipment	Special Form	Chimney	2.9	0
Smoking Material	Bedding	Bedroom	2.2	6.3
Solid Fueled Equipment	Structural Component, Finish	Wall Assembly	1.9	0
Solid Fueled Equipment	Other	Chimney	1.9	0
Solid Fueled Equipment	Trash, Waste	Chimney	1.8	0
Solid Fueled Equipment	Structural Component, Finish	Chimney	1.6	0
Smoking Material	Upholstered Furniture	Living Room	1.4	16.9

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

TABLE 6-11

Leading Accidental Ignition Scenarios in Residential Structure Fires in the Northcentral, 1982

Form of Heat of Ignition	Form of Material Ignited	Area of Origin	% of Incidents	% of Civilian Deaths
Solid Fueled Equipment	Trash, Waste	Chimney	10.7	0
Properly Operating Electrical Equipment	Cooking Material	Kitchen	6.3	1.1
Gas Fueled Equipment	Cooking Material	Kitchen	4.5	1.1
Solid Fueled Equipment	Other	Chimney	3.8	0
Smoking Material	Bedding	Bedroom	3.1	10.3
Smoking Material	Upholstered Furniture	Living Room	2.2	20.9
Solid Fueled Equipment	Structural Component, Finish	Living Room	1.6	1.5
Electrical Equipment Arcing, Overloaded	Cable Insulation	Kitchen	1.5	.4
Solid Fueled Equipment	Structural Component, Finish	Chimney	1.3	1.5

Source: NFIRS data from 8 states (Iowa, Illinois, Kansas, Michigan, Minnesota, Ohio, South Dakota, and Wisconsin) with 47,677 accidental residential structure fires and 283 civilian deaths in accidental residential fires with form of heat of ignition, form of material ignited, and area of origin reported [3].

TABLE 6-12

Leading Accidental Ignition Scenarios in Residential Structure Fires in the South, 1982

Form of Heat of Ignition	Form of Material Ignited	Area of Origin	% of Incidents	% of Civilian Deaths
Properly Operating Electrical Equipment	Cooking Material	Kitchen	10.2	0
Gas Fueled Equipment	Cooking Material	Kitchen	4.1	0
Solid Fueled Equipment	Trash, Waste	Chimney	3.5	0
Smoking Materials	Bedding	Bedroom	3.2	11.5
Solid Fueled Equipment	Other	Chimney	2.1	0
Electrical Equipment, Arcing, Overloaded	Cable Insulation	Kitchen	2.0	.6
Smoking Materials	Upholstered Furniture	Living Room	1.9	15.9
Match/Lighter	Bedding	Bedroom	1.7	1.3
Electrical Equipment, Arcing, Overloaded	Cable Insulation	Bedroom	1.2	1.3
Solid Fueled Equipment	Structural Component, Finish	Living Room	1.1	.6

Source: NFIRS data from 8 states (Arkansas, Florida, Louisiana, Maryland, Tennessee, Texas, Virginia, and West Virginia) and Washington, DC with 22,561 accidental residential structural fires, and 162 civilian deaths in accidental residential fires with form of heat of ignition, form of material ignited, and area of origin reported [3].

TABLE 6-13

Leading Accidental Ignition Scenarios in Residential Structure Fires in the West, 1982

Form of Heat of Ignition	Form of Material Ignited	Area of Origin	% of Incidents	% of Civilian Deaths
Properly Operating Electrical Equipment	Cooking Material	Kitchen	8.6	1.2
Solid Fueled Equipment	Trash, Waste	Chimney	6.2	0
Solid Fueled Equipment	Fuel	Chimney	4.9	0
Gas Fueled Equipment	Cooking Material	Kitchen	4.1	.9
Smoking Materials	Bedding	Bedroom	2.8	14.2
Smoking Materials	Upholstered Furniture	Living Room	2.2	26.3
Electrical Equipment, Arcing, Overloaded	Cable Insulation	Kitchen	1.7	0
Match/Lighter	Bedding	Bedroom	1.1	2.6
Solid Fueled Equipment	Structural Component, Finish	Living Room	1.0	3.0

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

TABLE 6-14

Upholstered Furniture Fires in One- and Two-Family Dwellings
with Unknowns Distributed

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

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

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

TABLE 6-15

Mattress and Pillow Fires in One- and Two-Family Dwellings with Unknowns Distributed

Mattresses and Pillows

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

May not add to 100% due to rounding errors.

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

TABLE 6-16

Bedding Fires in One- and Two-Family Dwellings with Unknowns Distributed

Bedding

Form of Heat	Incidents		Deaths		Injuries		Loss	
Open Flame	33%		21%		33%		32%	
Matches and Lighters		(27)		(16)		(28)		(25)
Candle		(2)		(1)		(3)		(3)
Smoking Materials	26		61		31		25	
Cigarettes		(24)		(54)		(29)		(23)
Electrical Equipment Arcing	19		3		16		20	
Hot Object	18		12		14		19	
Properly operating electrical equipment		(9)		(8)		(9)		(10)
Electric lamp		(4)		(1)		(2)		(3)
Fuel-Fired Objects	3		1		3		2	
Other Known	2		0		3		2	
Equipment Involved								
None	57%		84%		65%		60%	
Appliances	21		2		15		20	
Electric Blanket		(16)		(2)		(12)		(18)
Electrical Distribution Equipment	11		2		7		10	
Heating Systems	9		9		11		9	
Fixed local heating unit		(4)		(2)		(4)		(4)
Portable local heating unit		(4)		(8)		(6)		(4)
Other Known	2		2		2		1	
Area of Origin								
Bedroom	85%		88%		90%		86%	
Living Room	4		10		6		5	
Storage Areas	3		0		1		3	
Other Known	8		2		3		6	

May not add to 100% due to rounding errors.

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

TABLE 6-17

Curtain and Drapery Fires in One- and Two-Family Dwellings with Unknowns Distributed

Curtains and Drapes

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

May not add to 100% due to rounding errors.

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

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6.3 FIREDATA and the Data Base

6.3.1 Introduction

The material properties data base for the Hazard Assessment Method (HAZARD I) was created using DbaseIII Plus. (DbaseIII Plus will hereafter be referred to simply as Dbase.) To facilitate the use of the data base, a set of procedures was written to enter, edit, and retrieve data for use as input to HAZARD I. The procedures were written to give the casual Dbase user access to the information contained within the data bases as well as update them without understanding the data bases, their structure, or their relationship to each other.

It will be assumed that the user has successfully installed DbaseIII Plus on his PC (following the instructions which come with Dbase). It will also be assumed that the FIREDATA program and data base files are resident in the HAZARDI directory and Dbase is in a different directory (the HAZARD I installation program will ask for the name of this directory.) This is the way that the install program will place the files automatically.

6.3.2 Data Base Structure

The material properties data base is composed of five interlocked (not indexed) data bases. This was done to reduce the search time for specific pieces of information. The five data bases are:

- Material Directory (MATDIR.DBF);
- Material Property (PHYSICAL.DBF);
- Cone Calorimeter (DECOMCC.DBF);
- Furniture Calorimeter (DECOMFC.DBF);
- Toxicity (TOXICITY.DBF).

The data bases have two fields in common; the material code (Mcode) and the material identification or description (Mid). The data bases, however, are not indexed. For special applications, this will allow one or several of the data bases to be accessed by a user written retrieval program outside of the Dbase environment.

The material directory (MATDIR.DBF) contains information about the presence of data in the other four data bases for a given material code or material description. For example, if toxicity data is necessary, the procedures will first check the material directory data base to ascertain if the material of interest has been entered into the data bases and, in particular, if data exists in the toxicity data base. When data are entered into the data bases, a record for each material code is added to the material directory indicating the material code, material description and four TRUE/FALSE fields showing where data has been placed in the other four data bases.

The material property data base (PHYSICAL.DBF) contains information on the thermo-physical properties of a material. It is composed of a single input form, figure 6-4, that provides conductivity, specific heat, and emissivity values for a given material as a function of temperature. Up to six temperatures can be entered or retrieved. These values relate to a specific form and density of material. For other densities or forms, additional records must be entered. This data base contains records relating to combustible and noncombustible materials which serve as interior finish (walls, floor, ceiling) or as furnishings. For example, the thermo-physical properties of firebrick as well as carpeting will be found in the data base.

Three data bases exist that contain fire response or fire property data. Small-scale heat release and species yield data (grams of the species produced by each gram of fuel lost) are contained in the cone calorimeter data base (DECOMCC.DBF), while medium- and large-scale heat release and species yield data are contained in the furniture calorimeter data base (DECOMFC.DBF). Toxic potency data can be found in the toxicity data base (TOXICITY.DBF).

The cone calorimeter data base (DECOMCC.DBF) consists of a two screen forms, figures 6-5a and 6-5b. The first screen contains basic information about the test sample and exposure conditions (i.e. initial and final sample weight, orientation, ignition mode, incident energy, time to ignition). A summary of the test results, where available, can also be found on this screen. This is presented in the form of average and maximum values and the time for the maximum value (from either ignition or start of exposure for non-flaming exposures). The second screen contains time dependent data for heat release rate, mass loss rate, CO yield and CO_2 yield. Two additional time dependent fields are provided for user defined yields of other combustion products (e. g. soot, HCN, etc.).

The furniture calorimeter data base (DECOMFC.DBF) is similar to the cone calorimeter data base. It is also divided into two screens, figures 6-6a and 6-6b. The first presents test sample and exposure information as well as average and maximum values. The second screen represents time dependent information for the same properties as described for the second screen of the cone calorimeter data base. Data from furniture items tested in large scale compartments are also included in this data base.

The toxicity data base (TOXICITY.DBF) is composed of two screens of LC_{50} data. The first screen, figure 6-7a, provides data from the cup furnace toxicity screening protocol (NBS), while the second, figure 6-7b, provides data on material tests performed according to the University of Pittsburgh Protocol. For the NBS Toxicity Protocol, auto-ignition temperatures are listed. Provisions for several different LC_{50} endpoint times are made. This is intended to accommodate the input of pure gas data as well as possible future alterations in the protocol. The University of Pittsburgh screen also allows for variations in data reported by small alterations in the protocol. Here provisions are made for different heating rates of the sample and different endpoint times for the determination of LC_{50} values (in grams).

Thermophysical Data

Material Code:
Material ID:

Form: Volume Density: . kg/m3
Areal Density: . kg/m2

Temperature (C)	Conductivity (kW/(m·K))	Specific Heat (kJ/(kg·K))	Emissivity
.	.	.	.
.	.	.	.
.	.	.	.
.	.	.	.
.	.	.	.
.	.	.	.

FIG. 6-4 INPUT FORM FOR MATERIALS PROPERTIES DATA BASE

Decomposition Data from Cone Calorimeter

Material Code:

Material ID:

Form:

Density: . kg/m3 Thickness: . m

Orientation(V/H): Ignition Mode(P/N): Incident Energy: . kW/m2

Initial Mass: . g Final Mass: . g

Ignition Time: . s

	Units	Average
Heat of Combustion	kJ/kg	.
CO Yield	kg/kg	.
CO2 Yield	kg/kg	.
HC Yield	kg/kg	.
HCl Yield	kg/kg	.
HCN Yield	kg/kg	.
H2O Yield	kg/kg	.
SOOT Yield	kg/kg	.
Extinction Area	m2/kg	.

Time Dependent Data

Time (s)	Heat Release (kW/m2)	Mass Loss (kg/s)	CO Yield (kg/kg)	CO2 Yield (kg/kg)	Yield (kg/kg)	Yield (kg/kg)
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.

FIG. 6-5 INPUT FORM FOR CONE CALORIMETER DATA BASE

Decomposition Data from Furniture Calorimeter

Material Code:
Material ID:
Config
Ignition Source:

Initial Mass: . kg Final Mass: . kg
Ignition Time: . s

	Units	Average
Heat of Combustion	kJ/kg	.
CO Yield	kg/kg	.
CO2 Yield	kg/kg	.
HC Yield	kg/kg	.
HCl Yield	kg/kg	.
HCN Yield	kg/kg	.
H2O Yield	kg/kg	.
SOOT Yield	kg/kg	.
Extinction Area	m2/kg	.

Time Dependent Data

Time (s)	Heat Release (kW)	Mass Loss (kg/s)	CO Yield (kg/kg)	CO2 Yield (kg/kg)	Yield (kg/kg)	Yield (kg/kg)
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.

FIG. 6-6 INPUT FORM FOR FURNITURE CALORIMETER DATA BASE

Toxicity Data

National Bureau of Standards Protocol

Material Code:
Material ID:

Form:

Auto-Ignition Temperature: C

	Material Concentration	
Time (m)	Flaming (mg/l)	Non-Flaming (mg/l)
	.	.
	.	.
	.	.
	.	.
	.	.
	.	.

University of Pittsburg Protocol

	Material Loading	
Heating Rate (C/min)	10min-post (g)	14days-post (g)
.	.	.
.	.	.
.	.	.

FIG. 6-7 INPUT FORM FOR TOXICITY DATA BASE

6.3.3 Program Structure

FIREDATA is a program that operates in the Dbase environment. It is actually the main program of a series of programs that give the user the capabilities to add, edit, and retrieve data from a collection of data bases with only a casual familiarity with Dbase. Since Dbase is an interpretive data base system, all of the programs can be viewed and altered by the user using a text editor or the MODIFY command within Dbase. This allows a knowledgeable user to tailor the existing programs to a specific application. There are two levels to FIREDATA. The first level is FIREDATA.PRG. At this level the user is able to move to the second command level by selecting a specific operation (i.e., appending, editing, searching). The first command level is composed of the program FIREDATA.PRG and two menu programs- FPMENU.PRG AND SELECT.PRG.

The second command level is composed of a group of programs that are dedicated to perform a specific operation on a specific data base. There are four programs for adding data, one for each data base, and four programs for editing data, one for each data base. Associated with each data base, there is a format file that contains the input form that is used to enter data into each data base. These format files are shared by the ADD and EDIT options. They have files names of TOXFORM.FMT, CONFORM.FMT, FURNFORM.FMT, and PHYFORM.FMT.

Data can be recalled in one of two ways. One approach is to search for a specific data record. The other approach is to list blocks of data records. The FIND and LIST options implement these two approaches. Both options share the same print programs. These appear as TOXFMT.PRG, CONEFMT.PRG, PHYFMT.PRG, or FURNFMT.PRG.

Figure 6-8 is an overview of the FIREDATA program structure showing the relationship between the various parts. As can be seen, it is not possible to move between second level commands without first returning to the first level commands. This is done to ensure that data bases are properly closed before moving on to the next operation.

6.3.4 User Information

Dbase is started by typing <u>DBASE</u> at the DOS prompt. Dbase begins either in the ASSIST mode or at the "DOT" command mode. If the program begins in the ASSIST mode, depress the "Esc" key. This will place the program in the "DOT" command mode. In this mode, user written programs can be executed. Assuming the programs and data bases have been copied to a subdirectory called "\DBASEIII" on the "C:" drive (i.e., hard disk), the fire properties data base program is initiated by typing <u>DO FIREDATA</u>.

If the programs and data bases are not stored in a subdirectory called "\DBASEIII", one line of FIREDATA.PRG must be altered. Using the MODIFY COMMAND processor within DbaseIII Plus, the user should change the "SET PATH TO C:\DBASEIII" to reflect the correct location for the data bases and the programs.

A main menu screen is presented to the user that requests a character be entered from the list of six possible choices.

```
A)dd     E)dit    D)elete
    F)ind     L)ist
         Q)uit
```

Any other entry will be ignored. If the user depresses the Q key, the program will close all files, reset screen parameters, and return to the "DOT" command mode.

6.3.4.1 Adding Data

If the user selects A, a secondary menu is placed on the screen. This menu requires that the user select the data base to which the data will be appended. There are six selections at this point as well.

```
M)aterial property    C)one calorimeter
T)oxicity             F)urniture calorimeter
A)ll                  E)xit
```

If the user selects E, the program returns to the previous menu. If the user selects A, the program will sequentially request information for each data base beginning with material property (i.e., thermo-physical properties), cone calorimeter, furniture calorimeter, and, finally, toxicity. Any other selection, moves the user directly to entering data for that particular data base.

The selection of a particular data base for data addition results in one of four forms being presented to the user. These forms are: figure 6-4 for material property data; figures 6-5a and 6-5b for cone calorimeter data; figures 6-6a and 6-6b for furniture calorimeter data; and figures 6-7a and 6-7b for toxicity data. Each form is to be completed by the user in as complete a fashion as possible. Errors on a given field can be corrected by backspacing and typing over the incorrect information. If one has left the field, the cursor control keys (i.e., arrow keys) can be used to return to a previous field and type over the error. On a multi-screen form, either screen can be reviewed by using the "Page Down" key to move forward or the "Page Up" key to move backward. At the completion of each form, the user is required to depress the "End" key while holding down the "Ctrl" key. This ensures that the data are properly appended to the data base. The program prompts the user to determine if another record will be appended to the same data base.

"Do you want to exit this operation?(Y/N)"

If the user responds "Y", then the program returns to the previous menu. If the user responds "N", then the program presents the user with a blank form.

This enables the user to append information to a given data base on several materials without returning to the selection menu.

For the A)ll option, the forms that are presented to the user are those shown in: figure 6-4 for material property data; figures 6-5a and 6-5b for cone calorimeter data; figures 6-6a and 6-6b for furniture calorimeter data; and figures 6-7a and 6-7b for toxicity data. As each screen of a multi-screen form is completed, the program automatically presents the user with the second screen. Prior to completing the second screen the user may use the cursor control keys (i.e., arrow keys) to move about each screen and move from screen to screen with the "Page Up" and "Page Down" keys. The "Enter" key may be used to leave every field except the last field on the entire form. (That is, for multi-screen forms the last entry on the last screen.) It is preferable to use the cursor keys to leave each field. In order to actually append the data to the end of a data base, the user must depress the "End" key while holding down the "Ctrl" key. Once data has been appended to a data base, changes in a field must be accomplished by using the Edit option in the main menu.

6.3.4.2 Editing Data

If the user selects E, a secondary menu is displayed on the screen. This secondary menu is identical to that used in adding data to a data base.

```
M)aterial property     C)one calorimeter
T)oxicity              F)urniture calorimeter
A)ll                   E)xit
```

However, the All option is not functional under this selection choice. If the user selects E, the program returns to the previous menu. Upon selecting a data base, the program requests that you

"Enter MATERIAL CODE of record to be edited:".

This is the Mcode previously discussed. For the selected data base, the program searches for a match between the Mcode entered by the user and the Mcodes stored in the data base. If a match is not found, the program informs the user of that fact. The program responds in one of two ways. It either says

"Not found in {name of} data base"

or

"NO data in {name of} data base",

where {name of} is the name of one of the four data bases. The first response indicates that the data base may have been corrupted. This problem may be beyond the capabilities of the casual user to correct, because it indicates that the data should be present in the data base but is not. (The only protection from a corrupted data base is to keep regular back-up copies of the files and go back to the last good copy if a corruption occurs.) The second response simply means that the data has never been entered for this Mcode into this particular data base.

If a match is found, the program presents the information in the selected record using the original screen forms. Thus, for material property data, figure 6-4 is used; for cone calorimeter data, figures 6-5a and 6-5b are used; for furniture calorimeter data, figures 6-6a and 6-6b are used; for toxicity data, figures 6-7a and 6-7b are used. Corrections and additions on a given field can be accomplished by using the cursor control keys (i.e. arrow) to position the cursor in the desired field and type over existing data or type in missing data. Corrections within a field are done by backspacing and typing over the incorrect information. If one has left the field, the cursor control keys can be used to return to the offending field and type over the error. On a multi-screen form, either screen can be reviewed by using the "Page Down" key to move forward or the "Page Up" key to move backward. At the completion of each form, the user is required to depress the "End" key while holding down the "Ctrl" key. This ensures that the data are properly replaced in the data base. The program prompts the user to determine if another record with the same Mcode and data base will be edited. A response of "N" to the question,

"Search for next record?(Y/N)"

will return the program to the secondary menu, while a response of "Y" will continue searching the data base for additional records with matching Mcodes. If any are found the appropriate screen forms are used and the user is permitted to alter the data in these records as well.

6.3.4.3 Deleting Records

This option has not been implemented as of this date.

6.3.4.4 Retrieving Data

Data can be retrieved from specific data bases in two ways. Specific records can be found and displayed or groups of records can be automatically found and displayed. In either case the data can be displayed on the screen or printed on a printer. The output format is similar to the forms used for entering data.

If the user selects F, the program clears the screen and presents a short description of the procedure used for finding and displaying a specific record. Data are retrieved from the various data bases by an interactive procedure that utilizes the user's requirements to define the specific record of interest. Since the exact name of a material may not be known or may be ambiguously entered into the data bases, the program requests that the user enter a keyword(s) (At this point, the user can enter the word EXIT to return to the main menu screen.) and select the data base to be searched. For example, gypsum, an acceptable keyword, can modify many words such as gypsum wallboard or gypsum walls. Another example would be polyurethane which could be entered as polyurethane foam seat cushions or polyurethane foam insulation. This information is used to display MATERIAL CODE and MATERIAL

IDENTIFICATION fields containing the specified keyword(s) for the selected data base. Then, the user is required to enter the MATERIAL CODE (letters must be all caps.) so that a listing of records with the selected MATERIAL CODE can be displayed. This latter display presents the information contained in each record as it was entered into the data base. The user can print each screen of information to a printer for later use.

If the user selects L, he will be presented with a short description of the listing process. This option has been implemented to provide the user with a rapid means for determining the contents of the various data bases composing FIREDATA. [A word of warning. This procedure does not search each data base but instead searches the master directory. The programs provided automatically update the master directory when new entries are made to a file. If other means are used to add data, this will not be the case.] The listing procedure provides the user with the material code and material identification fields in addition to showing which of the four data bases contain entries for the listed materials. The listing can be performed based on record numbers or material codes. One leaves the listing program by selecting the E)xit option. This returns the user to the main menu.

The listing by record number requires that the user provide the numbers of the first record to be printed and of the last record to be printed. If the user leaves out the number of the first record, the system assumes that the first record in the data base is intended. Similarly, for the last record to be printed, the system assumes that if one is not entered the listing process continues to the end of the file. If a printer is connected to the system, the listing process can be directed to the printer instead of the screen.

Listing by material codes is primarily intended for the development of tables of materials. It functions in an analogous manner as the listing by record numbers. The absence of an entry implies that the listing is to proceed to the extremes of the data base.

6.3.4.5 Utilities

Utilities are a group of programs that work independent of FIREDATA. These programs are also written in DBASE and manipulate the FIREDATA data bases. Currently, there is only one utility program. This program is called DUMP.

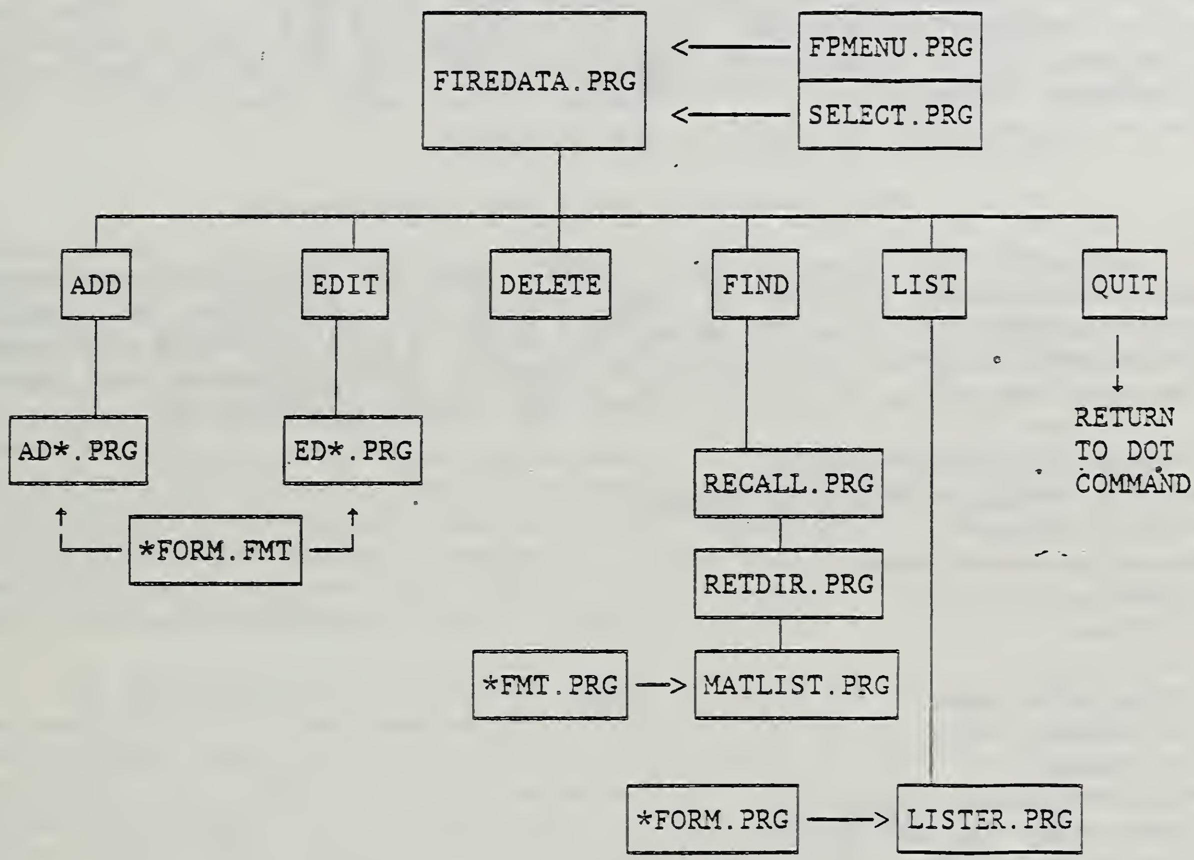
Dump

This program prints data base records only on a printer, not on the computer's display device. From the "DOT" command mode, the program is initiated by typing DO DUMP. A selection menu is shown that allows you to choose which data base will be printed. An additional option exists to print all of the data bases. The program assumes that the printer is ready and on-line when the selection is made. No warning is given prior to printing. Make sure sufficient paper is available to print the selected data base. When the printing has been completed, an exit option exists to return you to the "DOT" command mode. DUMP uses one of four subprocedures to format the output to match the input forms used for each data base. Two screen input forms are printed on one page, with one record per page. The print forms are CONEFORM.PRG, PHYSFORM.PRG, FURNFORM.PRG, and TOXFORM.PRG.

Exit

When this command is selected, the user is returned to the "DOT Level" commands. To return to DOS, type "QUIT".

Figure 6-8
Overview of FIREDATA



6.4 Determining the Rate of Heat Release

6.4.1 Introduction

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

6.4.2 Data Obtained by Full-Scale Measurements

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

- pools, liquid or plastic
- cribs (regular arrays of sticks)
- wood pallets
- upholstered furniture
- mattresses
- pillows
- wardrobes
- television sets
- Christmas trees
- curtains
- electric cable trays
- trash bags and containers
- industrial rack-stored commodities

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

6.4.3 Methods for Estimating Full-Scale Rates of Heat Release

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

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

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

6.4.3.1 Estimating Method for Upholstered Furniture

The method for determining the full-scale heat release rates of upholstered furniture is an example [9,10]. The method was based on experimental studies in the Furniture Calorimeter of a large number of commercial upholstered furniture items, and also of full-scale mockups. The studies showed that most of the furniture had rate of heat release curves which could be approximated as triangles (Figure 6-9). 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 [11,12].

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

<u>Peak heights based on bench-scale measurements</u>. 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:

$$\dot{q}_{fs} = 0.63 \, [\dot{q}''_{bs}] \begin{bmatrix}\text{mass}\\ \text{factor}\end{bmatrix} \begin{bmatrix}\text{frame}\\ \text{factor}\end{bmatrix} \begin{bmatrix}\text{style}\\ \text{factor}\end{bmatrix} \qquad (1)$$

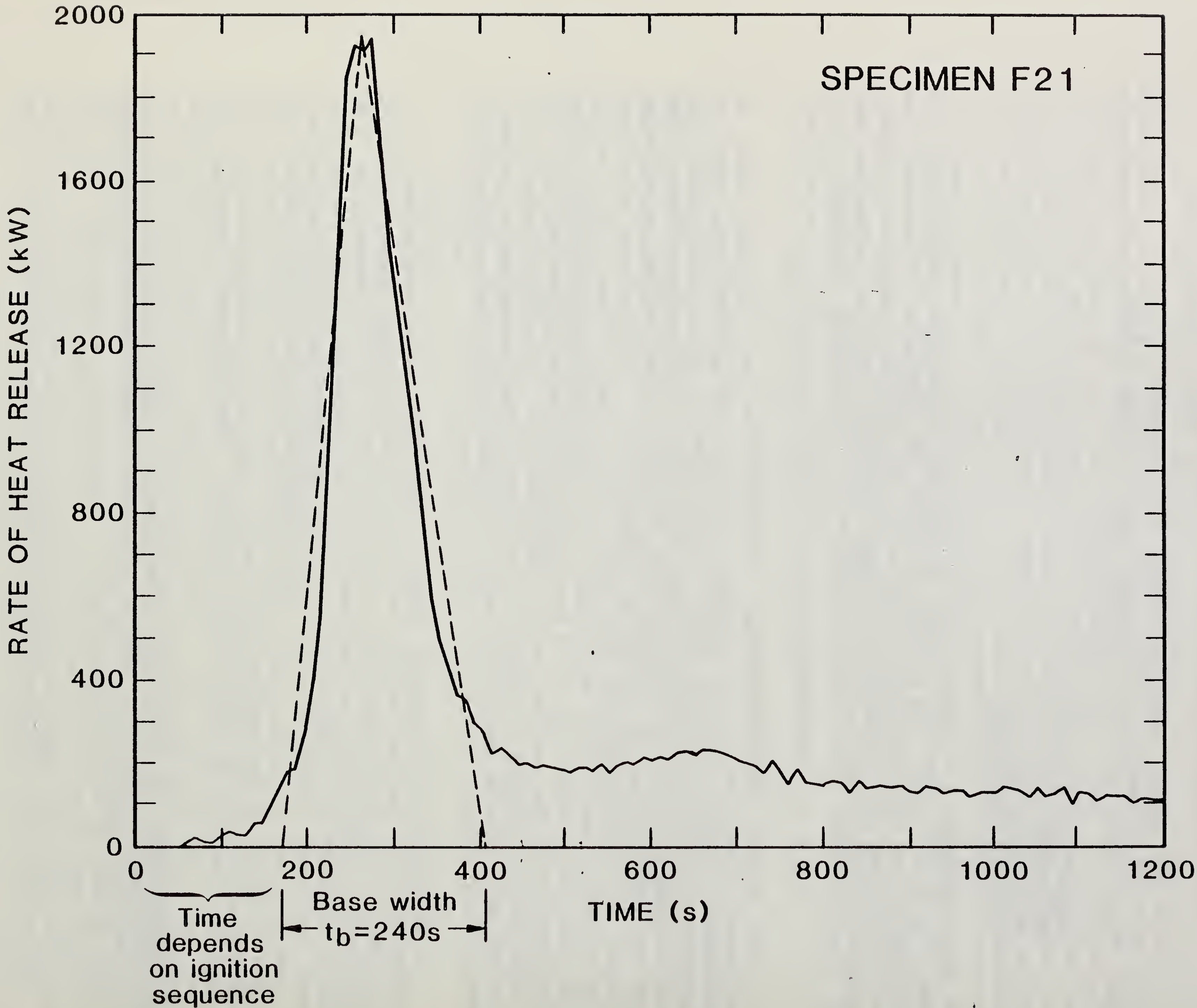


FIG. 6-9 APPROXIMATION OF THE RATE OF HEAT RELEASE FOR AN UPHOLSTERED CHAIR BY A TRIANGULAR SHAPE

where

$[\dot{q}''_{bs}]$ = rate of heat release (kW/m^2) in the bench-scale test,

$\begin{bmatrix}\text{mass}\\ \text{factor}\end{bmatrix}$ = combustible mass, in kg

$$\begin{bmatrix}\text{frame}\\ \text{factor}\end{bmatrix} = \begin{cases} 1.66 \text{ for non-combustible} \\ 0.58 \text{ for melting plastic} \\ 0.30 \text{ for wood} \\ 0.18 \text{ for charring plastic} \end{cases}$$

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

The constant 0.63 has units 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 [10].

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

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

where

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

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

and the constant 210 has units kW/kg.

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

$$t_b = \frac{C_3 m \Delta h_c}{\dot{q}_{fs}} \quad \text{(s)} \quad (3)$$

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

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

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

Limitations. Estimates for the peak heat release rate do not hold when both the fabric and the padding are highly fire resistive (e.g., wool and neoprene foam). In these cases full involvement of the furniture item does not take place. Estimates of the peak heat release rate using bench scale data should not be made for measured heat release rates below 75 kW/m^2. Estimates of peak heat release rate based on generic materials identification should not be made for those cases where the product of the [fabric factor] times the [padding factor] is less than 0.225. In such low-burning cases, it can be assumed that the burning rate hazard is much lower than in actively flaming fires, however, a specific method for estimating this low rate is not available at present.

Table 12 in reference 10 compares estimates of the total heat released made by the triangle method to the measured (full-scale) values for a series of upholstered chairs. For 11 chairs with combustible frames the triangle method averages 63% (range 46% to 83%) of the measured value for total heat content. For 26 chairs with non-combustible frames the triangle method averages 91% (range 46% to 103%) of the measured value.

Examples

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^{eff} in units of kJ/kg, this is expressed as 18,000 kJ/kg. For a wood frame, C_3 is 1.3. A computation of t_b can then be obtained as t_b = 1.3(20)(18,000)/756 = 619 s.

Example 2. A more fire resistive construction is considered, involving also a wood frame, but using neoprene foam and cotton upholstery fabric. The chair mass is 28 kg. Bench-scale test data are not available, and so the method based on generic materials identification is used. The fabric factor for cotton is 0.4. The padding factor of neoprene foam is 0.4. Multiplied together, this gives 0.16. The restriction above, however, tells us that if this product is less than 0.225, then sustained flaming fire propagation will probably not occur, and that the rate of heat release will be small. Thus, further computation is not done.

6.4.3.2 Estimates for Mattresses

Some years ago several studies were done at NBS on institutional mattresses and residential mattresses, all of "twin-size" (approximately 0.9 m by 2.0 m) and without combustible boxsprings. The data for the peak heat release rate have recently been correlated [10] and are shown in Figure 6-10. There are a number 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. Nonetheless, 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 equation 3 developed for upholstered furniture, and setting $C_3 = 1.8$, since a wood frame is not involved in mattress construction.

6.4.3.3 Estimating Method for Wall Lining Materials

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

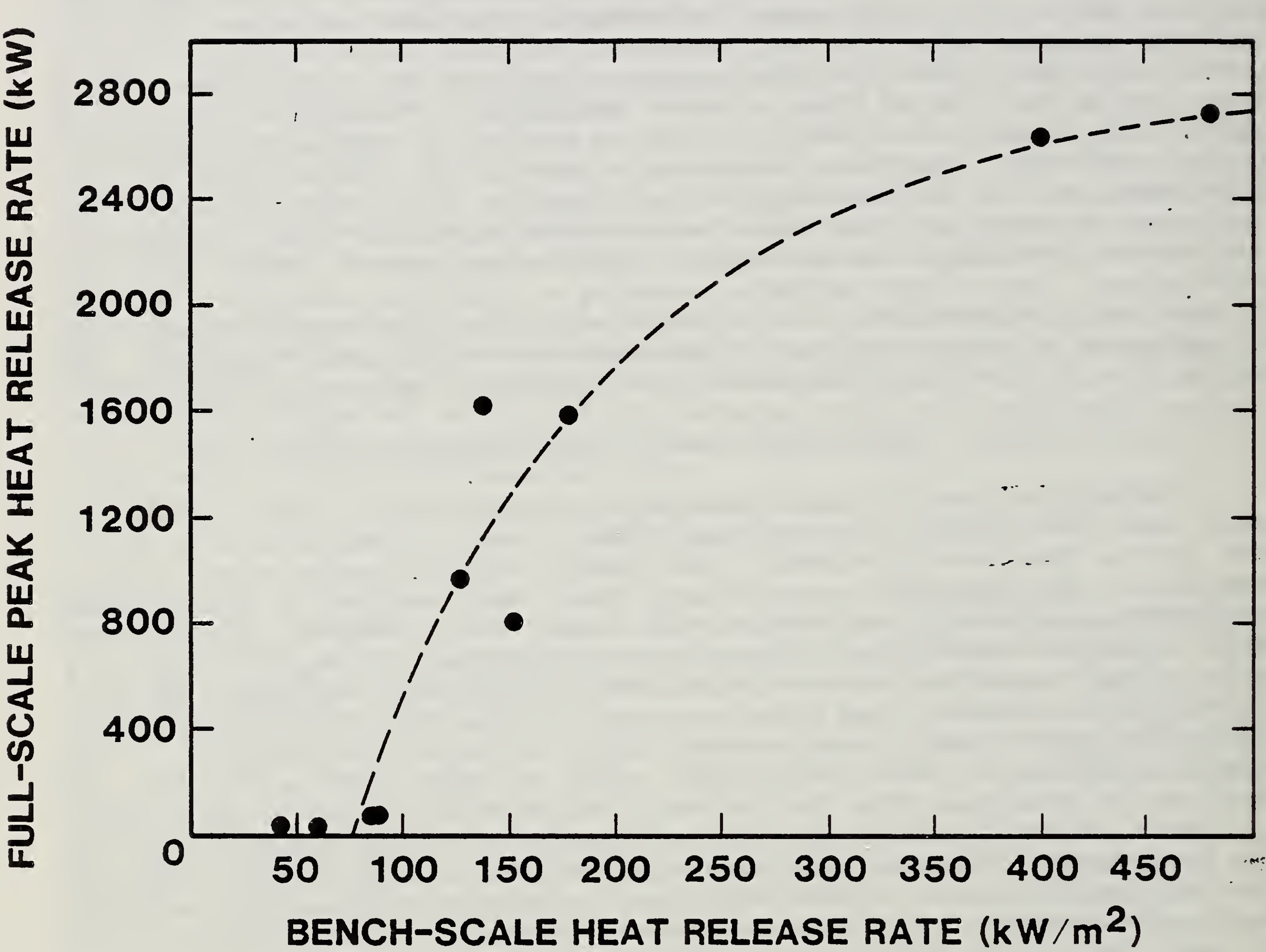


FIG. 6-10 CORRELATION BETWEEN BENCH-SCALE RATE OF HEAT RELEASE MEASUREMENTS FOR MATTRESSES AND PEAK FULL-SCALE RATES OF HEAT RELEASE

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

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

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

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

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 seen. Magnusson and Sundström [14] have recently proposed a more detailed, but still largely empirical, model for describing the initial rising portion of the heat release rate curve; their method is pertinent primarily to cellulosic type wall materials. Further general improvements await the ability of models to track the area of flame involvement and of the heat fluxes being imposed on wall surfaces by other objects and other wall elements.

6.4.3.4 Estimating Method for General Combustibles

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

In principle, the rate of heat release of full-scale combustibles can be directly evaluated from bench-scale data. To make this possible, it is necessary to know the rate of heat release per unit area, $\dot{q}''_{bs}$, as measured in bench scale for various irradiances, and also as a function of time. 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:

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

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

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

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

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

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

where C_4 = 1.0 if all surfaces are exposed to fire
= 0.5 if items are complex and only partly exposed to fire
and A_t = the total surface area of the specimen (m^2).

The bench-scale test conditions for determining $\dot{q}''_{bs}$ should be the following. An irradiance of 25 kW/m^2 is appropriate prior to room flashover. After flashover, 75 kW/m^2 can represent the post-flashover regime. The averaging period has also to be determined. The comparison for the wall data was to a bench-scale averaging of 60 seconds (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 rate of heat release corresponding to the exhaustion of the fuel available.

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6.5 Ignition of the Second Item

The ignition of a second (or subsequent) item from a burnir room can occur from direct flame contact or by sufficient r reaching its surface to heat that surface to its ignition tempera former case, the objects need to be spaced close enough together f contact to occur (essentially touching). In the latter case, comes from the flame above the burning object, the hot upper layer and from the bounding surfaces of the room (ceiling and walls). V piloted and non-piloted ignition are available, always use the fo more conservative.

For the case of direct flame contact, the ignition time item can be assumed to be the time at which contact occurs. (Th is conservative since time is required to pyrolyze fuel and he produced to their ignition temperature.) For radiant ignit assumption is that prior to flashover, the radiation from the up the room surfaces are negligible. Thus, the radiant energy tr surface of the second item all comes from the flame above the Based on this crude assumption, Babrauskas [1] has developed a estimating the ignition of the second item.

In this procedure, the radiant flux necessary to ignite assumed to be 10 kW/m^2 for easily ignited items such as thin curt newsprint, 20 kW/m^2 for "normal" items such as upholstered fur kW/m^2 for difficult to ignite items such as wood of 1/2 inc thickness. The mass loss rate of the burning item necessary to ignition flux at various separation distances between the items is figure 6-11. Thus, the time to ignition of the second item is which the mass loss rate of the burning object first reach necessary to produce the required flux at the distance between the

To make a better estimate, using FAST and FASTPLOT, the upper layer and room surfaces can be included. That is, an initia with only the first item burning will give the time-dependent flux in the lower layer in the variable RAD. This variable can be plotted with FASTPLOT (see the instructions on running these prog this chapter). When the predicted total flux (RAD plus the flux f estimated from Fig. 6-11) reaches the estimated ignition flux f item, ignition can be assumed. The second item is then added to described in the next section of this chapter, and FAST is re-run fire.

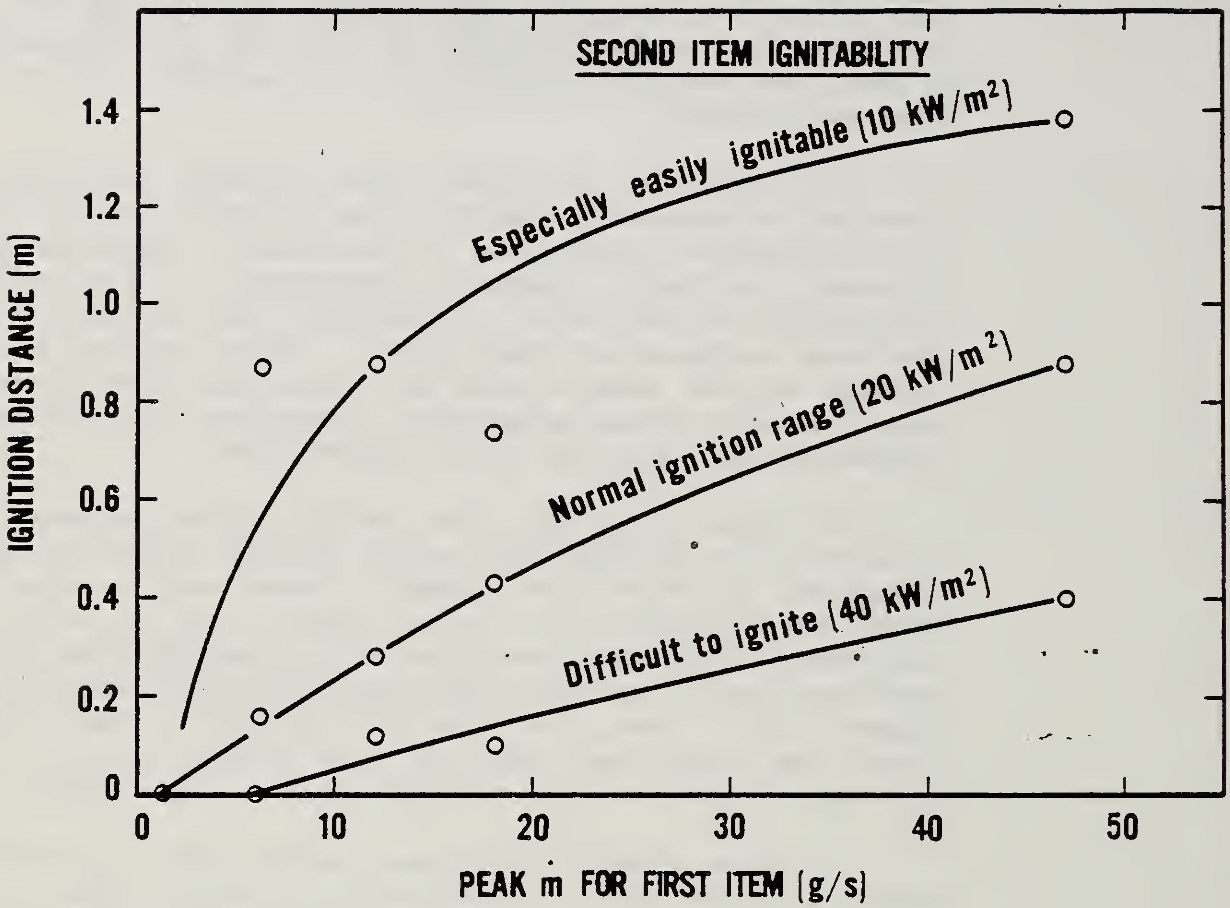

FIG. 6-11 RELATIONSHIP BETWEEN PEAK MASS LOSS RATE AND IGNITION DISTANCE FOR VARIOUS IGNITABILITY LEVELS.

Source: NBSIR 81-2271

The method of estimating the flux from the flame presented in figure 6-11 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 [2]. For materials tested in this apparatus, the parameters $\dot{q}''_{o,ig}$, t_m, and b are tabulated for use in the following relation:

$$\frac{\dot{q}''_{o,ig}}{\dot{q}''_e} = \begin{cases} b\sqrt{t}, & t \le t_m \quad (1) \\ 1, & t \ge t_m \quad (2) \end{cases}$$

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

The total flux to the surface of an object ($\dot{q}''_e$) is the sum of the flux from the flame of the burning object ($\dot{q}''_{r,f}$) and the flux from the upper layer and room surfaces ($\dot{q}''_{l,w}$). As in the previous method, the flux from the upper layer and room surfaces ($\dot{q}''_{l,w}$) is obtained from a run of FAST with only the first item burning, from the variable RAD (note that RAD 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 [3], 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:

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

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

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

where: $\dot{Q}$ is the rate of heat release of the burning item (W)
D is the flame diameter (cm)
ϕ is the configuration factor between the flame and target
ξ is the radiative fraction (assume .3 if a value is not available for the fuel involved).

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

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

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

$$t = (\dot{q}''_{o,ig}/b(RAD/10 + \dot{q}''_{r,f}))^2 \qquad (7)$$

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

$$\dot{q}''_{o,ig} < (RAD/10) + \dot{q}''_{r,f} \qquad (8)$$

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

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

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6.6 Program MLTFUEL

6.6.1 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.

6.6.2 Theory

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

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

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

3. Mass is also a conserved quantity. The mass of any species produced at any time is the mass lost by the fuel at that time times the yield of that species at that time. Thus, the effective yield of a given species for the composite fire at any time is obtained by multiplying the mass loss rate of each item at any time by its yield at that time (which gives the mass of the specie), summing these masses over all items, and dividing by the mass loss rate of the composite fire for that time.

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

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

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

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

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

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

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

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

The data presented in the cone and furniture calorimeters generally have $\phi < 1$, although a precise determination is impossible without knowing r_{ox} for the furniture array. For further information on yields as a function of equivalence ratio, see papers by Tewarson [1,2] and Beyler [3].

6.6.3 Running the Program

The program MLTFUEL is written in FORTRAN 77 and will run on any MS-DOS machine. Since it is interactive, no operating instructions are necessary. While the units of the results will be the same as the units input (everything is multiplied by dimensionless parameters), the program asks for the inputs in the SI units in which FAST works. It is suggested that these units be used to avoid confusion later.

The first two questions asked by the program are the number of items burning together and the number of time intervals over which the items burn. The number of intervals is one less than the number of times for which data will be entered.

The first time through, the program computes the heat of combustion, mass loss rates, and the yields of one specie. If species yield is not desired, any value (including zero) may be entered at the species prompt. If the yields of more than one species are desired, the first is computed on the first time through and, after the initial results are presented, the user will be asked if another species is desired. The program will ask for only the yields of the next species (it saves the other data) and again presents the results with the values for the new specie. This may be repeated as many times as necessary.

6.6.4 Limitations

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

6.6.5 Example of Constructing a Time Line for Multiple Burning Items

6.6.5.1 Scenario of the Fire

For this example, we will consider that the first item ignited is a wastebasket, ignited by a match. The wastebasket is directly adjacent to an upholstered chair, which ignites by direct flame contact. A loveseat is located 0.5 meters (1.6 feet) from the chair, and ignites from the radiant energy released by the burning chair.

6.6.5.2 Search the Data Base

In looking through the data base, we find furniture calorimeter data on a wastebasket (material code WPB001) and a chair (material code UPC001) which match the items which we have in mind. There is, however, no appropriate loveseat. Thus, for this item we go to the cone calorimeter data and select a polyolefin covered, polyurethane foam. This is the same data used in example 1 of the section "Determining The Rate Of Heat Release", except the total combustible mass is 40 kg.

6.6.5.3 Construct the Mass Loss Curves

The mass loss data for the first item (wastebasket) are transferred from the data base listing to a graph (figure 6-12a). Since the chair will not ignite instantly, we arbitrarily decide that ignition will occur at a heat release rate of about half the wastebasket peak value (8 kW, 0.5 g/s). The mass loss data for the chair are then transferred from the data base listing to a graph, with the ignition time shifted to 300 seconds (the time that the wastebasket reaches 8 kW - see figure 6-12b).

Using the procedure discussed in example 1 of the section on "Determining The Rate Of Heat Release" but substituting 40 kg for the mass, we determine that the triangular approximation for the loveseat has a peak heat release rate of 1512 kW (with a resulting peak mass loss rate of 0.084 kg/s), and a base width of 619 seconds. Using the procedure discussed in "Will The Second Item Ignite?" and assuming a "normal" ignition flux of 20 kW/m^2, we find that the loveseat will ignite when the mass loss rate of the chair is 20 g/s (0.02 kg/s). This occurs at 450 seconds (from figure 6-12b). The triangular curve for the loveseat is then drawn starting at 450 sec, as shown in figure 6-12c.

6.6.5.4 Establishing the Intervals

With these three curves drawn, time intervals are drawn such that the defined data points on any single curve are at an interval boundary, as shown in the figure. These data are then tabulated as in table 6-18a-c. In some instances, interpolation of a curve will be needed. The data in table 6-18 are used with the program MLTFUEL to obtain the composite heat of combustion and mass loss rate to use in the FAST model (see table 6-18d).

References

1. Tewarson, A., Quantification of Fire Properties of Fuels and Interaction with Fire Environments, NBSGCR 82-395, Nat. Bur. Stand. (1982).

2. Tewarson, A. and Steciak, J., Fire Ventilation, NBSGCR-83-423, Nat. Bur. Stand. (1983).

3. Beyler, C.L., Major Species Production by Solid Fuels in a Two Layer Compartment Fire Environment, pp 431-440, in Proc. of the First Intl. Symp. on Fire Safety Science, P.J. Pagni and C.E. Grant, eds., Hemisphere Publishing Corp., New York (1986).

Table 6-18

A. DATA ON WASTEBASKET (WPB001)

Time	$\dot{M}$	f_{CO}	f_{CO2}	f_{OD}
0	0.0	0.01	0.05	0.01
240	0.0001	0.01	0.05	0.01
350	0.00085	0.01	0.05	0.01
450	0.00075	0.01	0.05	0.01
500	0.00072	0.01	0.05	0.01
560	0.00068	0.01	0.05	0.01
625	0.00055	0.01	0.05	0.01
750	0.00014	0.01	0.05	0.01
1020	0.00011	0.01	0.05	0.01
1025	0.0	0.01	0.05	0.01
1200	0.0	0.01	0.05	0.01

B. DATA ON CHAIR F21 (UPC001)

Time	$\dot{M}$	f_{CO}	f_{CO2}	f_{OD}
0	0.0	0.0	0.0	0.0
240	0.0	0.0	0.0	0.0
350	0.0	0.0	0.0	0.0
450	0.005	0.03	0.67	0.008
500	0.025	0.024	0.76	0.015
560	0.116	0.016	1.07	0.02
625	0.033	0.016	0.71	0.022
750	0.008	0.016	0.59	0.001
1020	0.0055	0.016	0.54	0.0
1069	0.005	0.016	0.75	0.0
1200	0.0	0.0	0.0	0.0

C. DATA FOR APPROXIMATED LOVESEAT

Time	$\dot{M}$	f_{CO}	f_{CO2}	f_{OD}
0	0.0	0.0	0.0	0.0
240	0.0	0.0	0.0	0.0
350	0.0	0.0	0.0	0.0
450	0.0	0.0	0.0	0.0
500	0.002	0.01	1.0	0.008
560	0.0275	0.03	1.3	0.02
625	0.045	0.03	2.0	0.02
750	0.08	0.03	2.0	0.02
1020	0.015	0.02	1.5	0.02
1069	0.0	0.0	0.0	0.0
1200	0.0	0.0	0.0	0.0

D. RESULTS FROM MLTFUEL
Average Heat of Combustion = 17,933

Time	$\dot{M}$	f_{CO}	f_{CO2}	f_{OD}
0	0.0	0.0	0.0	0.0
240	0.000098	0.0102	0.0510	0.0102
350	0.00083	0.0102	0.0510	0.0102
450	0.0058	0.0272	0.5858	0.00082
500	0.0280	0.0224	0.7524	0.0140
560	0.1456	0.0185	1.0990	0.0197
625	0.0792	0.0238	1.4310	0.0206
750	0.0887	0.0284	1.8520	0.0181
1020	0.0208	0.0190	1.2250	0.0145
1069	0.0051	0.0159	0.7431	0.0
1200	0.0	0.0	0.0	0.0

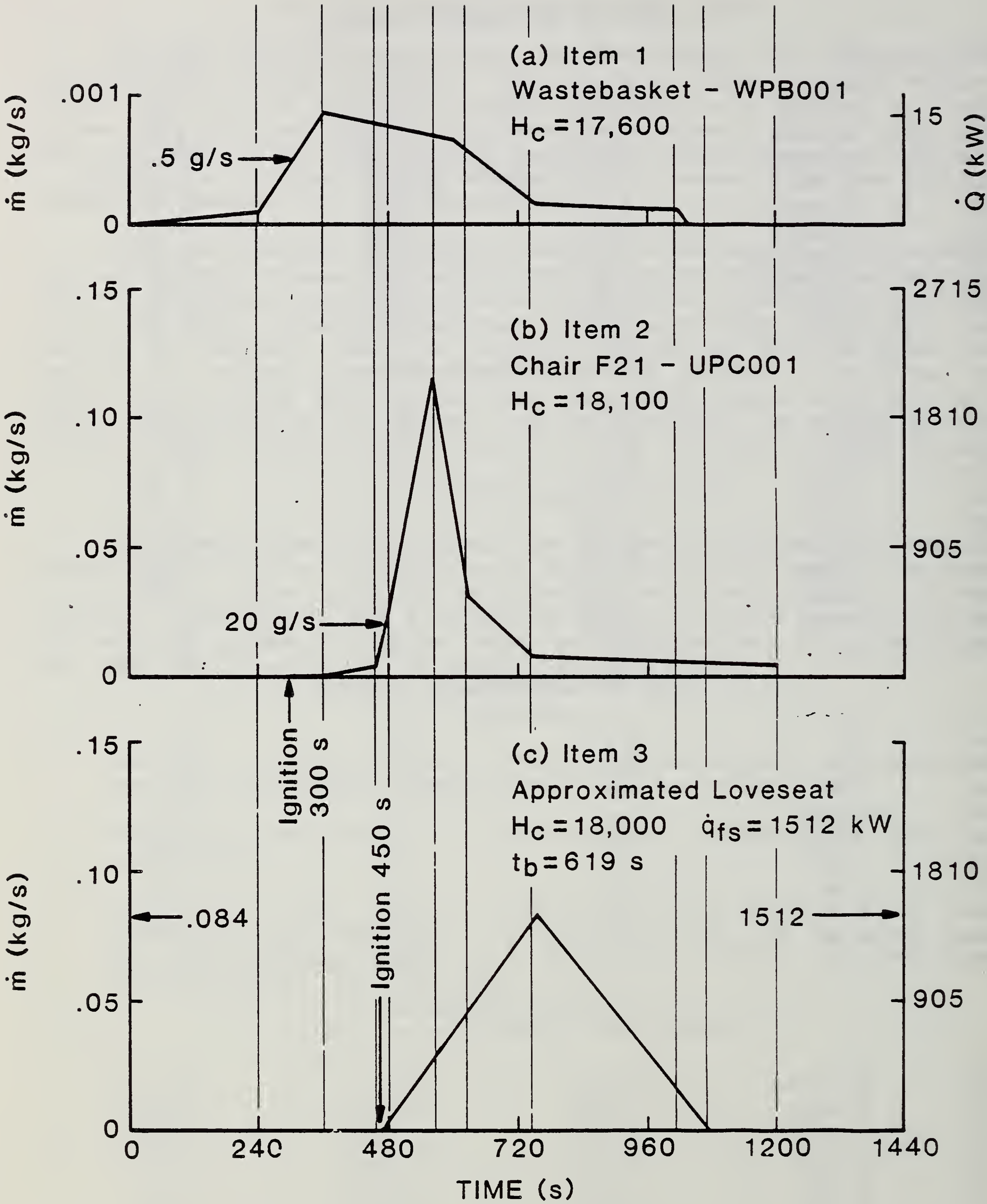

FIG. 6-12 CONSTRUCTING THE TIME LINE FOR MULTIPLE FUELS BURNING

6.7 Instructions for FINPUT

6.7.1 Introduction

FINPUT is an interactive utility program which is used to create or edit an input file to be executed by the FAST model(see the FAST User's Guide in the appendix). As such, it makes no predictions and contains no assumptions. The only calculations done in FINPUT are units conversions and error checking. The data requested by FINPUT are divided into 8 sections. These are:

1. Title and Timestep
2. Ambient Conditions
3. Floor Plan Data
4. Connections
5. Thermophysical Properties of the Enclosing Surfaces
6. Fire Specification
7. Species Production
8. Output Files

Each of these sections starts with a major prompt located at the left margin. In addition, there are several miscellaneous commands which provide functions such as SAVE, CHANGE, SET UNITS, END, COPY, and HELP.

When the program is started, the user is prompted for the name of an existing FAST input file with the prompt DEFAULT FILE>. If a new file is to be created, press <RETURN>; otherwise, enter the name of the file to be changed. If the user has entered the name of an existing file to be edited, the data in the named file will exist as default values and will be printed to the screen as each section is reached. If the user has indicated that this is a new file no values will appear.

When an existing file is being changed the user will have three options as follows:

a. Leave the data unchanged exactly as shown on the screen. To do this enter the word "NO" or press <RETURN>.

b. Change the entire entry; to do this the user must enter every data value required in the section being revised for his problem.

   Example - 1 2. 3. 2. 0.

c. Review and enter each data item one by one, to do this the user enters "Y" or "YES." The program will then call up each element of the section, individually presenting the user with the value in the existing file. If this value is satisfactory then press <RETURN>. If this is not correct enter the correct value.

If the user has previously indicated that this is a new file, the procedure will be the same as the second and third options for revising the existing file except that no data will be shown and the user must either enter all of the data as a single entry or enter "YES" and provide an entry for every prompt that follows.

6.7.2 Title and Timestep

In this section, the program asks for a version number and title for identification of the run, and for the times associated with the simulation; total time and the frequency at which predicted data is recorded.

6.7.2.1 Version

Enter a three digit number giving the version of FAST to be run. The version currently available for micro computers is version 17. If this is the version to be used enter 017, or press <RETURN>.

6.7.2.2 Title

Although this is an optional heading, use of a title is strongly encouraged. The title may be up to 50 characters. A suggested title might be a short identification of the building or portion of building involved, the initials of the person executing the run, or the date and the run number if multiple runs are being made. Example: CITY POWER PLANT JKJ 030186 RUN05.

6.7.2.3 Simulation Time Period

Enter the length of time in seconds over which the simulation takes place. Simulation time is the only method of controlling the length of time of the simulation. The maximum time value currently allowed is 86400 seconds (1 day).

6.7.2.4 Print Interval

Enter the time interval between each printing of the output value summary. Approximately one page of computer printout is generated for each such interval. The user should specify intervals that are close enough together to give the needed resolution. A very short interval will produce massive amounts of output, causing some difficulties in interpretation. If graphics capabilities are available, specify relatively long intervals and use graphic presentations to obtain the data or interpolate between the values shown in the printout. Ten print summaries per simulation (or a print interval of one tenth of the total simulation time) is usually sufficient when a dump file is being used.

6.7.2.5 Dump Interval

This is the time interval between the points to be written to a special file (DUMP file) used for graphics and tabular listings from FASTPLOT. If the user does not have plotting capability ENTER 0. Where plotting is available, a value of (Simulation Time/25) will give 25 data points for the graph, enough for good resolution (more than 25 dump intervals will result in a warning message when the program starts). CAUTION: The dump file requires 20.5 k of disk space per dump interval, and the number of such intervals is (SIMULATION TIME/DUMP INTERVAL +1). The user must make sure that enough free space is available on the disk before the run is started. Otherwise, when the available space is full, the run will stop, and the data produced may not be usable.

6.7.3 Ambient Conditions

In this section, the initial conditions within the building are specified.

6.7.3.1 Ambient Temperature

Initial interior building temperature is in degrees. Default units are degrees Kelvin (degrees Celsius plus 273). To use other units see "SET UNITS."

6.7.3.2 Ambient Pressure

Initial interior building (absolute) pressure at the reference height in the building used to specify the floor height for the rooms. The default units are pascals. To use other units see "SET UNITS".

6.7.3.3 Station Elevation

The vertical elevation above mean sea level (which allows the program to account for the variation in density of ambient air with altitude) of the reference height is entered in the default units (meters). To use other units see "SET UNITS".

6.7.4 Floor Plan Data

In this section a number is assigned to each room and the width, height, and depth of each room and the height of the floor of each room above a reference point is entered. Each room is entered separately, but compartment dimensions can be duplicated using "COPY."

6.7.4.1 Number of Rooms

Enter the number of rooms (compartments) inside the structure to be analyzed. A room is a compartment bounded by walls or partitions, a floor, and a ceiling. The PC version of FAST V17 can accommodate up to 5 rooms. However, the execution time for the program increases approximately by the square of the number of rooms being evaluated. That is, the run time for a 5 room facility will be of the order of 25 times as long as that for a one room analysis. In addition to the number of rooms entered, the program automatically adds one more room for the outside atmosphere (if the number of rooms is entered as 3 the room number assigned to the exterior is 4). Normally this is the exterior of the building.

Any stairwells or other shafts that are to be part of the analysis are also entered as rooms. For stairwells, the area (but not the height) can be reduced to partially account for the stairs. The complex actual flow phenonema, however, are beyond the capabilities of this version of the model.

6.7.4.2 Room Number

The room number may be any whole number. Rooms are numbered 1, 2, 3, etc. It is important however that each room number be unique. No letters can be used in room number identification.

6.7.4.3 Width

Enter the room width in feet or meters as selected earlier. The dimension may be either the longer or shorter dimension of the room so long as the other dimension is entered as depth. If the room is not a single rectangle, the entry for width and depth should be revised from their actual length to values that produce the correct floor area of the room involved. (see Depth)

6.7.4.4 Room Depth

Enter the room depth in feet or meters as selected earlier. The dimension may be either the longer or shorter dimension of the room so long as the other dimension is entered as width. If the room is not a single rectangle the entry for depth and width should be revised from their actual length to values that produce the correct floor area of the room involved. (See Width)

6.7.4.5 Room Height

Enter the room height in feet or meters as selected earlier. The dimension entered is the distance from the top surface of the room floor to the underside of the ceiling above. If the ceiling is sloped or otherwise a varying level, use the average distance from the floor to the ceiling.

6.7.4.6 Floor Height

Enter the elevation of the top surface of the floor. The value entered is the distance that the floor surface is above the reference point. If the reference point is at the same elevation as the floor surface, enter zero (0).

6.7.5 Connections

Connections refer to horizontal openings connecting any two compartments (including openings to the outside of the building) through which energy and mass flow. The model cannot handle openings in the floor or ceiling. Connections are specified by entering the room numbers of the two compartments between which the opening exists (both rooms must be defined first) followed by the dimensions of the opening. These dimensions are the opening width, height of the top of the opening above the floor, and height of the bottom of the opening above the floor. The default units are meters for each of these dimensions. To use other units see "SET UNITS".

6.7.5.1 Compartment Numbers

The program will prompt the user for the numbers of the two, connected compartments. If the opening is to the outside of the building, the room number assigned to the outside is one more than the total number of compartments.

6.7.5.2 Vent Width and Height

The vent width and height are entered in the current units of length (default is meters). If the vent height entered is greater than the ceiling height, or the vent width is greater than the largest dimension of either of the joined compartments, an error message is printed to the screen, and the input is not accepted.

6.7.5.3 Sill Height

This refers to the bottom of an opening relative to the floor of the compartment. Normally the sill of a door is at floor level and a sill of a window or other opening is above floor level.

6.7.6 Thermophysical Properties of Enclosing Surfaces

This section enters the thermophysical properties of the ceilings, walls and floors in each room. The program assumes that all of the walls in any room are of the same material or at least are of materials that have identical thermophysical properties and thickness. The properties of both the ceiling and floor in any room can differ from the walls. Each room can have different wall, ceiling, and floor properties. The properties required and entered in this section are conductivity, specific heat, density, thickness, and emissivity.

The model can also account for ceilings, walls or floors, that are composed of up to three layers of different materials. Unfortunately, it was not possible to include entry of multiple layers in FINPUT. Thus, the procedure for entering multiple layers is to enter the data for one layer with FINPUT and edit the resulting data file (with an editor or word processor) as described in the FAST User's Guide (see Appendix).

The data for each room and each boundary are entered separately. These values can be duplicated from room to room (see "COPY"). CAUTION: Be very careful of units. The required units for an input value may not be the most common units nor the units provided in the data base. For example, the common unit for energy in thermophysical data is kilojoules where the program requires joules unless the user changes the unit in SET UNITS.

6.7.6.1 Room Number

Enter one of the room numbers assigned in the previous section. This may be any of the room numbers previously assigned.

6.7.6.2 Ceiling Conductivity

Enter the conductivity of the ceiling in (kW/m/K) if metric or (btu/hour/ft/R) if engineering dimensions have been previously selected.

6.7.6.3 Ceiling Specific Heat

Enter the specific heat of the ceiling material. Enter in (J/kg/K) if metric or (btu/lb/R) if engineering dimensions have been previously selected.

6.7.6.4 Ceiling Density

Enter the density of the ceiling material. Default units are (kg/m^3). To use other units see "SET UNITS".

6.7.6.5 Ceiling Thickness

Enter the thickness of the ceiling material. Default units are meters. To use other units see "SET UNITS".

6.7.6.6 Ceiling Emissivity

Enter the emissivity of the ceiling. (Normally about 0.9 - non-dimensional).

6.7.6.7 Walls

See instructions for Ceiling.

6.7.6.8 Floor

See instructions for Ceiling.

6.7.7 Fire Specification

This section describes the characteristics of the fire that will occur. The details entered by the user will drive the computations of fire effects through the entire simulation. This section identifies which room will be the room of fire origin, the position of the fire in that room, and combustion chemistry properties. Description of the fuel mass loss rate, the height of the burning fuel above the floor and the energy released per unit mass is required.

6.7.7.1 Room of Fire Origin

Enter the number of the room containing the fire. The user may select any one of the rooms that has previously been defined.

6.7.7.2 Fire Position

Enter [1] if the fire is in the center of the room or any other position not in close proximity to one of the walls or in a corner. Enter [2] if the fire is to be located very close to a room corner. Enter [3] if the fire is located very close to a wall, but is not in a corner.

Fire position is used to account for the amount of air that is entrained in the fire plume as it rises from the burning fuel. The entrainment will be restricted if the fire is very close to the wall or corner.

6.7.7.3 Heat of Combustion

Enter the effective net heat of combustion of the fuel. The net heat of combustion is the amount of energy released to the surrounding environment by the combustion of a specific amount of a fuel. Each fuel has a different net heat of combustion. The heat of combustion is entered as energy released/unit mass, such as J/kg or BTU/pound. BE CAREFUL OF THE UNITS!

6.7.7.4 Number of Intervals of Fire Growth

Enter a number from one to twenty-one. The number entered indicates the number of time intervals that the user desires (or finds necessary) to describe the mass loss rate, fuel height, and species production as they vary through the course of the fire. The mass loss rate, fuel height, and each species to be tracked will be entered as a series of points with respect to time. When evaluating a fire FAST performs a linear interpolation between these points to determine the actual value at any time. It is important that a sufficient number of intervals be selected to provide a reasonable approximation using straight line segments for the mass loss rate, changes in fuel height, and rate of species production that will be evolved by the fire. The time intervals are the time gaps between these points. They do not have to be of equal length. If the source data being used would not plot as a series of straight lines the user should make the best reasonable approximation of the curve as a series of straight lines. The number of straight lines equals the number of intervals to be entered for this prompt. (See figure 2 in the FAST User's Guide in the Appendix.)

6.7.7.5 Interval

Time interval is the length of each of the intervals specified in the previous prompt. The total duration of the fire is the sum of all of the time intervals. The length of time of any interval is independent of the time during the fire when that interval will occur. For example if the first time interval after ignition lasts 60 seconds, time for that interval is 60 seconds. If the second time interval runs from 60 seconds into the fire to 100 seconds the length of the time interval is 40 seconds. If the next segment runs from 100 seconds into the fire to 300 seconds into the fire the length of that time interval is 200 seconds.

Enter in sequence starting with the first interval called for in the previous prompt in seconds. Separate each entry by a space. An example for a three interval fire is: 60 40 200. It may be easier to enter a single number (which will set each time interval to that value) and then change the values to those desired using the CHANGE command.

6.7.7.6 Mass Loss Rate

Mass loss rate is the rate at which fuel is pyrolyzed at times corresponding to the start of the fire and the end of each of the time intervals. The burning rate values are entered in kg/s if default units are used. To use other units see "SET UNITS". Enter the rate of burning at the start of the fire. If the simulation starts from the moment of ignition enter zero. Leave a space and then enter the rate of fuel burning at the end of each of the (N) time intervals entered in the description of the fire. The total number of entries will be (N + 1). An example for a four interval fire is: 0 .02 .1 .01 0. A convenient way to do this is to enter a single number which the program will extend to all points and then to modify these values using the "CHANGE" section.

6.7.7.7 Fuel Height

Enter the height of the base of the flames above the floor at the start of the fire and at the end of each time increment. Separate each entry by a space. A total of (N + 1) entries must be made. Enter the height in meters if metric or feet if engineering dimensions have been previously selected. If the entire course of the fire takes place without reducing the height of the burning material the fuel height will be the same throughout the course of the fire. Conversely if the fuel burns away from the surface or climbs to a higher position, the fuel height may change during the course of the fire. A convenient method is to enter a single value which will be extended to all points and then modify these values with the "CHANGE" section.

6.7.8 Species Production

Species production is optional. Any or all of the species can be omitted in which case no calculation of those species concentrations will be made. If a calculation of species concentration is desired FAST will evaluate and separately track the average concentration in the smoke layer of any of the following ten species: Nitrogen (N2); Oxygen (O_2); Carbon Dioxide (CO_2); Carbon

Monoxide (CO); Hydrogen Cyanide (HCN); Hydrogen Chloride (HCL); Unburned Hydrocarbons (TUHC); Water (H_2O); Smoke Density (OD); and Concentration-Time Product (CT). (The names in parentheses are the keywords for each species which are entered at the species prompt to input yields for that item.)

The term species is used to mean either a chemical species (product of combustion) produced by the burning process or a fire product related to the tolerability of the smoke layer. Heat and energy release are not classified as species. The ten specific species are the only ones currently traceable. Each of these species has a separate help call. The production of a species is specified as a dimensionless (actually mass per mass) yield. For each species enter either the complete time history or a single value which the program will extend to all points. These values can then be modified with the "CHANGE" section.

Yield is the fraction of the mass of each species generated by a fire to the mass of fuel lost. Typically this is obtained by dividing the mass of a species produced per second by the mass of fuel lost per second, as the fuel is combusted in an apparatus such as a calorimeter. For example if the rate of burning is 1 kilogram per second and the rate of production of a species is 0.02 kilogram per second the yield is 0.02/1.0 or 0.02.

6.7.8.1 Nitrogen

Nitrogen is neither produced nor consumed in a fire. It is included as a tracked species because it is sometimes used as a fire inerting agent and for use in the chemistry calculations within the model. This species will not normally be used.

6.7.8.2 Oxygen

As a fire burns it consumes oxygen. The rate of oxygen consumption has been found to be fairly constant with the rate of energy release; a fact which is the basis for oxygen consumption calorimetry. This constant is generally assumed to be 13,100 kJ of energy released per kg of oxygen consumed. The heat of combustion of a fuel is defined as the energy released per unit mass of fuel burned. Thus, the "yield" of oxygen (mass of oxygen produced per unit mass of fuel lost) is obtained by dividing the heat of combustion by the oxygen consumption constant, or ($-H_c/13,100$) when all fuel mass lost is burned (100% efficiency). When more detailed combustion chemistry is added to the model, the appropriate correction will be made for the actual combustion efficiency. Since yields are defined as production rates and oxygen is consumed, a negative value must be used. Also, since the yield of oxygen is defined by the heat of combustion entered elsewhere, this yield is set simply by entering the keyword O2 at the SPECIES prompt. Note that because this is a fixed value based on the heat of combustion the yield of oxygen cannot be changed by CHANGE.

6.7.8.3 Carbon Dioxide

If carbon dioxide is entered as a species to be tracked, FAST will report the average concentration of carbon dioxide in the smoke layers for each room as a function of time. Enter the yield of carbon dioxide production at the start of each of the (N) time intervals entered in the description of the fire, plus one for the final value. Separate each entry by a space (n + 1 values must be entered). The keyword is CO2.

6.7.8.4 Carbon Monoxide

FAST can track the concentration of carbon monoxide (CO) in the smoke layer for each room as a function of time. Enter the yield of carbon monoxide production at the start of the (N) time intervals entered in the description of the fire, plus one for the final value. Separate each entry by a space. A total of (N + 1) entries must be made. An example of a four interval fire is: 0.0 0.2 0.2 0.8 0.0. The keyword is CO.

6.7.8.5 Hydrogen Chloride

It is generally assumed that all of the chlorine atoms available in the fuel end up as HCl gas (a "worst case" assumption). Thus, the yield of HCl can be derived from the fuel structure where actual yield data are unavailable. For example, for pure PVC, this value is 0.58 (58% of the fuel mass becomes HCl). However, most PVC products are not pure PVC, but contain fillers and plasticizers. Rigid PVC is generally of the order of 90% pure PVC and flexible PVC is generally of the order of 50% pure PVC. Thus, yields of 0.52 and 0.29 would be used for rigid and flexible PVC respectively. The yields of HCl for other chlorine-containing fuels would be calculated in a similar manner. The keyword is HCL.

6.7.8.6 Hydrogen Cyanide

If hydrogen cyanide is entered as a species, FAST will report the average concentration of hydrogen cyanide in the smoke layer for each room as a function of time. To cause FAST to track hydrogen cyanide enter YES when the prompt HYDROGEN CYANIDE appears. Next enter the yield of hydrogen cyanide at the start of each of the (N) time intervals entered in the description of the fire, plus one for the final value. Separate each entry by a space. A total of (N + 1) entries must be made. An example for a four interval fire is: 0.0 0.02 0.02 0.04 0.0. The keyword is HCN.

6.7.8.7 Total Unburned Hydrocarbons

If total unburned hydrocarbons is entered as a species, FAST will report the average concentration of unburned hydrocarbons in the smoke layers for each room as a function of time. To cause FAST to track total unburned hydrocarbons enter YES when the prompt TOTAL UNBURNED HYDROCARBONS appears. Next enter the yield values at the start of each of the (N) time intervals entered in the description of the fire. Separate each entry by a space and end with the yield at the end of the final time interval. A total of (N+1) entries must be made. The keyword is TUHC.

6.7.8.8 Water Production

If water production is entered as a species, FAST will report the average concentration of water production in the smoke layer for each room as a function of time. To cause FAST to track water production enter YES when the prompt water production appears. Next enter the yield of water production at the start of each of the (N) time intervals entered in the description of the fire plus one for the final value. Separate each entry by a space. A total of (N + 1) entries must be made. An example for a four interval fire is: 0.0 2.0 2.0 2.0 0.0. The keyword is H2O.

6.7.8.9 Optical Density

The optical density (which relates to visibility through smoke) is derived from soot production. Enter the yield of soot generated at the start of each of the (N) time intervals entered in the description of the fire, plus one for the final value. Separate each entry by a space. A total of (N + 1) entries must be made. An example for a four interval fire is: 0.0 0.02 0.02 0.1 0.05. A conversion from soot mass density to optical density in the units of 1/m is automatically made. The keyword for optical density is OD.

6.7.8.10 Concentration-Time Product

Species Ct is used as an indicator of toxicity (see section 6.12.6.2 for a detailed discussion). It is the concentration-time product (actually the time integral of concentration) of the total fuel mass lost during the fire. The fuel mass lost is distributed into the upper layers in the various compartments and is divided by the layer volume to obtain a mass concentration. This mass concentration is then integrated over time to give Ct. The "yield" of Ct is defined as 1.0 for each interval since it represents the total fuel mass lost rather than a fraction thereof. The keyword is Ct.

6.7.9 Output File

This is an optional section. If an output (dump) file is desired for plotting or additional listing the name of that file is specified here. If no file name is specified, the dump interval entered earlier must be a zero. If a non-zero value is entered for the dump interval, a file name must be specified here. It should be remembered that the output file created by one run of the model will be automatically replaced by the next run of the model if the output file name is not changed between runs.

This section will also prompt for a CONFIGURATION file. This will be used in a future version of FAST, but is not used now. Thus, no file name need be entered. But if one is, nothing will happen.

6.7.10 Functions

Function commands are available to the user at any time during program execution, and there are no user prompts for them.

6.7.10.1 Save

The command SAVE is used to save the file being created or edited for use in executing the run with FAST. There is no prompt for SAVE, as it can be entered at any prompt within FINPUT. If SAVE is called and all of the required data for running FAST have not been specified, an error message is printed to the screen which identifies which required parameters have not been specified. After these have been input, SAVE should be called again. SAVE will not let the user save a file under an existing file name (this would overwrite the existing file), nor can a KEYWORD be used as a file name. Again, if such is attempted, an error message is printed to the screen and the user should select a different file name.

6.7.10.2 End

Like SAVE, END has no prompt since it can be entered at any prompt. If the user calls END before the current file has been SAVEd, a message is printed stating that the file has not been SAVEd and "ARE YOU SURE (Y OR N?)". If the user types N, the program will return to the current prompt. If the user types Y, the program ENDs and the current file is lost.

6.7.10.3 Set Units

The call to SET UNITS can be made from any prompt. The current units are presented, and the user can change any of the units by typing the unit desired (the HELP message gives the units available). Any data previously entered are automatically changed to the new units. It is not necessary to change back before saving the file as the program SAVEs all data in the units required by the model. If the user desires to work in english units, it is only necessary to type ENGLISH, and all units are changed. Mixed english and metric are allowed (be careful!). The default units are SI, and not necessarily the most common units for a given parameter. When entering a parameter from a source (or even the data base), be very careful of the units.

6.7.10.4 Change

The call to CHANGE can be made from any prompt. It is used to CHANGE any previously entered, time-dependant data (time intervals, pyrolysis or mass loss rate, species production rate, and height of fuel). When CHANGE is called, the current values for each interval are printed along with a small graph. Each point can then be changed by answering the prompts. After all changes are made, entering a RETURN at the prompt will return to the prompt from which CHANGE was called.

6.7.10.5 Copy

The call to COPY can be made from any prompt. COPY allows the user to copy the dimensions or properties of the walls, ceiling, or floor from any existing compartment to any other. COPY will prompt for the parameter(s) to be copied and the compartment number to copy from and to. The possibilities are DIMENSION to copy width, depth, height or floor height; or WALL, FLOOR, or CEILING to copy the thermophysical properties of each respectively.

6.8 FAST User Information

6.8.1 Introduction

FAST (Fire and Smoke Transport) is a multi-room fire model which predicts the conditions within a structure resulting from a user specified fire. FAST version 17 for the PC can accommodate up to five rooms (within the building) with multiple openings between the rooms and to the outside. The required program inputs are the geometrical data describing the rooms and connections, the thermophysical properties of the ceiling, walls and floors, the fire as a rate of mass loss and the generation rates of the products of combustion. The program outputs are the temperature and thickness of, and species concentrations in, the hot upper layer and the cooler lower layer in each compartment. Also given are surface temperatures and heat transfer and mass flow rates. FAST was written in ANSI/FORTRAN 77.

For a description of the program, the user should refer to A Model for the Transport of Fire, Smoke and Toxic Gases (FAST), NBSIR 84-2934, or A Multicompartment Model for the Spread of Fire, Smoke and Toxic Gases, Fire Safety Journal, Volume 9 May/July, 1985. For a description of the input data, the user should refer to the User's Guide for FAST, NBSIR 85-3284. These reports appear in the appendix to this report.

Several changes have been made to the original program to permit the use of the program on personal computers, however the basic structure of the program remains the same. The input data file remains as described in the User's Guide for FAST.

6.8.2 Program Files

An executable program file is included on the disk. The program will run directly on computers without a FORTRAN compiler. However, it requires an 8087 or 80287 coprocessor. The program files are contributions of the National Bureau of Standards and are not subject to copyright.

All FORTRAN compilers are not the same. As a result, this program may not compile with all versions of FORTRAN on the market. This program has been compiled with Ryan-McFarland FORTRAN version 2.11. The OPEN statements in the source code provided (subroutine INPUTP) have been tailored for the Ryan-McFarland FORTRAN.

6.8.3 Program Use

All programs in HAZARD I are run from a master menu which is obtained by typing HAZARD while in the HAZARDI directory. The desired program is then selected by entering its number as it appears on the list. When completed, the computer will return to the menu.

Two additional inputs have been added to the program. The first asks for an input file name. This is the name of the input data file which has been prepared using FINPUT or other editor. Some word processing editors place special codes within the text and may not be appropriate for this purpose. Detailed information on the data file can be found in A Computer User's Guide for FAST, NBSIR 85-3284 (see Appendix). ALL LETTERS FOR THE LABELS MUST BE IN UPPER CASE.

The second additional input asks for an output file name. This may be any of the operating system reserved device names such as PRN for printer, CON for the screen, etc. It may also be a file name for output to a file. Note that when the output is directed to a file the carriage control codes are printed in column one.

Program execution times for typical data sets are generally on the order of 10-20 times the simulation time. For example a data set specifying 6 minutes of fire simulation could be expected to require from 1-2 hours to run. The sample data set DATA.DAT requires approximately 1.5 hours to run on an IBM XT and 50 minutes on an IBM AT. In general the more complex the data set (e.g., large number of rooms and openings) the longer the run time. There are however, very simple data sets which can result in very long run times (e.g., openings which are large with respect to room size or a rapidly changing fire size).

6.8.4 Sample Input Data File

An input data file containing the test case found in Appendix B of the User's Guide for FAST, has been included on the disk as DATA.DAT. Due to the effect of the computer's internal precision on the solution of the equations and revisions to the program, it is expected that the output from this example will differ from the output listed in Appendix C of the user's guide.

6.8.5 Correction to User's Guide for FAST, NBSIR 85-3284

The input line beginning with VERSN must be the first line in the data file and the line beginning with TIMES must be the second line. The order of these lines may not be reversed. The version of FAST included with HAZARD I is called version 17.5, (although the number in the first line of the input file is still 17), and includes all corrections which previously have been released for FAST version 17.

6.8.6 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 which have been identified include:

1. When the case involves a room (which is not the room of fire origin), with a door which is closed except for a small gap at the bottom (i.e. an undercut), the model may predict a temperature in the lower layer of the closed room which exceeds the upper layer temperature. This is caused by the fact that the initial flow into the closed room (through the undercut) is by expansion of the lower layer gases in the adjacent room. The model has no way to transport these gases to the upper layer until the layer interface at the door drops to the level of the undercut. At this time, the temperatures should correct themselves. The situation may be corrected by including a vertical crack at the door, but sometimes this also does not work. As long as the lower layer temperature is not a great deal higher than the upper layer, the results will not be too far in error. It should also be noted that this is a physically impossible condition, and as such should immediately raise a flag with the user.

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

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

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

5. FAST assumes that there will be a sufficient supply of air to effect complete combustion within the room of fire origin. This can lead to erroneous results (particularly within the room of origin) under conditions involving ventilation controlled burning. At this time, the fire room should have reached a maximum temperature and the products of combustion should be fuel-rich. Here, ventilation controlled burning is defined as where the oxygen entrained into the plume is insufficient to burn all of the fuel and the upper layer has been depleted of its oxygen. Under these conditions, a message is produced on the printer which gives the time at which the ventilation limit was reached, and warns the user that the predicted values which follow may not be valid. Whenever this message appears, it is strongly suggested that the oxygen concentration be plotted (with FASTPLOT) and the values examined to determine how long these conditions lasted. The user should also realize that under these conditions, the properties of an individual material should have a minimum effect on the total hazard posed by a flashed over room and that the conditions in any room open to the fire room will become intolerable in a very brief time.

6.9 Instructions for FASTPLOT

FASTPLOT is a graphing program which runs in conjunction with "FAST". The results for "FAST" are dumped to a special data file after each prescribed time step, which only certain of the programs in the HAZARD I package can read. FASTPLOT has the capability to form a list of variables, read in their values at each time interval, list the values in tabular form, plot the values (hard copy or screen), and save the variables in a formatted file for use with other software.

The FAST model predicts the environment produced by a fire in one of several compartments, or rooms, and follows smoke and toxic gases from one compartment to another. It separately predicts values for each of the variables in both the upper and lower layers.

The list of variables presently available through FASTPLOT are:

AREA.................. burning area of the fire (m^2)
CONCENT................ species density in parts per million
CONV.................. heat loss from layer to solid surface due to convection (kW/m^2)
DOORJT................. buoyant mass flow through a vent (kg/sec)
DOSE.................. species concentration integrated over time (ppm-min)
ENTR.................. mass entrained by a plume (from lower layer to the upper layer)
INTERFACE............. height of the two-zone discontinuity (m)
MASS.................. mass density in a layer (kg/m^3)
MFIRE................. mass loss rate of the fire source (kg/sec)
NEUT1
NEUT2................. neutral planes (maximum of two) for each vent
PLUME................. total mass flow into the plume (kg/sec)
PRES.................. reference pressure at the floor of the compartment (Pa)

QC.................... total convective heat gain by a layer
QF.................... total enthalpy increase from the fire source
QR.................... total radiative heat gain by a layer
RAD................... heat loss from layer due to radiation (kW/m^2)
TEMP.................. temperature of the layer (C)
VENT.................. mass flow through a vent (kg/sec) - bidirectional
VOL................... volume of the upper zone (m^3)
WALLTEM............... temperature of the wall (C)

The CONCENTRATION, DOSE, AND MASS also have associated with them a species number. The species currently tracked and their associated numbers are:

1. NITROGEN
2. OXYGEN
3. CARBON DIOXIDE
4. CARBON MONOXIDE
5. HYDROGEN CYANIDE
6. HYDROGEN CHLORIDE
7. TOTAL UNBURNED HYDROCARBONS
8. WATER
9. SMOKE OPTICAL DENSITY
10. CONCENTRATION-TIME PRODUCT

At specific points in the program, a list of available options is presented to the user. These options are:

ADD
CHANGE
CLEAR
DEFAULT
DELETE
END
HELP
LIST
PLOT
REVIEW
SAVE

Upon running the program, the first input requested will be the name of the dump file to be plotted. Normally it will be of the form:

filename.DMP

Next, the user will be asked to select an option which he wishes to have performed. The following is a description of each of the options available. They are in the order that they usually will be encountered. However, some may be executed before the other without any problems. The minimum number of characters required to recognize and option is enclosed in the parenthesis at the beginning of each word.

6.9.1 (DE)FAULT

This enables the user to set his own default parameters for the following:

COMPARTMENT NUMBER
VENTFLOW DESTINATION
LAYER
SPECIES NUMBER

This option may be done at any time and if is not done the defaults are set to 1, 2, upper, and 9" respectively. The purpose of this option is to change the default available for other commands and data input.

6.9.2 (VA)RIABLES

The purpose of this option is to allow the user to recall the possible variables for use. They will be listed on the screen.

6.9.3 (AD)D

This command is used to build a list of variables to be read into the active list. When an option is requested, ADD may be entered by itself or together with a list of variables that are to be added. If it is entered alone, a message will be printed asking for the variables that are to be added to the list. For example:

```
> ADD
- INPUT VARIABLES TO BE ADDED>
          or
> ADD TEMP,PRES,......
```

For each variable selected there is a series of questions that will be asked to identify the type of that variable wanted. Questions asked about all variables are:

```
WHICH COMPARTMENT? ->
WHICH LAYER? ->
```

If VENTFLOW is chosen the compartment origin and destination will be requested; if CONCENTRATION, MASS, or DOSE are selected the species number of each will be requested.

The maximum number of variables allowed in the active list at any one time is 25. If the list is full or the variable is presently in the active list the addition will be disallowed and another option requested.

6.9.4 (DEL)ETE

When this option is entered the present list of variables will be printed to the screen and the user will be asked to input the variables to delete by the number associated with them on the list. They must be entered on a single line separated by commas or blanks.

If the variable number that is input does not correspond to one that is currently on the list it will be skipped. After the deletions have been processed a new list is presented and another option requested. If the list is presently empty then that fact will be stated in an error message.

6.9.5 (HE)LP

This command may be input at any time that the user is asked for an option. Its purpose is to simply list to the screen, a list of the available commands and a brief explanation; after which another option will be asked for.

6.9.6 (RE)VIEW

At times the user may wish to see what is presently on his list before entering a command. This may be done with the REVIEW command. It will print out the current list along with the compartment number, species, and layer of each of the variables. After the printing of the entire list, the option request is again displayed.

6.9.7 (LI)ST

After variables have been added to the list and their data values read in, the user may list the values of any of the variables on the list to the screen. After entering the (LI)ST command, the variables presently in the list will be displayed. The user will then be asked to input the corresponding number(s) of the variable(s) to be listed. They must be entered on a single line separated by commas or blanks. The maximum number of variables which can be listed at one time is 5. After the list appears on the screen, it can be printed with the PRINT SCREEN key.

6.9.8 (PL)OT

After entering the PLOT command, the current list of variables will be displayed along with their numbers. The user will be asked to input the numbers of the variable(s) to be plotted from the list. They should be entered in a string separated by commas or blank spaces. For example:

```
ENTER VARIABLES TO BE PLOTTED ->1,2,3,4
          or
ENTER VARIABLE TO BE PLOTTED ->1 2 3 4
```

Variables to be plotted together on a single graph are grouped in parentheses. For example:

```
ENTER VARIABLES TO BE PLOTTED -> (1,2,3,4)
```

When plotting on the screen, only one graph at time should be made in this manner. With the addition of appropriate device drivers, the program will drive plotters with multiple graphs per page.

Before the graph is drawn, the user is given the opportunity to change the range of the X and Y axes. The maximum and minimum value of the X and Y axes will be displayed, followed by a request for a change in each, which will be of the form:

```
CHANGE (X or Y) AXIS TO? ->
```

If no change is desired simply enter a <RETURN> and the next axis change will be displayed. If a change is made, the value will be entered and the same change request will be made again. This will be repeated until a <RETURN> is entered.

When all the changes have been made (if any) the graph of that particular variable will be plotted. After the graph has been completed the option request will be displayed and a new option may be entered.

6.9.9 (SA)VE

This option allows the user to save the values of the variables in the list in a file. The format used will make the data directly compatible with an data processing program (RAPID)[1] designed for the reduction of experimental data in the Center for Fire Research, or with other programs after editing or reformatting as needed.

The user will be asked for the name to be used for the file. A check will be made to see whether that file presently exists or not. If it does, the user will be asked if he wants to write over the old file with this new data. If his answer is NO, nothing will be placed in the file and other option requested. If, however, he does want the file rewritten, or the file does not already exist, the new file will be created and the data stored in it.

Each variable in the list will be saved with the following format at the beginning of each block of data:

I6,I6,A6,*-----------COMMENT----------

The first I6 will be for the number of data points for that variable, the next I6 is for the number given to that variable on the list, and the A6 is the actual variable name. Everything after the * is a comment block and will be filled with information relevant to that particular variable, such as species number, compartment number, layer, etc. The actual numerical data will be written using the format 7E11.5.

6.9.10 (CL)EAR

The input of this command empties the current variable list.

6.9.11 (CH)ANGE

This option restarts the program by asking for a new file and resetting all variable lists.

6.9.12 (EN)D

This function terminates the execution of the FASTPLOT program.

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[1] Breese, J. N. and Peacock, R. D., A Users Guide to RAPID, Reduction Algorithms for the Presentation of Incremental Fire Data, NBS Special Publication 722, National Bureau of Standards, Gaithersburg, MD. 20899 (1986).

6.10 Instructions for DETACT-QS

6.10.1 Introduction

DETACT-QS is a BASIC program to predict the response of thermal detectors to fires of arbitrary heat release rate (see Appendix C). It is an interactive program where the user answers questions to input the data, and the results are presented in tabular form. Any user familiar with the calculation procedure described in Appendix C of ANSI/NFPA 72E should have no problem with this program as the procedures are similar. The questions asked are as follows:

1. HEIGHT OF CEILING ABOVE FUEL (METERS) - This is not the floor to ceiling height, but rather the distance from the top surface of the burning object to the ceiling.

2. DISTANCE OF DETECTOR FROM AXIS OF FIRE (METERS) - This is the radial distance to the detector from a point directly above the fire.

3. INITIAL ROOM TEMPERATURE (CELSIUS) - The room ambient temperature.

4. DETECTOR ACTIVATION TEMPERATURE (CELSIUS) - The temperature rating of the device.

5. DETECTOR RESPONSE TIME INDEX (RTI) - For sprinklers, this is now often given in the manufacturer's catalog. For fixed-temperature heat detectors, table 6-19 gives RTI values corresponding to UL spacings. For rate-of-rise detectors, table 6-20 gives RTI values for three rate-of-rise settings (NOTE: 15 F/min would be the normal threshold rate used).

6. RATE OF HEAT RELEASE - The rate of heat release of the fire (which can be obtained from the FAST run with FASTPLOT by LISTing the variable QF) is entered one point at a time by answering the questions TIME (SEC) and HEAT RELEASE RATE (kw) starting with time=0. When the last desired point is entered, the user enters a -1 value for time, which stops the request for data. The results are then sent to the printer (or the screen if the user answers the question SEND OUTPUT TO PRINTER? with a N) in tabular form.

TABLE 6-19 RTI VALUES FOR
FIXED-TEMPERATURE HEAT DETECTORS

UL Listed Spacing (ft)	UL Listed Activation Temperature 128 F	135 F	145 F	160 F	170 F	196 F	All FM Listed Temps.
10	894	738	586	436	358	217	436
15	559	425	349	246	199	101	246
20	369	302	235	157	116	38	157
25	277	224	174	107	72	---	107
30	212	179	136	81	49	---	81
40	159	128	92	40	---	---	---
50	132	98	67	---	---	---	---
70	81	54	20	---	---	---	---

NOTE: These RTI's are based on an analysis of the Underwriters Laboratories (UL) and Factory Mutual (FM) listing test procedures. Plunge test results on the detector to be used will give a more accurate response time index.

TABLE 6-20 RTI VALUES FOR
RATE-OF-RISE HEAT DETECTORS

Listed Spacing (ft)	UL Listed Activation Rate of Temp. Rise 15 F/min	20 F/min	25 F/min
10	1834	1308	984
12.5	1453	1073	805
15	1185	872	637
20	872	581	425
30	559	380	280
40	447	291	206
50	425	246	161

6.11 Simulation of Occupant Decisions and Actions

6.11.1 Introduction

The HAZARD I 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 the fire. The model is called EXITT (since the word exit is reserved in most computer operating systems).

The EXITT model is designed to be easily used. It does not require the user to be trained in the use of the program nor to be knowledgeable about computer languages. The user controls the model by answering simple questions that appear on the screen.

The fires, buildings and occupants that are modeled can come from three sources: (1) Three buildings, each with two or more fires, are stored in the files supplied; (2) The user can add an additional building or fire by adding information about the specifics of the building or fire to the computer programs that are reserved for that purpose; and (3) The user can define a building and/or fire by answering a large number of simple questions appearing on the screen.

6.11.2 General Nature of the Model

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 a narrative of the occupants decisions as they are assigned by the computer, e.g., "OCCUPANT 3 WILL START LOOKING FOR THE SOURCE OF THE SMOKE AT 30 SECONDS (THAT IS 5 SECONDS FROM NOW). It also creates a file of occupant locations over time which is used by other programs in HAZARD I.

The building is represented within the computer by: instructions that will draw the building on the computer's monitor; 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. The computer will print the occupants movements as they are determined by the computer, e.g., "OCCUPANT 3 ARRIVED AT NODE 15 IN ROOM 7 AFTER 32.7 SECONDS".

The occupants also complete actions in addition to arriving at nodes. These are also printed, usually in conjunction with other information, e.g., "OCCUPANT 3 STOPPED INVESTIGATING WHEN SEEING FLAME OR MODERATE SMOKE. OCCUPANT 3 ARRIVED AT NODE 19 IN ROOM 4 AFTER 61.2 SECONDS".

Occupants move within the building from node to node. The path assigned is largely based on a shortest path algorithm. The path is also based on smoke conditions and exit doors are preferred to windows.

All the decision rules programmed in the computer are designed to make the decisions as similar as possible to decisions that building occupants would make. To the degree that time permitted, the decision rules were based on the relevant research literature. Of course, future versions will make better use of the literature and should have improved decision rules. Now that this version is completed and being distributed, it will be possible for other researchers to make suggestions that will contribute to improving the model.

6.11.3 Current Status of the Model

The current early version of the model has been used in demonstrating the Hazard Assessment Method. Future versions will have improved decision rules and improved validation of those rules. Despite the limitations of using an early version, 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.

The user should be aware of the limitations of the current model. These limitations include:

1. The model is deterministic. Only typical behavior is modeled: aberrant behavior is not permitted.

2. The model has not been used previously: this is its first "field test".

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

4. The computer code is very large and some significant "bugs" may remain in the program. These must be corrected as they are identified.

5. Data entered through the keyboard are not permanently stored. It will all be lost when the computer run is completed.

6.11.4 User Options

The program is written to allow many options. These include:

1. Using building stored in the program or designing own building;

2. If using building stored in program, selecting one of several fire scenarios or providing own fire scenario by answering questions on the screen;

3. Printing results on printer for a permanent record;

4. Printing extensive or minimal information on the screen;

5. Overriding some computer assignments of decisions;

6. Assigning times for the smoke detectors to work rather than letting the computer calculate the time based on smoke conditions.

These options are all selected through answering questions on the screen.

The number of options available will be curtailed if the user answers the following question affirmatively, "IS THIS YOUR FIRST EXPERIENCE WITH THIS PROGRAM?" Getting familiar with the program should be easier with fewer options available.

More extensive instructions are included in the users manual in Appendix B. However, it is suggested that the user experiment with the program before intensive studying of the users manual. It is not recommended that the user design his own building through keyboard entries for practical use of the model because in this early version of the model information entered through the keyboard is not permanently stored. It is suggested, however, that the user enter a very small building through the keyboard to gain an appreciation for the necessary data inputs.

The User's Manual describes how to enter an additional building of the user's choice permanently into the model. This is not difficult but it is very time consuming because of the large amount of data and information that must be very carefully entered.

6.11.5 Fire Inputs

The program is designed to use the output of the FAST model for distributing smoke throughout the building. The fire/smoke conditions that are stored in the program are all from the outputs of the FAST model. In this early version, there is no provision for directly connecting with the output of FAST: the printed output of FAST is used and entered into the EXITT program.

6.11.6 Model Outputs

The program provides outputs in three formats:

1. A description of the decisions and movements of the occupants is printed on the screen as the simulation progresses. There will be frequent pauses to permit the user to read the text on the screen: the user can end each pause and permit the simulation to continue by pressing the return key.

2. A description of the decisions and movements of the occupants can be printed on the printer. Once the program starts, the first question posed to the user is, "DO YOU WANT TO USE YOUR PRINTER?"

3. A record of the movements of the occupants can be stored on the hard disk. The information recorded on the disk is designed to be used as input to program TENAB which determines the hazard for each occupant according to the room conditions encountered along the escape route. The model provides this output only when the program is in the C disk drive, that is, on the hard disk.

6.12 Tenability Limits

6.12.1 Introduction

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

For most hazard calculations, it can be assumed that the individual at risk is a "healthy" individual. Even this, of course, is an indistinct concept, since endurance limits for healthy individuals are not identical for various threats. In most cases, only animal data are available. Thus, the assumption is made that the response of the healthy individual can be represented by a well-chosen animal model. Also, there is almost no information on the sub-lethal response of humans, or, indeed, of animals, to fire situations. In many instances it would be more appropriate to ask not if the fire atmosphere is, by itself, lethal, but, rather, is it sufficient to introduce confusion, narcosis, or such strong irritancy that the individual will no longer act to rescue himself. At the University of Pittsburgh, studies of the sub-lethal effects of carbon monoxide (CO) currently are being conducted [1]; but have not yet resulted in conclusions on appropriate limits for such exposures.

6.12.2 Flashover

Flashover is a perceived event which can be denoted by any of a number of interrelated phenomena which can occur simultaneously during the course of a serious building fire. These include the reaching of temperatures of 500°C to 700°C in the upper portions of the room [2,3,4]; the reaching of a heat flux of 25 kW/m^2 at the floor level, with the near-simultaneous ignition of combustibles not previously ignited [5,6]; the filling of almost the entire room volume with flames [7]; and the dropping of oxygen levels to low values, typically 5% or less [8]. When flashover is reached in a room, habitability is completely precluded, due to high temperatures, high heat fluxes, low oxygen, and high concentration of combustion products. Tenability will generally be precluded at conditions prior to flashover; nonetheless, it is important to emphasize that room flashover is an easily calculable time at which it is definitely known that tenability is no longer possible. 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.

6.12.3 Temperature

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

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

$$t = 2.46 \times 10^{10}/T^{3.61} \qquad (1)$$

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

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

The permeability and insulating value of the clothing worn can also have a significant effect on the ability to withstand elevated temperatures. For long exposures (> 30 minutes), extensive experimental data are available [e.g., 18]. Similar data have not been obtained for short exposures, such as may occur in building fires, however. In previous fire hazard evaluation recommendations, the tenability values for brief exposures at face level ranged from 65°C [19] to 100°C [20]. Based on these references, we are suggesting the use of temperatures of 50°C as a threshold of severe discomfort, 65°C as an incapacitating level, and 100°C as a lethal exposure, for short times. As will be discussed in the next section, the output of the program TENAB provides a simple sensitivity analysis of this, and all tenability criteria selected.

6.12.4 Heat Flux

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

From heat transfer studies, Henriques [21] 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 $\Omega \geq 1$.

$$\Omega = 3.1\times10^{98} \int_o^t e^{-75,000/T}\, dt \qquad (2)$$

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

Hendler [22], meanwhile had made measurements of the thermal properties of human skin, and reported data on the spectral reflectance of human skin, both white and black, over the spectral range of 0.4 to 20 μm. He also obtained an experimental value for $k\rho C$ = 111 ±8 $\times10^{-5}$ $cal^2/cm^4/C^2/s$. Stoll [23], however, concluded that the $k\rho C$ of human skin varies according to irradiance, changing from 96 to 159 as the irradiance was quadrupled. She also determined that a more complex expression than Henriques' Ω value may be more realistic.

Stoll and coworkers [23,24,25] and Derksen and coworkers [26] have over the years collected a large amount of experimental data, some of which are summarized in Table 6-21. Table 6-21 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 [25] also gives data for pain thresholds, and shows that both pain and blistering can be very well represented as power laws:

<u>Pain</u>

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

<u>Burn</u>

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

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

Table 6-21

Time required to blister or burn blackened skin

Stoll/Greene [23]		Stoll/Chianta [25]			Derksen/Monahan/deLhery [26]		
Time (s)	Flux (kW/m²)	Time (s)	Flux (kW/m²)	Tot. heat (kJ/m²)	Time (s)	Flux (kW/m²)	Tot. 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.	29.3	58.6
		3.	25.1	75.3			
					5.	13.38	66.9
		5.6	16.7	93.7			
		7.8	12.55	97.9			
8.6	12.55						
					10.	9.2	92.0
		13.4	8.37	112.2			
					20.	6.06	121.3
		20.8	6.28	130.5			
24.4	6.28						
		33.8	4.18	141.4			
37.2	4.18						
					50.	3.10	154.8
					100.	2.13	213.4

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

Pain

$$H = 26.8\ t^{0.26} \tag{5}$$

Burn

$$H = 54.7\ t^{0.26} \tag{6}$$

In assessing the capability to withstand pain, the experimental data and the derived equations above are all for relatively short times of exposure to constant flux levels. For longer exposures, some older experimental data indicate that heat flux values of 2.5 kW/m^2 can be tolerated for 3 minutes without reaching unbearable pain and that this value does not change appreciably for longer times [27-30]. By comparison, some 1943 Japanese data reported by Hasemi [31] showed that an asymptotic value is not quite reached even at 30 minutes. From 3 minutes to 30 minutes, however, the fluxes endured in the Japanese study changed only from 2.9 kW/m^2 to 2.1 kW/m^2, thus indicating general agreement to the 2.5 kW/m^2 limit derived from U.S. studies. This value has been used as a tenability criterion for some time [5,20], and can be used for evaluation purposes. The appropriate height for evaluation will normally be at face level.

For evaluating burn injuries, in work on protective clothing, researchers [32] have employed a direct comparison of the time-integrated flux exposure of exposed skin to the relation in equation (6). The time at which the time-integrated flux exposure curve intersects the curve from equation (6) is assumed to define the occurrence of second degree burns, representing the point of irreversible cell damage requiring grafting.

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

6.12.5 Smoke Obscuration

The setting of limiting values for smoke obscuration is very difficult. Unlike temperature, heat flux, or toxic gases, visibility obscuration is not, itself, lethal. A hazard results only if the reduction in visibility prevents required escape activity. This restriction of escape activity is crucial, however, and thus smoke production has, in fact, been regulated longer than any other product of combustion [33]. The most significant body of work in this area has been due to Jin [34,35], who found that there is an approximate reciprocal relationship between smoke and visibility distance (the distance at which a person can identify an exit sign), according to:

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

where k = smoke extinction coefficient (m^{-1}), and V = visibility distance (m). While this relationship permits visibility to be estimated, further data are needed to set criteria values. Jin conducted experiments where the walking speed of individuals exiting buildings was measured as a function of smoke levels, and compared to the exiting speed for blindfolded subjects. For "non-irritating" smoke the walking speed of the subjects dropped to the blindfolded speed when a value of $k = 1.2\ m^{-1}$ was reached. For "irritating" smoke, the comparable figure was $k = 0.5\ m^{-1}$. Irritancy in Jin's experiments was not well-quantified; for the purposes of setting limit values, it may be appropriate to select $k = 1.2\ m^{-1}$ as the limit. This limit also corresponds to a visibility of 1.67 m by the relationship above, which appears to be a reasonable distance to see a room door in a residence, or the edge of a hallway. In some cases in the literature a much more stringent criterion, typically $k = 0.5\ m^{-1}$, has been selected [20,36].

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

6.12.6 Toxic Gases

Studies on the causes of fire deaths have typically indicated that CO poisoning accounts for roughly one-half of total fatalities [37,38]. The remaining half is accounted for by direct burns, explosive pressures, and various other toxic gases. Although the analysis of blood cyanide (which would come from exposure to hydrogen cyanide) in fire victims is sometimes reported in autopsy data, blood carboxyhemoglobin saturation, resulting from exposure to CO is often the only data provided. This provides no information on the potential effect of other toxic gases on the lethality. Nonetheless, a significant emphasis on studying other toxic gases is placed by most research organizations in this field, due to the fact that high hazards may exist from additional combustion products whose presence is suggested by the decomposition chemistry, although not necessarily confirmed by medical evidence. Table 6-22 lists, in order of increasing estimated toxicity, those primary gases which have been suggested by various investigators as being potentially significant in fire situations. Human data are in most cases unavailable, and even primate data are rare. The tabulated values represent the estimated LC_{50}'s (in ppm), i.e., those concentrations which would be lethal to 50% of the exposed subjects for the specified time. Data on the combined effects are, as yet, rare, inconsistent, and insufficient for a general tabulation [39,45-55].

Table 6-22

Preliminary List of Primary Toxic Gases

Gas	Assumed LC_{50} (man) 5 min	Assumed LC_{50} (man) 30 min	Ref. No.	Reference data (species, mins.)
	(in ppm)			h=man r=rat m=mouse p=primate gpg=guinea pig
CO_2 carbon dioxide	>150,000	>150,000	[39]	r
C_2H_4O acetaldehyde		20,000	[40]	LC(m,240)=1500 LC_0(r,240)=4000 LC(ham,240)=17,000
			[41]	LC(r,30)=20,000 LC(r,240)=16,000
$C_2H_4O_2$ acetic acid		11,000	[40]	LC(m,60)=5620
NH_3 ammonia	20,000	9,000	[42]	EC(m,5)=20,000 EC(m,30)=4400
			[43]	EC(r,5)=10,000 EC(r,30)=4000
$HC\ell$ hydrogen chloride	16,000	3,700	[44]	r,p
			[45]	LC(r,5)=40,989
CO carbon monoxide		3,000	[39]	LC(r,30)=4600
			[46]	LC(h,30) 3000
HBr hydrogen bromide		3,000	[40]	LC(m,60)=814 LC(r,60)=2858
NO nitric oxide	10,000	2,500	[41]	1/5 as toxic as NO_2
				LC(h,1) 15,000
COS carbonyl sulfide		2,000	[40]	LC_0(var.,35-90)=1000-1400
H_2S hydrogen sulfide		2,000	[40]	LC(m,60)=673 LC_0(h,30)=600 LC_0(mam,5)=800
			[46]	LC(h,30) 2000
HF hydrogen fluoride	10,000	2,000	[40]	LC(gpg,15)=4327 LC(p,60)=1774 LC_0(h,30)=50
				LC(m,60)=456 LC(r,60)=1276
			[45]	LC(r,5)=18,200
			[46]	LC(gpg,2)=300 LC(m,5)=6247 LC(r,5)=18,200
C_3H_4N acrylonitrile		2,000	[40]	LC(gpg,240)=576 LC(r,240)=500
COF_2 carbonyl fluoride		750	[41]	LC(r,60)=360
NO_2 nitrogen dioxide	5000	500	[42]	EC(m,5)=2500 EC(m,30)=700
			[43]	EC(r,5)=5000 EC(r,30)=300
			[45]	LC(m,5)=831 LC(r,5)=1880
C_3H_5O acrolein	750	300	[40]	LC(m,360)=66 LC_0(p,10)=153
			[47]	LC(p,5) 505 to 1025
CH_2O formaldehyde		250	[40]	LC_0(r,240)=250
			[46]	LC(r,30)=250 LC(r,240)=830(??)
			[41]	LC(cat,480)=700 LC(m,120)=700
SO_2 sulfur dioxide	500		[40]	rodents poor; LC_0(m,300)=6000
			[46]	LC(var.,5) 600 to 800
HCN hydrogen cyanide	280	135	[48]	LC(r,5)=570 LC(r,30)=110
			[45]	LC(r,5)=503 LC(m,5)=323
			[46]	LC(h,30)=135 LC(h,5) 280
$C_9H_6O_2N_2$ toluene diisocyanate		≃100	[40]	LC(gpg,240)=13 LC(rbt,180)=1500
				LC(r,360)=600 LC(m,240)=10
			[46]	LC(m,r,rbt,gpg,240)=9.7 to 13.9
$COC\ell_2$ phosgene	50	90	[40]	rec. 50 ppm short exp.
			[49]	LC(h,30) 90
C_4F_8 perfluoroisobutylene	28	6	[40]	LC(r,10)=17 LC(r,5)=28

Notes: EC - concentration for effect
LC0 - concentration at which first 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% [46]. Exposure to decreased oxygen levels alone is very unlikely in fire, however. More commonly expected is some diminution in oxygen levels (although it can be argued that any significant reduction in oxygen is always accompanied by temperatures in excess of survivable levels), together with the presence of CO, CO_2, and other toxic species. Such combinations have, in general, not been explored, although a few experimental points are available [48]. Currently, the potential effects of reduced oxygen are not addressed in either the FED or Ct parameters discussed below.

Toxicity from fire atmospheres can result not only from gases, but also from solid aerosols, or from material adsorbed onto soot particles. Data in this field are almost non-existent [56].

6.12.6.1 Fractional Effective Dose (FED)

Researchers at CFR [57] and at the Southwest Research Institute (SwRI) [58] have been exploring the hypothesis that the observed effect of the exposure of animals (and humans) to the products produced by burning materials can be explained by the impact of a small number of the gases actually released during combustion. That is that, while there are hundreds of compounds that can be identified, the effect is caused by only a few (N), key gases. By investigating the effect of exposure to these key gases, singly and in combination, a predictive model can be constructed. Thus, this model is referred to as the N-Gas model.

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

The first version of such a model has been derived from the pure gas studies of Levin, _et al._, and Hartzell, _et al._ [57,58]. It includes the three gases CO, CO_2, and HCN, combining their effect in a parameter called Fractional Effective Dose (FED) which is dimensionless and is defined as lethal at a value of one. The hypothesis of FED states that the total observed effect equals the sum of the effects of each of the component parts. That is, if one receives 50% of the lethal dose of CO and 50% of the lethal dose of HCN, a lethality will occur. This has, in fact, been demonstrated by Levin, _et al._, for these two gases [48]. Simply stated then, FED is the sum of the effects of each of the gases toward the total effect on the exposed person.

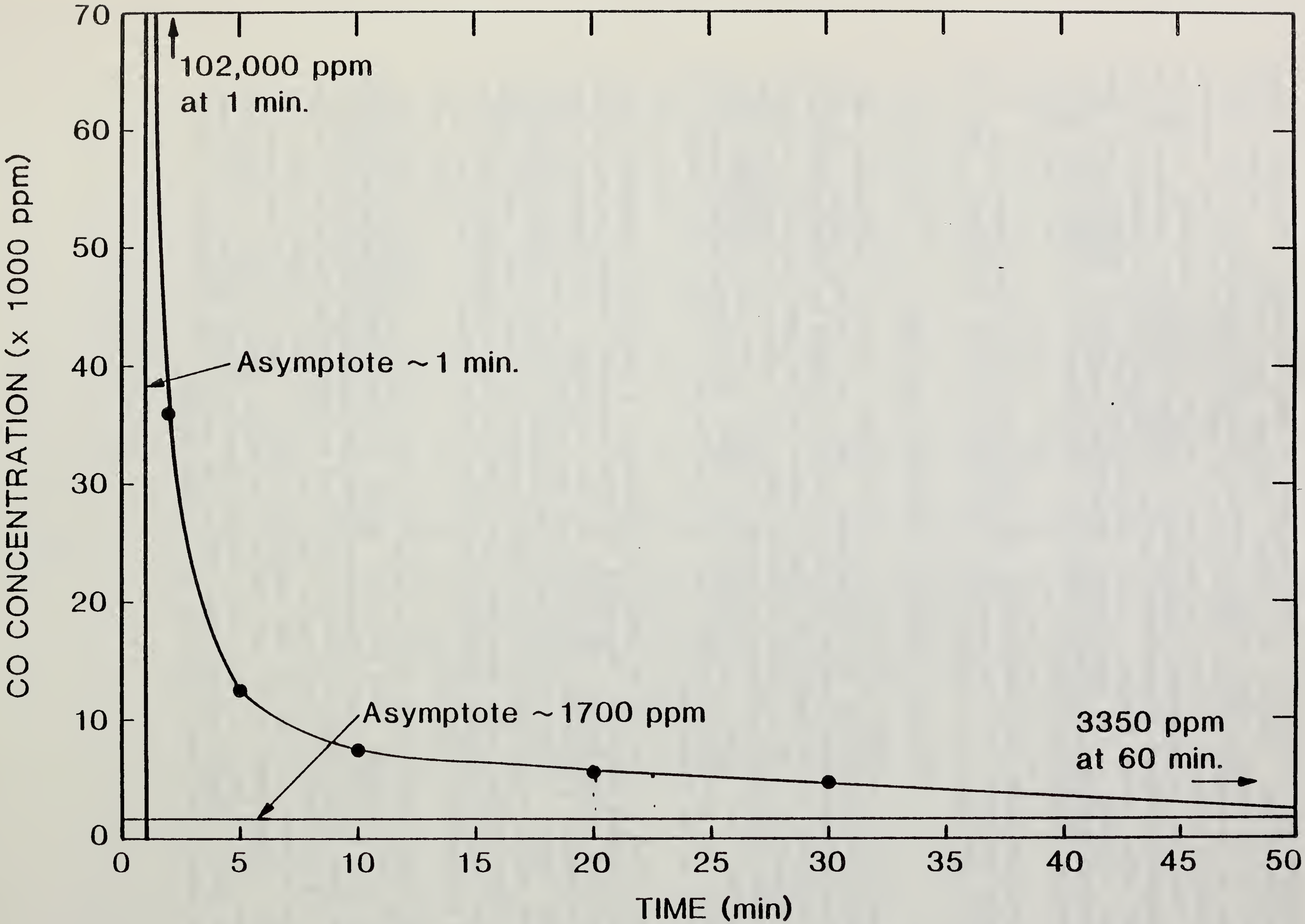


FIG. 6-13 CARBON MONOXIDE CONCENTRATION vs. TIME TO LETHALITY OF 50% OF EXPOSED RATS

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. 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 6-13), shows that the curve has two asymptotes; an exposure time (about 1 min) below which no effect is seen for any concentration, and a concentration (about 1700 ppm) below which no effect is seen for any time. In the former case, this would represent such physiological effects as breath holding and the time required for the gas to be transferred to the blood and then to the tissues. In the latter case, this represents an exposure concentration for which the equilibrium concentration of COHb in the blood is below the level which causes a lethality [48].

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

$$(C_{co} - 1700)t = 80000 \quad (8)$$

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

The FED concept states that the effect is the dose received (dose is the time integral of the concentration) divided by the critical dose to produce the effect. As shown in figure 6-13, the critical dose is not constant, but rather varies with concentration. Thus, equation 8 is used within the FED calculation to determine the critical dose at the particular incremental concentration (see figure 6-14 [48]).

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 6-15 [39]) was the observation that the "effective toxicity" of CO increases linearly with increasing CO_2 concentration, doubling at a level of 5% (50000 ppm). The physiological effects of the CO_2 are to increase the respiration rate and reduce the blood pH, producing a metabolic acidosis.

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

$$[100,000 - C_{co_2}/100,000] \quad (9)$$

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

Finally, HCN and the combination of CO and HCN were studied. The data on HCN [59] showed that the lethal dose (time-integral of concentration) was relatively constant at a value of 3100 ppm-min for exposure times from 2 to 30 min. Thus, this value is used in the HCN term of the FED calculation. The data on CO and HCN combinations showed that the effects are directly additive [48] (again for 30 min exposures). This is not surprising since they both act to reduce the transfer of oxygen to the tissues; CO by tying up the hemoglobin so that it cannot carry the oxygen, and HCN by preventing the utilization of the oxygen by the tissues.

The resulting equation for FED, which represents the current N-Gas model (N=3) is as follows:

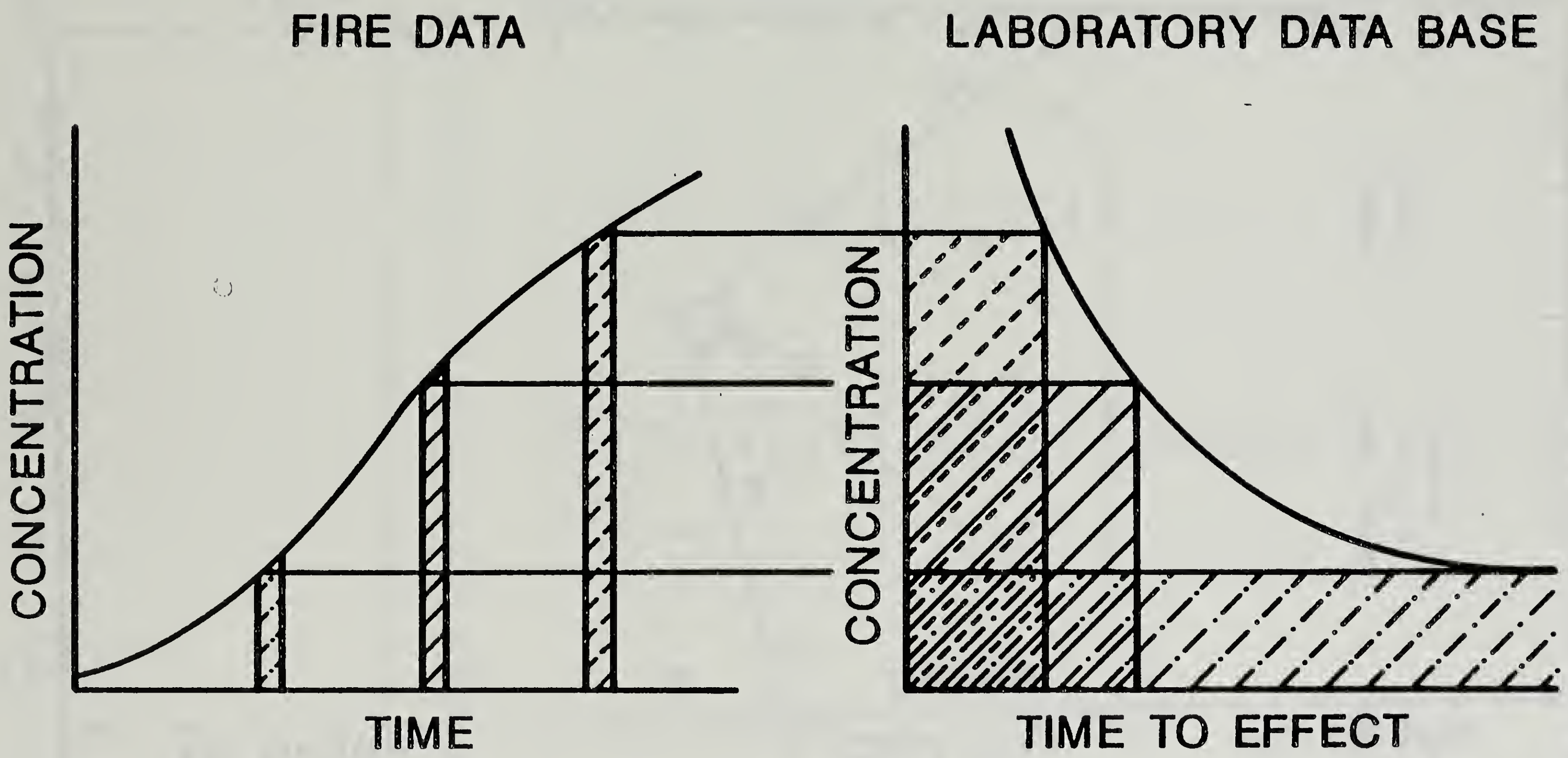
$$FED = \sum \left\{ \frac{\bar{C}_{CO}\,\Delta t}{\bar{C}_{CO}\{80{,}000/(\bar{C}_{CO} - 1700)\}\ \{(100{,}000 - \bar{C}_{CO_2})/100{,}000\}} + \frac{\bar{C}_{HCN}\,\Delta t}{3100} \right\} \qquad (10)$$

where $\bar{C}_{co}$, $\bar{C}_{co2}$, and $\bar{C}_{HCN}$ are the average concentrations over the time interval (ppm) and Δt is the length of the time interval (min).

The predictive capability of equation 10 was tested against the material toxicity data included in the NBS Toxicity Screening Protocol report [60]. First, the average gas concentration data provided in the report was used, assuming a constant value throughout the 30 min exposure period (i.e. a square-wave exposure). The equation successfully predicted the observed results of 14 materials, with two more within 10%. Levin proposed an equation for predicting the interactions of these same gases for 30 minute, square-wave exposures only [48], which successfully predicts the results of the same 16 materials plus flaming red oak. The reason for equation 10 falling 30% short on red oak is currently unclear.

Next, the exposure time-independent nature of equation 10 was tested against the data reported by Hartzell, et al., for two ramped exposures to CO only [61]. 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.

MODELING OF TOXICOLOGICAL EFFECTS OF FIRE GASES



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

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

FIG. 6-14 FRACTIONAL EFFECTIVE DOSE

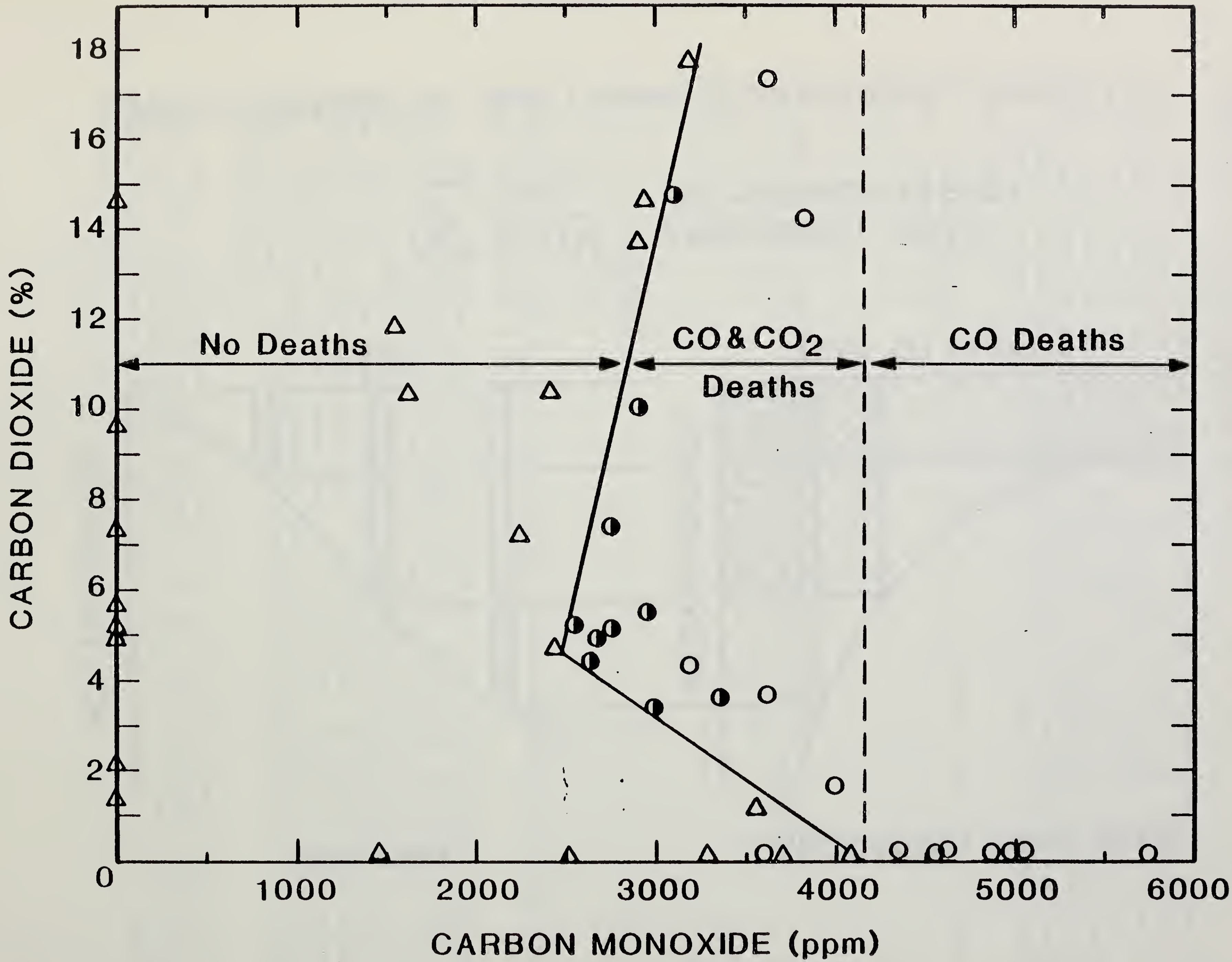


FIG. 6-15 COMBINATION OF CARBON MONOXIDE AND CARBON DIOXIDE WHICH IS LETHAL TO 50% OF EXPOSED RATS

Table 6-23
Predictions from Average Gas Concentrations

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

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

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

Table 6-24

Prediction of Ramped CO Exposure

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

Table 6-25

Prediction from Time-Varying Gas Concentrations

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

Since the gas data reported in the NBS report were averages over the 30 minutes while, in fact, they increased exponentially over some finite time in the experiment, the actual gas analyzer data from the tests of four materials were obtained and input into the equation. The results showed that, for materials which produced only within-exposure fatalities (except MOD,NF), the predicted FED reached unity (lethal) at 30 min. For materials which produced some or all post-exposure fatalities, the predicted FED reached unity earlier, in some cases, as early as 10 min. This would indicate that this is the time at which a lethal dose was received, even though the death occurred later. The details of these comparisons are provided in tables 6-23 to 6-25.

6.12.6.2 Species Ct

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

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 [62]. The concept of Ct evolved from the NBS Toxicity Screening Protocol [60] 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:

$$Ct = \int_0^t Y \rho \, dt$$

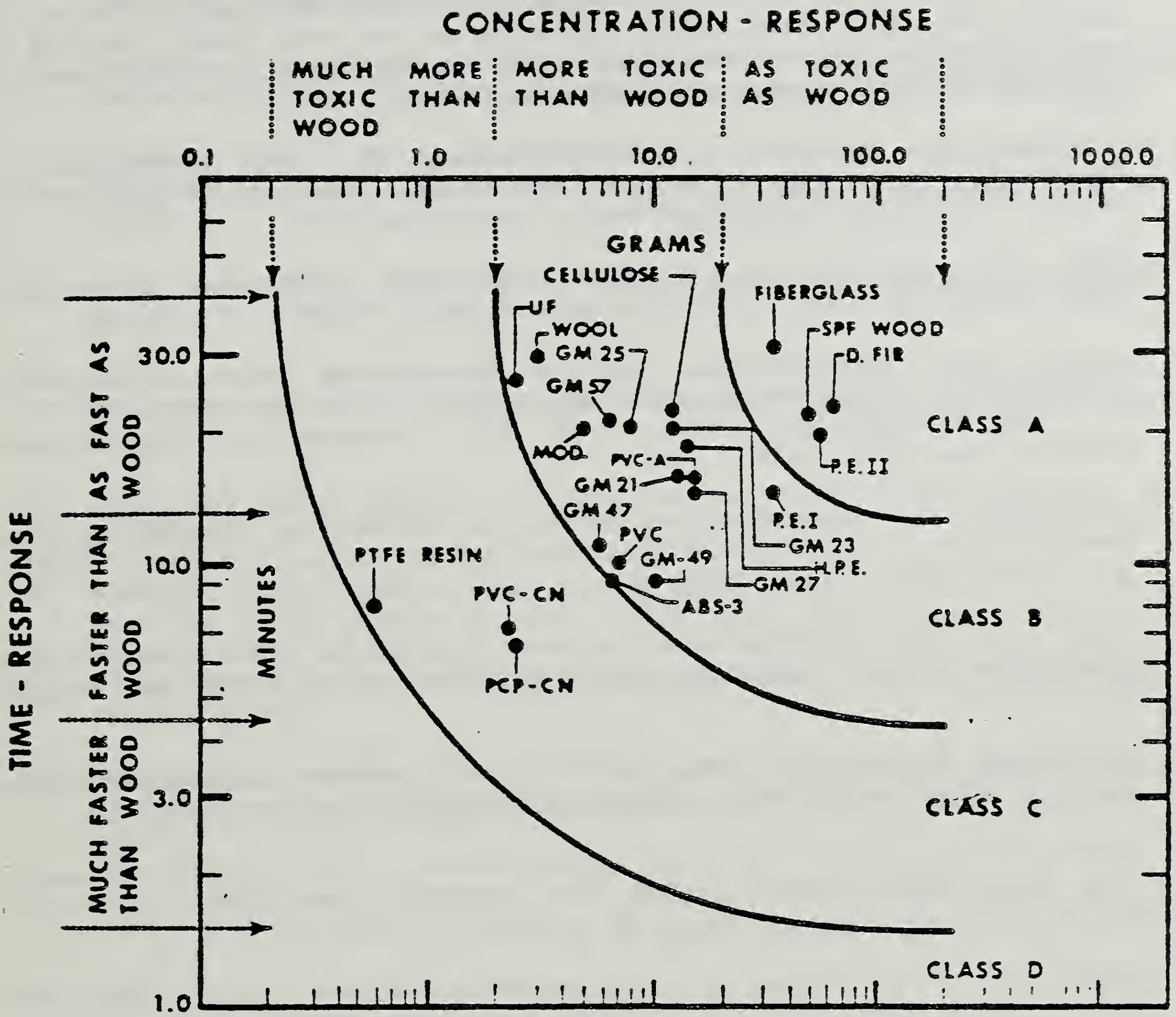
Where $f_i = 1$ in the equation of section 6.6.2 and Y is the corresponding mass fraction of the layer and ρ is its density.

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 [63].

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 ten (fig. 6-16 [64]). 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 ten (e.g. for a material one class more toxic, use a value of 90 for the lethal level).

6.12.6.3 Incapacitation

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 suggested that values of 1/3 to 1/2 of the lethal values of FED and Ct be used as incapacitation indicators [65] 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.



Each point represents the amount of material (gram on the X axis) which produced sufficient smoke to kill 50% of the animals (LC50) and the time (minutes on the Y axis) required to kill 50% of the animals (LT50) using that amount of material. Reading the graph vertically each material is classified in terms of potency while each material is classified in terms of onset of action by reading horizontally. To combine both, parallel quadrants separate class A, B, C, and D.

FIG. 6-16 EXAMPLE OF A TOXICITY GRADING SCHEME BY ORDER OF MAGNITUDE OF OBSERVED EFFECT

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6.12.7 Program TENAB

6 12.7.1 Introduction

The FORTRAN program 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 BASIC program EXITT, determines for each occupant of a burning building the optimal escape route according to knowledge about occupant behavior and building layout. The purpose of TENAB is to estimate the hazard for each occupant according to the room conditions encountered along the escape route. The hazard is assessed by determining the fractional effective dose of gases (FED), the flux (FLUX), integrated concentration-time product (Ct) and the temperatures (TEMP) to which each occupant is exposed. When any of the hazards exceed certain limits, then the occupant is considered either incapacitated or dead.

The first section discusses the general logic underlying TENAB. The second section discusses how the various hazards are computed and the third section briefly describes the output generated by TENAB.

6.12.7.2 Logic

From EXITT, TENAB obtains for each time step, 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 room of the building. At each time interval, (t_{i-1}, t_i), TENAB determines for each occupant of the building the current room being occupied and the layer (upper or lower) to which the occupant is being exposed. From this information, the average layer (upper or lower as appropriate) temperature of the room, the fractional-effective dose, the flux and integrated concentration-time product are computed. If the FED, Ct, or temperature for a particular occupant exceed certain "critical" incapacitation or lethal levels (which can be supplied by the user), then the occupant is deemed incapacitated or killed by the appropriate cause. If the flux at time t_i seconds exceeds the corresponding Derksen Curve value then the occupant is deemed incapacitated. When an occupant exits the building or becomes incapacitated or dead, the program records the time, the room, the occupant's condition (incapacitated, dead, or alive), the cause (if applicable) and the levels of FED, Ct, flux and temperature. At the final time (the end of the simulation), the program records for each occupant, the final time, the room occupied at the final time, and the levels of FED, Ct, flux, and temperature. The program then prints out the information on each person to a disk file, the screen, or the printer.

6.12.7.3 Computation of FED, Ct, Flux and Temperature

A discussion of the selection of the critical values used and the derivation of the equations for FED and Ct are contained in the section of this report titled Tenability Limits.

$ACCUMCT_k(t_i)$	:	The total integrated-time concentration accumulated by person k by time t_i (g-min/m^3)
$ACCUMFLUX_k(t_i)$	:	The total accumulated flux to which person k has been exposed by time t_i (KW-min/m^2)
$AVGTEMP_k(t_i)$	:	The average temperature person k is expose to at time t_i (degrees Centigrade)
CO(room,t_i,layer)	:	Amount of carbon monoxide at time t_i in a particular layer of a particular room (ppm)
CO_2(room,t_i,layer)	:	Amount of carbon dioxide at time t_i in a particular layer of a particular room (ppm)
CT(room,t_i,layer)	:	The integrated-time concentration at time t_i in a particular layer of a particular room (g-min/m^3)
DELTAT	:	The length of the time interval (t_{i-1}, t_i) (minutes)
$FED_k(t_i)$	:	Total fractional effective dose due to gases by time t_i
$FEDCO_k(t_i)$	:	Fractional effective dose due to carbon monoxide by time t_i
$FEDHCN_k(t_i)$	:	Fractional effective dose due to hydrogen cyanide by time t_i
FLUX(room,t_i,layer)	:	The flux at time t_i in a particular layer of a particular room (KW/m^2)
HCN(room,t_i,layer)	:	Amount of hydrogen cyanide at time t_i in a particular layer of a particular room (ppm)
INTERFACE(room,t_i)	:	The interface height at time t_i in a particular room (m)
TEMP(room,t_i,layer)	:	The temperature at time t_i in a particular layer of a particular room (degrees Centigrade)
t_i	:	The i-th time step (seconds)

The following computations are made for occupant k during time (t_{i-1}, t_i). The room, r, occupied during the time interval (t_{i-1}, t_i) is determined by examining the data provided by EXITT. The room layer determination is as follows:

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

The fractional effective dose is determined by two components; the fractional effective dose due to carbon monoxide (CO) and carbon dioxide (CO_2), $FEDCO_k(t_i)$, and the fractional effective dose due to hydrogen cyanide (HCN), $FEDHCN_k(t_i)$.

$$FED_k(t_i) = FEDCO_k(t_i) + FEDHCN_k(t_i).$$

The fractional effective dose due to CO and CO_2 is determined as follows:

```
If  (CO(room,t_i,layer) = 0):  FEDCO_k(t_i) = FEDCO_k(t_i-1)
Otherwise:
    If HCNAVG > 0:  COTH = 1300
    If HCNAVG = 0:  COTH = 1700
    If CO2AVG <= 50000:
        DCO = COAVG*(80000/(COAVG-COTH))*(1-CO2AVG*.00001)
    If CO2AVG > 50000:
        DCO = COAVG*(80000/(COAVG-COTH))*(.5)
    If DCO < 0 and FEDCO_k(t_i) <= 0:
        FEDCO_k(t_i) = FEDCO_k(t_i-1)
    If DCO >= 0 or FEDCO_k(t_i) > 0:
        FEDCO_k(t_i) = FEDCO_k(t_i-1)+COAVG*DELTAT/DCO
```

where

```
COAVG  = [CO(room, t_i-1, layer)   + CO(room, t_i, layer) ]/2
CO2AVG = [CO2(room, t_i-1, layer)  + CO2(room, t_i, layer)]/2
HCNAVG = [HCN(room, t_i-1, layer)  + HCN(room, t_i, layer)]/2
COTH   = carbon monoxide threshhold.
```

The fractional effective dose due to HCN is determined as follows:

```
If HCNAVG = 0:  FEDHCN_k(t_i) = FEDHCN_k(t_i-1)
Otherwise:
    FEDHCN_k(t_i) = FEDHCN_k(t_i-1) + HCNAVG*DELTAT/3100.
```

The average temperature is determined as follows:

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

The accumulated integrated-time concentration is determined as follows:

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

The accumulated flux is determined as follows:

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

Determination of a Person's State:

A person k's state (alive, incapacitated, or dead) at time t_i is determined by comparing the values of $FED_k(t_i)$, $AVGTEMP_k(t_i)$, and $ACCUMCT_k(t_i)$ with corresponding incapacitation and lethality critical levels (which the user may specify) or by comparing the $ACCUMFLUX_k(t_i)$ with the total heat required to cause burns (for incapacitation). The incapacitation and lethality critical levels are discussed in the tenability limits section (6.12) of this report. 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.

6.12.7.4 Input from FAST

TENAB requires a "dump" file from a FAST run and, upon running TENAB, the user will be prompted for the name of that file. If a file name corresponding to a non-existent file is input, the user will be informed that no such file exists and will be prompted for another file name. If it is then desired to halt TENAB, the user may enter a / for a file name, which aborts the run and returns to the system.

6.12.7.5 Input from EXITT

TENAB requires input from an EXITT run corresponding to the FAST dump file. The data may be entered from the terminal, in which case TENAB prompts the user for the necessary information, or the data may be read from a disk file created by the user or the EXITT program.

After being prompted for the FAST file name, the user will be prompted for the name of the file created by the program EXITT. If no EXITT created file exists the user should enter a return and he will then be prompted for the user created file's name. If the user wishes to enter the data at the terminal the user should enter the device name corresponding to the keyboard/terminal (CON on the PC). If the data is to be read from a user created disk file the appropriate file name is input. If a file name corresponding to a non-existent file is entered, the user will be informed that no such file exists and will then be prompted for another file name. If it is then desired to halt TENAB, the user may enter a / for a file name, which aborts the run and returns to the system.

6.12.7.6 Format for an EXITT Data File

The EXITT data file consists of 4 sections of which 2 are required and 2 are optional. The first section, which is required, is a single entry consisting of the number of rooms in the floor plan upon which the EXITT run was made. The second section, which is also required, consists of the data corresponding to the escape routes taken by the occupants. The third section, which is optional, consists of the mapping between the "FAST" rooms and the "EXITT" rooms. (Since FAST is limited to at most 5 rooms, some rooms may be grouped together as one room for FAST, but appear as separate rooms for EXITT.) This third section is necessary if FAST and EXITT have been run with a different number of rooms. If this is the case and this section is not provided, TENAB will prompt the user for the information. The fourth and last section which is also optional, contains data on the threshold values for incapacitation and lethality for Ct, temperature, and the fractional effective dose. If this section is omitted, default values will be used.

The format for the EXITT data file is as follows:

The first section is just a single integer denoting the total number of rooms, NR, in the floor plan.The second section, describing the escape routes taken by the occupants is entered as ordered, integer quadruplets as follows:

Occupant No., Room No., Time entered the room (seconds), Height

where: Occupant No. must be a positive integer,
Room No. must be a positive number between 1 and 1+no. of rooms in the building,
Time entered must be non-negative and in seconds.
Height entered is the distance in meters the occupant is from the base floor (when a room has a loft or balcony). It is a non-negative floating point number (usually 0.0).

The maximum number of rooms visited by an occupant is 100. A zero entry for time denotes the location of the occupant at the start of the fire.

The third section (optional) consists of NR integers, separated by commas or spaces, which lie between 1 and the number of rooms with which FAST was run. The row(s) would appear as follows:

$N_1, N_2, N_3, \ldots, N_{NR}$ where: N_i represents to which FAST room the i-th room of EXITT corresponds.

The last section of the file (optional) indicates whether the user wants to specify his own critical levels for FED, Ct, or temperature for incapacitation or lethality. The data values for the critical levels are to be entered as ordered real triplets. The first triplet represents the incapacitation level for FED, the incapacitation level for Ct, and the incapacitation level for temperature. The second triplet represents the lethality level for FED, the lethality level for Ct, and the lethality level for temperature. An entry of -1. indicates that the user wishes to use the default value.

In order for TENAB to know that an optional section is present one of the following rows of data must immediately follow the second section.

1. The third and fourth sections are not present.
   0,0,0,0.
2. The third section is present but not the fourth.
   -1,0,0,0.
3. The fourth section is present but not the third.
   -2,0,0,0.
4. The third and fourth sections are both present.
   -3,0,0,0.

An annotated sample data file is shown below (EXITT assumes 6 rooms and FAST assumes 5 rooms):

```
6               (EXITT run with a floor plan of 6 rooms)
1,1,0,0.        (person 1 in room 1 at time   0 seconds on base floor level)
2,2,0,0.        (person 2 in room 2 at time   0 seconds on base floor level)
1,2,120,0.      (person 1 in room 2 at time 120 seconds on base floor level)
1,3,600,0.      (person 1 in room 3 at time 600 seconds on base floor level)
1,6,500,0.      (person 1 in room 6 at time 500 seconds on base floor level)
2,3,720,0.      (person 2 in room 3 at time 720 seconds on base floor level)
-3,0,0,0.       (indicates third and fourth sections follow)
1,2,2,3,4,5     (indicates that room 1 of EXITT corresponds to room 1 of FAST,
                                room 2 of EXITT corresponds to room 2 of FAST,
                                room 3 of EXITT corresponds to room 2 of FAST,
                                room 4 of EXITT corresponds to room 3 of FAST,
                                room 5 of EXITT corresponds to room 4 of FAST,
                                room 6 of EXITT corresponds to room 5 of FAST)
-1.,400.,-1. (default value for FED & temperature, 400. for Ct incapacitation)
-1.,-1.,110. (default value for FED & Ct, 110. for temperature lethality)
```

If the data file does not contain the third section when it is necessary (when the number of rooms for EXITT exceeds the number of rooms used for FAST), Tenab will prompt the user for the information relating the room numbers of EXITT to the room numbers of FAST.

> Note: Tenab assumes that the number of rooms for FAST is always less than or equal to the number of rooms for EXITT and whenever FAST and EXITT assume the same number of rooms, that room number i of FAST corresponds to room number i of EXITT.

6.12.7.7 Entering EXITT Data from the Terminal

To enter the EXITT data from the terminal when running TENAB the user needs to respond to the prompts. When prompted for the number of rooms, the user keys in an integer value denoting the total number of rooms in the floor plan upon which the escape routes are determined and hits the return key.

When prompted for the Occupant No., Room No., Time Entered & Height, the user can key in the data by one of three formats:

```
Occupant No.,Room No.,Time (seconds),Height  (Entries separated by commas
                                              and line ended with a return)
```

or

```
Occupant No. Room No. Time (seconds) Height  (Entries separated by blank
                                              spaces and line ended with a
                                              return)
```

or

```
Occupant No. (return key)
Room No.     (return key)
Time         (return key)
Height       (return key).
```

The occupant number must be a positive integer. The room number must be an integer between 1 and 1+number of rooms in the building. The time must be a non-negative integer in seconds. The height from base floor level (as occurs when there is a room with a loft or balcony) is a non-negative floating point number (usually 0.0).

To end the input of occupant information, the user enters three integer zeros and a floating point zero (0,0,0,0.0).

If the number of rooms entered in response to the first prompt is different than that provided by the FAST data file, the user will be prompted to enter the FAST room to which the i-th room of EXITT corresponds.

After the occupant and possibly the room information are entered, the user will be prompted as to whether he wishes to set his own incapacitation and lethality critical levels for FED, Ct, or temperature. If so, the user hits the Y-key and the return key and is then prompted for the new value. The user should then enter his critical value as a real number (with decimal point) and hit the return key. If the default values are to be used, the user need only hit the return key in response to the prompt for changing the critical values.

6.12.7.8 Output from TENAB

After the user is prompted for the input FAST and EXITT file names, the user is prompted for the name to be given to the output file. The user may have the output written to disk by entering a valid file name, provided no file by that name already exists, or he may have the output routed directly to the printer by entering the printer device name (PRN on the PC), or to the screen by entering the screen device name (CON on the PC).

The output from TENAB begins by listing the FAST and EXITT file names used. Then TENAB writes out the EXITT data and the incapacitation and lethality critical levels for FED, Ct, and temperature.

The last part of the output is in tabular form. For each person, TENAB outputs in time order the pertinent information corresponding to when a person's FED, Ct, temperature, or flux exceeded a critical level or when a person was able to exit the building. The pertinent information consists of the time of the occurrence, the room (according to EXITT) of occurrence, the condition of the person (dead or incapacitated) due to the occurrence, the factor cause, and the values of FED, Ct, temperature, and flux at that time. Information related to the final time (the occupant's condition at the end of the simulation) is also recorded. A sample of the output is shown on the next page.

INPUT FAST FILE : RANCH.FST
INPUT EXITT FILE : RANCH.EVA
TENABS OUTPUT FILE: RANCH.TEN

OCCUPANT 1	ROOM NUMBER	ENTER TIME (S)
	6	0
	5	170
	1	180
	8	190

OCCUPANT 2	ROOM NUMBER	ENTER TIME (S)
	4	0
	7	160
	6	170
	7	180
	3	190

FACTORS	INCAPACITATION LEVEL	LETHAL LEVEL
FED	0.5	1.0
CT (G-MIN/M3)	450.0	900.0
TEMP (C)	65.0	100.0

PERSON 1

TIME (MIN)	ROOM	CONDITION	CAUSE	TEMP (C)	FLUX (KW-MIN/M2)	FED	CT (G-MIN/M3)
1.	6	INCAPACITATED	TEMP	92.7	155.3	0.00	1.
1.	6	DEAD	TEMP	109.4	160.1	0.00	3.
2.	6	INCAPACITATED	FLUX	123.6	221.4	0.01	4.
30.	OUT	FINAL TIME		27.0	225.4	0.02	9.

PERSON 2

TIME (MIN)	ROOM	CONDITION	CAUSE	TEMP (C)	FLUX (KW-MIN/M2)	FED	CT (G-MIN/M3)
3.	7	INCAPACITATED	TEMP	171.2	0.2	0.00	2.
3.	7	DEAD	TEMP	171.2	0.2	0.00	2.
12.	3	INCAPACITATED	FED	92.6	0.7	0.51	287.
15.	3	INCAPACITATED	CT	81.3	0.7	0.77	450.
19.	3	DEAD	FED	74.4	0.7	1.00	597.
25.	3	DEAD	CT	62.5	0.8	1.47	903.
30.	3	FINAL TIME		52.3	0.8	1.87	1179.

CHAPTER 7. CONCLUDING REMARKS

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

The scope of applicability of the system can be extended to additional occupancies through expansion of the data base and example cases. The next occupancies to be considered will probably be hotel/motel and health care (see figure 7-1).

Improved usability will be guided by input from users, but will most likely include additions that would eliminate most of the manual transfers of data to the input program, FINPUT. Data base files would be accessed directly. That is, material properties provided in the data base will be loaded automatically by selecting the material by name from a list which appears on the screen. If the desired material is not on the list, the current procedure of entering the individual properties would be followed.

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

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

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

FIRE

BUILDING	In Room										
	Cigarette/ Sofa	Grease/ Kitchen	Mattress	Xmas Tree	Waste Basket	Closet	Electrical Fire In Wall	Heating Equipment	Duct	Flammable Materials	
Ranch	X	X	X	✓	✓	✓					
2 Story	X	✓	✓	✓	X	✓					
Town House	✓	✓	✓	X	✓	X					
Hotel	?		?		?						
Office					?						
Hospital	?		?		?						
Mercantile											
Restaurant											
Place of Assembly											
Prison											
Warehouse											

FIG. 7-1 MATRIX OF EXAMPLE FIRE SCENARIOS

APPENDIX A

NBSIR 85-3284

USER'S GUIDE FOR FAST

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ABSTRACT

FAST is a multicompartment zone type computer model which predicts the smoke hazard development in each compartment based on a description of the compartments and the fire. A FORTRAN program has been written for the model. This user's guide provides a detailed description of the data input requirements and the output produced by version 17 of the program. Also included are sample program input and output.

Key Words: compartment fires; computer programs; fire growth; manuals; mathematical models; room fires; smoke; toxicity.

1. INTRODUCTION

In 1984 Walter W. Jones published a report describing a computer model for the transport of fire, smoke and toxic gases (FAST) [1,2][1]. The report describes the basic phenomena used in the model and a computer program (FAST Version 15) which performs the calculations. Although that report includes a sample input data set, it does not provide information about the input format and options. This user's guide supplements the initial report by providing a detailed description of the program input and output, as well as information on installing and running a slightly revised version of the program, FAST 17. This user's guide does not include a catalog of fire related materials property data. A recent report by Gross [3] provides examples and sources for such data.

1.1 Summary of the Model Features

FAST is a multicompartment control volume (zone) type fire model. It assumes that each room or compartment can be separated into volumes in which the properties such as temperature and pressure are relatively uniform. The two volumes of most importance to the user are the hot upper layer, sometimes known as the smoke layer, and the relatively cool lower layer. A schematic of the upper and lower layer control volumes is shown

----

[1] Figures in brackets indicate literature reference at the end of this report.

in Figure 1. The primary purpose of FAST is to predict the conditions in the two layers as a result of a fire.

FAST considers the fire to be a source of heat and combustion products. The heat generation rate used by the program is the result of multiplying an effective net heat of combustion by a time varying rate of mass loss ("burning rate") of the fuel. Both of these values are user specified. The FAST model assumes that the fire burns at the rate specified by the user regardless of the conditions in the room.

The product or species generation rates are user specified inputs in terms of the rate a species is generated per unit mass loss of fuel. The generation rates may vary as a function of time. FAST has the ability to track a number of common fire species such as oxygen, nitrogen, carbon dioxide, carbon monoxide and smoke. As with the mass loss rate, the fire conditions do not affect the user specified species generation rates.

Using the specified heat and product generation rates and geometrical and thermophysical data, FAST solves equations for the conservation of mass, momentum and energy plus heat conduction and mixing within each control volume as a function of time. The results are the thickness and temperature of, and species concentration in, both the upper and lower layers in each compartment. Also given are the heat transfer and mass flow rates, and boundary surface temperatures.

1.2 Using the Computer Program

The FAST program consist of over 3000 lines of FORTRAN and is believed to adhere fully to the FORTRAN 77 standard [4]. The program source code is supplied on either magnetic tape or disk and includes information on installing the program. Users may require assistance from their local computer systems staff in installing the program. The procedure used to run the program will depend on the installation at a particular site.

The FAST program is written for "batch input." An input data file is prepared by the user with a text editor. This data file is then assigned as input to the FAST program. FAST does not prompt the user with questions concerning the input data. The following section of this paper describes the structure of the input data file.

2. DESCRIPTION OF THE INPUT DATA

The input must be grouped in the following order 1) Title and time step, 2) Configuration parameters, 3) Floor plan data, 4) Connections, 5) Thermophysical properties of the enclosing surfaces, 6) Fire specifications, 7) Species production, 8) Output file. Although the above sequence of groups must be followed, the sequence of the lines within the groups is not significant. The number of lines in a given data set will vary depending for example on the number of openings or the number of species tracked. A sample input data file is given in

Appendix A. A number of parameters such as heat transfer and flow coefficients have been set within the program as constants [1,2].

Each line of input consists of a label followed by one or more numerical values associated with that input variable. The label must always begin in the first space of the line and be in capital letters. If the label is less than five characters in length, spaces must be added to the end of the label to complete the required five character length. Following the label, the first of the values may start in any column and all values must be separated by either a comma or a space. Values may contain decimal points if needed. Units are standard SI units except energy (kJ) and power (kW). In the following examples, the symbol ~ is used to indicate a space. The symbol 0 indicates the number zero and the symbol O indicates the letter O. FAST will successfully run with the omission of some input lines or values. These cases are indicated throughout this document.

2.1 Title and Timestep

VERSN

INPUT:
VERSN [Number] [Title]

EXAMPLE:
VERSN~~017~BUILDING XYZ

NOTES:
VERSN must be typed in to the first five spaces of the line followed by two blank spaces in columns six and seven and the number 017. [Title] is optional and may consist of letters, numbers, and/or symbols that may be entered in the next 50 spaces and permits the user to label each run.

TIMES

INPUT:
TIMES [Simulation time (sec)] [Print interval (sec)] [Dump interval (sec)]

EXAMPLE:
TIMES~360~30~10

NOTES:
[Simulation time] is the length of time over which the simulation takes place. The maximum value for this input is 86400 seconds (one day).

[Print interval] is the time interval between each printing of the output values. In this example, the output will be printed for every 30 seconds of the simulation.

[Dump interval] is the time interval between each writing of the output to the dump file. See Section 2.8. In this example, data will be written to the dump file for every ten seconds of the simulation. A zero must be used if no dump file exists.

2.2 Configuration Parameters

NROOM

INPUT:

NROOM [Number of rooms]

EXAMPLE:

NROOM~3

NOTES:

[Number of rooms] is the number of rooms (compartments) inside the structure to be analyzed. The maximum allowable number of rooms is 10 for version 17 of FAST. The space outside the structure is automatically numbered 1 greater than the specified number of rooms. In the above example, the outside would be room 4. Rooms in the structure which are not part of the analysis do not have to be numbered.

NMXOP

INPUT:

NMXOP [Maximum number of connections (openings) between any two rooms]

EXAMPLE:

NMXOP~1

NOTES:

[Maximum number of connections] is the maximum number of connections (openings) between any two rooms. For example, if two windows and one door connect adjoining rooms then 3 is used as the input. The [maximum number of connections] cannot exceed 4.

The maximum number of connections is not a limit on the number of connections to a single compartment. For example if five rooms, each with a single opening, are all connected to the same room then the maximum number of connections is 1.

TAMB

INPUT:
TAMB~ [Ambient temperature (K)]

EXAMPLE:
TAMB~300

NOTES:
[Ambient temperature] is the temperature of the ambient atmosphere in Kelvin (Kelvin = degrees Celsius + 273).

2.3 Floor Plan Data

INPUT:
HI/F~ [Floor height (m)]
WIDTH [Room width (m)]
DEPTH [Room depth (m)]
HEIGH [Room height (m)]

EXAMPLE:
```
HI/F~~~0.0~~0.0~~0.0
WIDTH~~6.1~~4.6~~4.6
DEPTH~~9.1~~4.3~~4.3
HEIGH~~3.6~~2.4~~2.4
```

NOTES:
[Floor height] is the height of the floor of each room with respect to some reference datum (e.g., the ground).

[Room width], [Room depth], and [Room height] are the dimensions of each room.

The number of values in each line must equal the number of rooms specified for NROOM.

2.4 Connections

INPUT:

HVENT [From room number] [To room number] [Opening width (m)] [Sill height (m)]

EXAMPLE:

```
HVENT~1~~2~~1.1~~2.1~~0.0
HVENT~1~~3~~1.1~~2.1~~0.0
HVENT~2~~4~~1.3~~2.1~~0.6
```

NOTES:

[From room number] is the room number from which the smoke is assumed to be originating.

[To room number] is the room number to which the smoke is assumed to be flowing. The program will automatically correct the flow direction if the assumed direction is incorrect.

[Opening width] is the width of the opening.

[Opening height] is the height of the top of the opening above the floor.

[Sill height] is the height of the bottom of the opening (sill) above the floor.

Openings to the outside are included as openings to the room with a number 1 greater than the number of rooms specified for NROOM, which in the above example is room number 4.

2.5 Thermophysical Properties of Enclosing Surfaces

INPUT:

```
[Label]
COND~ [Conductivity (kW/(m·K))]
SPHT~ [Specific heat (kJ/(kg·K))]
DNSTY [Density (kg/m^3)]
THICK [Thickness (m)]
EMISS [Emissivity]
```

EXAMPLE:

```
CEILI
COND~~.00018~.00018~.00018
SPHT~~.9~~~~~.9~~~~~.9
DNSTY~790.~~~790.~~~790.
THICK~.016~~~.016~~~.016
EMISS~.9~~~~~.9~~~~~.9

WALLS
COND~~.00018~.00018~.00018
SPHT~~.9~~~~~.9~~~~~.9
DNSTY~790.~~~790.~~~790.
THICK~.016~~~.016~~~.016
EMISS~.9~~~~~.9~~~~~.9

FLOOR
COND~~.0017~~.0017~~.0017
SPHT~~1.0~~~~1.0~~~~1.0
DNSTY~2200.~~2200.~~2200.
THICK~.15~~~~.15~~~~.15
EMISS~.9~~~~~.9~~~~~.9
```

NOTES:

CEILI, WALLS, and FLOOR are the required [Labels] for the ceiling, walls, and floor respectively.

The number of values in each line should equal the number of rooms specified for NROOM except as noted below.

COND, SPHT, DNSTY, THICK and EMISS are the labels for the thermophysical properties of the enclosing surfaces (walls, ceiling or floor). If the thermophysical properties of the enclosing surfaces are not included FAST will treat them as adiabatic (no heat transfer). Since most of the heat transfer is through the ceiling and the conduction calculation takes more than half of the computation time, it is recommended that initial calculations be made using the ceiling only. Adding the walls generally makes little change in the results and the floor contribution is negligible. Clearly, there are cases where the above generalization does not hold, but it may prove to be a useful screening technique.

It is possible to account for enclosing surfaces composed of a maximum of three layers of different materials. To do this, the thermophysical parameters are separated by "/" for each surface and each compartment. As an example using the sample data above, the ceiling in compartment 2 is divided into three layers. Each of these layers has the same thickness but the properties of the center layer differ from the outer two layers.

```
CEILI
COND~~.00018~.00018/.00004/.00018~.00018
SPHT~~.9~~~~~.9/.8/.9~~~~~.9
DNSTY~790.~~~790./50./790.~~~790.
THICK~.016~~~.016/.08/.016~~~.016
EMISS~.9~~~~~~~~~~~.9~~~~~~~~~~~.9
```

Note there is only a single value for the emissivity and it applies to the interior surface of the enclosing surface.

2.6 Fire Specifications

LFBO

INPUT:

LFBO~ [Room of fire origin] [Description]

EXAMPLE:

LFBO~~2~ROOM OF FIRE ORIGIN

NOTES:

[Room of fire origin] is the room number in which the fire originates.

[Description] is an optional user comment and has no effect on the program, but serves to clarify the data file to the user.

LFBT

INPUT:

LFBT~ [Fire type] [Description]

EXAMPLE:

LFBT~~1~TYPE OF FIRE (SPECIFIED FIRE)

NOTES:

[Fire type] is the type of fire and in version 17 of FAST is limited to:

1 = SPECIFIED FIRE

[Description] is an optional user comment and has no effect on the program, but serves to clarify the data file to the user.

LFPOS

INPUT:

LFPOS [Fire position] [Description]

EXAMPLE:

LFPOS~1~FIRE POSITION (CENTER)

NOTES:

[Fire position] is the area of the room in which the fire originates and in version 17 of FAST is limited to the following:

1 = CENTER OF ROOM
2 = CORNER OF ROOM
3 = ALONG WALL

The fire position is used to account for the entrainment rate of the plume, which depends on the location of the plume within the compartment. Fire positions 2 and 3 should only be used when the fire is very close to the corner or wall respectively.

[Description] is an optional user comment and has no effect on the program, but serves to clarify the data file to the user.

CHEMI

INPUT:

CHEMI [Fraction of pyrolysis] [Fraction of water] [Fraction of carbon] [Fraction of hydrogen] [Fraction of oxygen] [Heat of combustion (kJ/kg)] [Initial fuel temperature (K)]

EXAMPLE:

CHEMI~1.0~~0.0~~0.0~~0.0~~0.0~18000~300

NOTES:

[Fraction of pyrolysis] is the mass fraction of fuel which actually burns. The remaining fuel is considered to be char. For version 17 of FAST, use a value of 1.0, see discussion below.

[Fraction of water] is the mass fraction of water in the fuel by weight. For version 17 of FAST, use a value of 0.0, see discussion below.

[Fraction of carbon], [Fraction of hydrogen], and [Fraction of oxygen] are the respective mass fractions of carbon, hydrogen, and oxygen in the fuel by weight. For version 17 of FAST, use a value of 0.0 for these inputs, see discussion below.

[Heat of combustion] is the effective net heat of combustion of the fuel.

[Initial fuel temperature] is the initial temperature of the fuel and for version 17 of FAST should be the ambient temperature specified for TAMB.

This input line provides for future capabilities of the program. For version 17 of FAST a value of 1.0 should be used for the [Fraction of pyrolysis] and 0.0 should be used for the [Fraction of water], [Fraction of carbon], [Fraction of hydrogen] and the [Fraction of oxygen].

LFMAX

INPUT:

LFMAX [Number of intervals] [Description]

EXAMPLE:

LFMAX~5~NUMBER OF INTERVALS OF FIRE GROWTH

NOTES:

[Number of intervals] is the number of time intervals for the mass loss rate, fuel height and species inputs. The mass loss rate, fuel height and species are entered as series of points with respect to time. This is referred to in this document as a specified fire. The program performs a linear interpolation between these points to determine the values at all times. A sufficient number of intervals should be selected to provide a reasonable approximation (using straight line segments) for the input variables which specify the fire. A graphical example of this is shown in Figure 2. The mass loss rates P1-P6 are specified over the time intervals I1-I5. The number of points specified must be one greater than the number of time intervals. For example, if there are six mass loss points there should be a total of five time intervals (or one interval between every two consecutive points). The maximum number of intervals allowed in version 17 of FAST is 21.

[Description] is an optional user comment and has no effect on the program, but serves to clarify the data file to the user.

FTIME

INPUT:
FTIME [Time interval (sec)]

EXAMPLE:
FTIME~60~30~120~45~60

NOTES:
[Time interval] is the time between each point (mass loss rate, fuel height and species) specified for the fire. The total duration of the fire is the sum of the time intervals which in the example above is 315 seconds. This time is independent of the simulation time which is specified for TIMES. If the simulation time is longer than the total duration of the fire, the final values specified for the fire (mass loss rate, fuel height and species) will be continued until the end of the simulation.

The number of time interval values must equal the number of intervals specified for LFMAX.

FMASS

INPUT:
FMASS [Mass loss rate (kg/s)]

EXAMPLE:
FMASS~0~.01~.1~.01~.01~0

NOTES:
[Mass loss rate] is the rate at which fuel is pyrolyzed at times corresponding to each point of the specified fire (See Figure 2.).

The number of mass loss rate values must be 1 greater than the number of intervals specified for LFMAX.

FHIGH

INPUT:

FHIGH [Fuel height (m)]

EXAMPLE:

```
FHIGH~0.5~0.5~0.5~0.4~0.4~0.4
```

NOTES:

[Fuel height] is the height of the base of the flames above the floor of the room of fire origin for each point of the specified fire.

The number of fuel height values must be 1 greater than the number of intervals specified for LFMAX.

2.7 Species Production

INPUT:

[Label] [Species (kg/kg)]

EXAMPLE:

```
CO~~~~.02~.02~.02~.02~.02~.02
OD~~~~.02~.02~.02~.02~.02~.02
CT~~~~1.0~1.0~1.0~1.0~1.0~1.0
```

NOTES:

[Species] is an optional input and specifies the mass production rates of each of the constituents for each point of the specified fire.

Available [Labels] are as follows:

```
N2~~~  =  NITROGEN PRODUCTION RATE
O2~~~  =  OXYGEN PRODUCTION RATE
CO2~~  =  CARBON DIOXIDE PRODUCTION RATE
CO~~~  =  CARBON MONOXIDE PRODUCTION RATE
HCN~~  =  HYDROGEN CYANIDE PRODUCTION RATE
HCL~~  =  HYDROGEN CHLORIDE PRODUCTION RATE
TUHC~  =  TOTAL UNBURNED HYDROCARBONS
H2O~~  =  WATER PRODUCTION RATE
OD~~~  =  SMOKE DENSITY (SOOT PRODUCTION)
CT~~~  =  CONCENTRATION-TIME PRODUCT
```

Units for [Species] are kilogram of species produced per kilogram of fuel burned. The input for CT is the kilograms of "toxic" combustion products produced per kilogram of fuel burned.

The number of values for each specie must be 1 greater than the number of intervals specified for LFMAX.

2.8 Output File

INPUT:

DUMPR [Dump file]

EXAMPLE:

DUMPR~FAST1.DAT

NOTES:

[Dump file] specifies the name of the file (up to 17 characters) to which the program outputs for plotting are written. The dump file is read by the program FASTPLOT which generates plots of the output.

[Dump file] is an optional input. If omitted, the file for use by the plotting routine FASTPLOT will not be generated. A discussion of the program FASTPLOT is given in reference [1].

3. DESCRIPTION OF THE OUTPUT

The output of the FAST program consists of two major parts. The first is a summary of the input data and the second consists of the calculated results at the end of each print interval. A sample of the program output is shown in Appendix B. Due to the effect of the computer's internal precision on the solution of the equations, it is expected that the results from other computers will differ slightly from those found in Appendix B. The output is labeled and most of it is self explanatory. There are however, a number of abbreviations used which are explained in the following sections along with a general description of the output. The outputs pertaining to each of the compartments are listed across the page beginning with compartment one in the left most column and proceeding to the right to the highest number compartment.

3.1 Summary of Input Data

The summary of input data is divided into three sections. These are geometrical data, thermophysical properties and the fire specifications.

3.1.1 Geometrical Data

This section lists the run title, the total number of compartments, the maximum number of openings per pair of compartments and the width, 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 parenthesized 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)

3.1.2 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 thermophysical properties are the thermal conductivity, specific heat, density, thickness and emissivity.

3.1.3 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.

The second part lists the initial fuel temperature, the ambient air temperature, the ambient sea level reference pressure and the effective heat of combustion.

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, and the fractional production rates of the species. Also listed is the duration of each time interval.

3.2 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. For the sample output in Appendix

B, the results have only been included for times 0, 60, and 360 seconds. Following the time are the temperatures of the upper (U.TEMP) (K) and lower (L.TEMP) (K) layers, the upper layer volume (U.VOLUM) (m^3) and thickness (U.DEPTH) (m), and the temperatures of the ceiling (CE.TEMP) (K), upper (UW.TEMP) (K) and lower (LW.TEMP) (K) walls, and the floor (FL.TEMP) (K).

Next is the flow rate of combustion products and entrained air into the upper layer from the plume (EMS) (kg/s), the pyrolysis rate of the fuel (EMP) (kg/s), the enthalpy release rate of the fire (QF) (kW), the total radiant heat transfer to the upper layer (QR) (kW), the total convective heat transfer from the surfaces surrounding the layers to the upper and lower layers respectively (QC) (kW), and the difference between the current pressure and the initial pressure at the floor (Pres) (kpa).

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 specie, a concentration (PPM) or opacity (1/M) is also given. For CT, the concentration-time product, only the time integrated (from time=0) concentration (mg-min/l) for the upper layer in each compartment is given. The use of this time integrated concentration is discussed in reference [5].

4. REFERENCES

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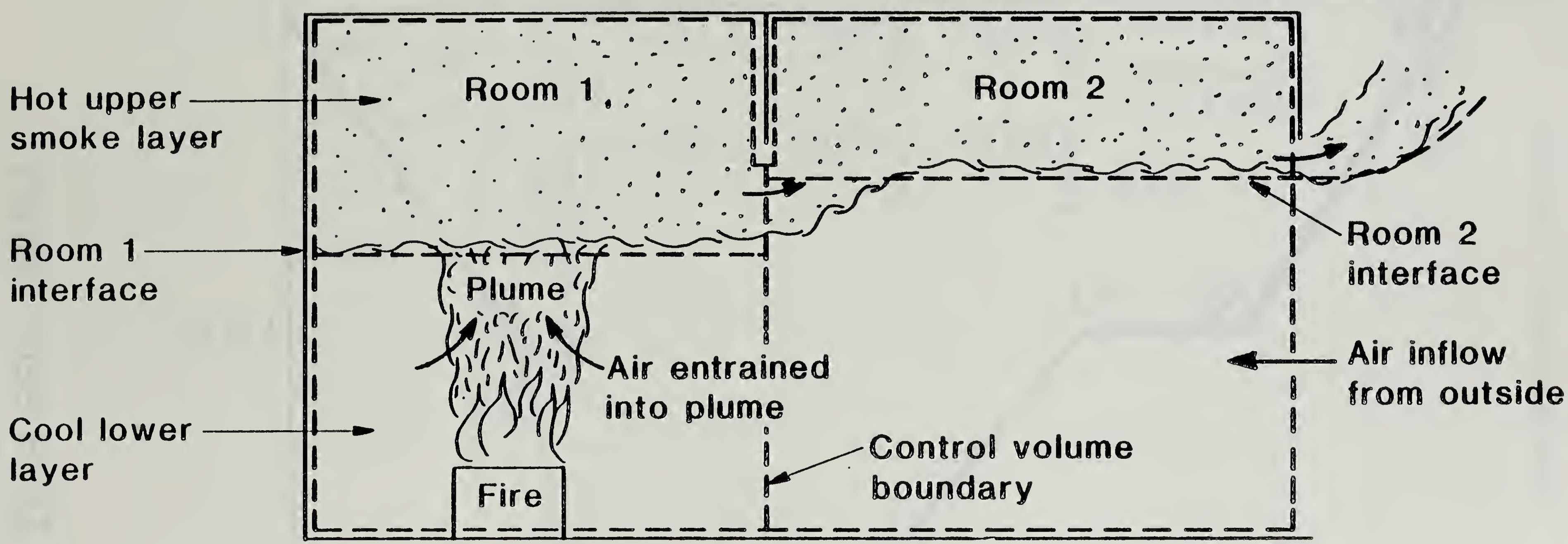

Figure 1. Schematic of upper and lower layer control volumes

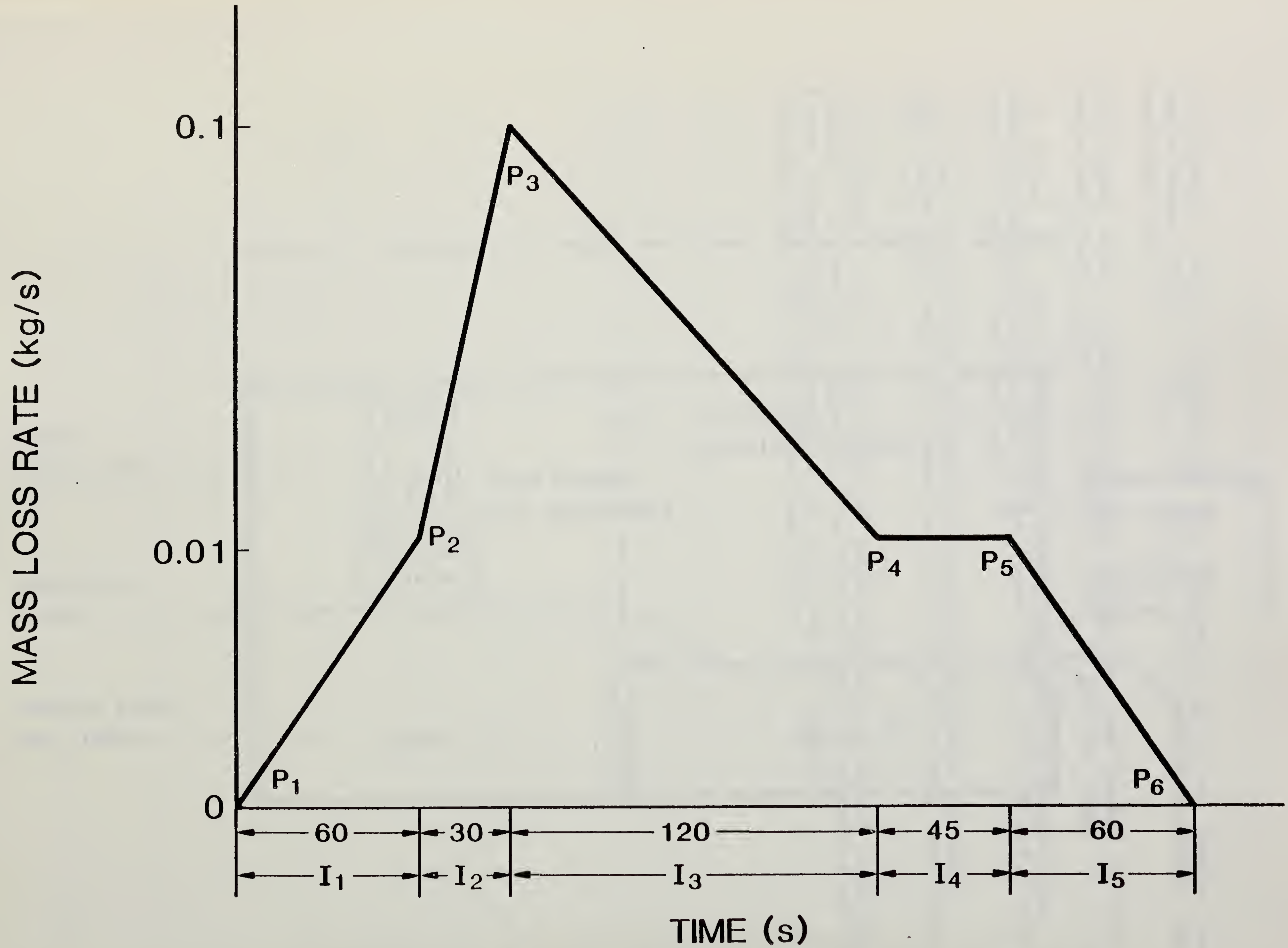

Figure 2. Example of mass loss data for a specified fire

APPENDIX A: SAMPLE INPUT

```
VERSN  017 BUILDING XYZ
TIMES 360 30 0
NROOM 3
NMXOP 1
TAMB 300
HI/F   0.0  0.0  0.0
WIDTH  6.1  4.6  4.6
DEPTH  9.1  4.3  4.3
HEIGH  3.6  2.4  2.4
HVENT 1  2  1.1  2.1  0.0
HVENT 1  3  1.1  2.1  0.0
HVENT 2  4  1.3  2.1  0.6
CEILI
COND  .00018 .00018 .00018
SPHT  .9     .9     .9
DNSTY 790.   790.   790.
THICK .016   .016   .016
EMISS .9     .9     .9
WALLS
COND  .00018 .00018 .00018
SPHT  .9     .9     .9
DNSTY 790.   790.   790.
THICK .016   .016   .016
EMISS .9     .9     .9
FLOOR
COND  .0017  .0017  .0017
SPHT  1.0    1.0    1.0
DNSTY 2200.  2200.  2200.
THICK .15    .15    .15
EMISS .9     .9     .9
LFBO  2 ROOM OF FIRE ORIGIN
LFBT  1 TYPE OF FIRE (SPECIFIED FIRE)
LFPOS 1 FIRE POSITION (CENTER)
CHEMI 1.0  0.0  0.0  0.0  0.0 18000 300
LFMAX 5 NUMBER OF INTERVALS OF FIRE GROWTH
FTIME 60 30 120 45 60
FMASS 0 .01 .1 .01 .01 0
FHIGH 0.5 0.5 0.5 0.4 0.4 0.4
CO    .02 .02 .02 .02 .02 .02
OD    .02 .02 .02 .02 .02 .02
CT    1.0 1.0 1.0 1.0 1.0 1.0
```

BUILDING XYZ

TOTAL COMPARTMENTS = 3
MAXIMUM OPENINGS PER PAIR = 1

FLOOR PLAN

WIDTH	6.1	4.6	4.6
DEPTH	9.1	4.3	4.3
HEIGHT	3.6	2.4	2.4
AREA	55.5	19.8	19.8
VOLUME	199.8	47.5	47.5
CEILING	3.6	2.4	2.4
FLOOR	0.0	0.0	0.0

CONNECTIONS

1 (1)	BW=	0.0	1.1	1.1	0.0
	HH=	0.0	2.1	2.1	0.0
	HL=	0.0	0.0	0.0	0.0
	HHP=	0.0	2.1	2.1	0.0
	HLP=	0.0	0.0	0.0	0.0
2 (1)	BW=	1.1	0.0	0.0	1.3
	HH=	2.1	0.0	0.0	2.1
	HL=	0.0	0.0	0.0	0.6
	HHP=	2.1	0.0	0.0	2.1
	HLP=	0.0	0.0	0.0	0.6
3 (1)	BW=	1.1	0.0	0.0	0.0
	HH=	2.1	0.0	0.0	0.0
	HL=	0.0	0.0	0.0	0.0
	HHP=	2.1	0.0	0.0	0.0
	HLP=	0.0	0.0	0.0	0.0

CEILING

COND =	1.800E-04	1.800E-04	1.800E-04
SPHT =	9.000E-01	9.000E-01	9.000E-01
DNSTY=	7.900E+02	7.900E+02	7.900E+02
THICK=	1.600E-02	1.600E-02	1.600E-02
EMISS=	9.000E-01	9.000E-01	9.000E-01

FLOOR

COND =	1.700E-03	1.700E-03	1.700E-03
SPHT =	1.000E+00	1.000E+00	1.000E+00
DNSTY=	2.200E+03	2.200E+03	2.200E+03
THICK=	1.500E-01	1.500E-01	1.500E-01
EMISS=	9.000E-01	9.000E-01	9.000E-01

UPPER WALL

COND =	1.800E-04	1.800E-04	1.800E-04
SPHT =	9.000E-01	9.000E-01	9.000E-01
DNSTY=	7.900E+02	7.900E+02	7.900E+02
THICK=	1.600E-02	1.600E-02	1.600E-02
EMISS=	9.000E-01	9.000E-01	9.000E-01

LOWER WALL

COND =	1.800E-04	1.800E-04	1.800E-04
SPHT =	9.000E-01	9.000E-01	9.000E-01
DNSTY=	7.900E+02	7.900E+02	7.900E+02
THICK=	1.600E-02	1.600E-02	1.600E-02
EMISS=	9.000E-01	9.000E-01	9.000E-01

FIRE ROOM NUMBER IS 2
TIME STEP IS 1.00 SECONDS
PRINT EVERY 60 TIME STEPS
NUMBER OF FIRE INTERVALS = 5
TOTAL TIME INTERVAL = 360
FIRE SOURCE = 1
FIRE TYPE = SPECIFIED

INITIAL FUEL TEMPERATURE (K) = 300.
AMBIENT AIR TEMPERATURE (K) = 300.
AMBIENT REFERENCE PRESSURE (kPa) = 101.30
EFFECTIVE HEAT OF COMBUSTION (KJ/KG) = 18000.

FMASS=	0.00	1.00E-02	0.10	1.00E-02	1.00E-02	0.00
FHIGH=	0.50	0.50	0.50	0.40	0.40	0.40
CO=	2.00E-02	2.00E-02	2.00E-02	2.00E-02	2.00E-02	2.00E-02
OD=	2.00E-02	2.00E-02	2.00E-02	2.00E-02	2.00E-02	2.00E-02
CT=	1.0	1.0	1.0	1.0	1.0	1.0
FTIME=	60.	30.	1.20E+02	45.	60.	

TIME = 0.0 SECONDS.

U.TEMP.	300.0	300.0	300.0
L.TEMP.	300.0	300.0	300.0
U.VOLUM	0.2	0.0	0.0
U.DEPTH	0.0	0.0	0.0
CE.TEMP	300.0	300.0	300.0
UW.TEMP	300.0	300.0	300.0
LW.TEMP	300.0	300.0	300.0
FL.TEMP	300.0	300.0	300.0
EMS(I)=	0.000E+00	0.000E+00	0.000E+00
EMP(I)=	0.000E+00	0.000E+00	0.000E+00
QF(I)=	0.000E+00	0.000E+00	0.000E+00
QR(I)=	0.000E+00	0.000E+00	0.000E+00
QC(I)=	0.000E+00	0.000E+00	0.000E+00
	0.000E+00	0.000E+00	0.000E+00
Pres(kpa)	0.000E+00	0.000E+00	0.000E+00

Upper layer species concentration

CO MASS !	0.000	0.000	0.000
PPM !	0.000	0.000	0.000
OD MASS !	0.000	0.000	0.000
1/M !	0.000	0.000	0.000
CT mg-m/l !	0.000	0.000	0.000

TIME = 60.0 SECONDS.

U.TEMP.	321.7	440.6	300.0
L.TEMP.	300.2	300.8	300.3
U.VOLUM	37.9	15.3	0.0
U.DEPTH	0.7	0.8	0.0
CE.TEMP	301.6	316.4	300.0
UW.TEMP	301.6	316.4	300.0
LW.TEMP	300.1	301.3	300.0
FL.TEMP	300.0	300.2	300.0
EMS(I)=	0.000E+00	7.910E-01	0.000E+00
EMP(I)=	0.000E+00	1.000E-02	0.000E+00
QF(I)=	0.000E+00	1.800E+02	0.000E+00
QR(I)=	-1.836E+00	-8.550E+00	-6.990E-03
QC(I)=	-8.981E+00	-3.598E+01	-9.722E-03
	-1.090E-03	-3.904E-03	-3.226E-02
Pres(kpa)	2.190E-01	-5.125E-01	-4.926E-02

Upper layer species concentration

CO MASS	:	1.489E-03	2.659E-03	0.000
PPM	:	33.7	205.	0.000
OD MASS	:	1.489E-03	2.659E-03	0.000
1/M	:	0.137	0.609	0.000
CT mg-m/l	:	0.811	4.54	0.000

TIME = 360.0 SECONDS.

U.TEMP.	348.4	345.9	338.7
L.TEMP.	302.2	318.8	302.1
U.VOLUM	137.5	17.3	28.0
U.DEPTH	2.5	0.9	1.4
CE.TEMP	320.4	351.6	312.8
UW.TEMP	320.4	351.6	312.8
LW.TEMP	306.2	324.3	303.1
FL.TEMP	301.1	304.5	300.4
EMS(I)=	0.000E+00	1.835E-01	0.000E+00
EMP(I)=	0.000E+00	0.000E+00	0.000E+00
QF(I)=	0.000E+00	3.000E+00	0.000E+00
QR(I)=	-5.147E+00	-4.475E-01	-1.445E+00
QC(I)=	-2.018E+01	2.910E-01	-6.271E+00
	3.123E-01	3.596E-01	3.589E-02
Pres(kpa)	-9.113E-01	-7.843E-01	-6.492E-01

Upper layer species concentration

CO MASS	:	3.401E-02	2.433E-03	7.398E-03
PPM	:	230.	130.	239.
OD MASS	:	3.401E-02	2.433E-03	7.398E-03
1/M	:	0.866	0.491	0.924
CT mg-m/l	:	53.8	64.5	45.7

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

FAST is a multicompartment zone type computer model which predicts the smoke hazard development in each compartment based on a description of the compartments and the fire. A FORTRAN program has been written for the model. This user's guide provides a detailed description of the data input requirements and the output produced by version 17 of the program. Also included are sample program input and output.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

Compartment fires; computer programs; fire growth; manuals; mathematical models; room fires; smoke; toxicity

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A Multicompartment Model for the Spread of Fire, Smoke and Toxic Gases*

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1. INTRODUCTION

In recent years there has been considerable research in the area of 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 be able to 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 from ignition. The motivation is two-fold. Being able to correlate laboratory scale experiments with full-scale tests is desirable from a cost standpoint. More important, however, from a life-safety and operational standpoint, the ability to make accurate predictions of the spread of fire, smoke and toxic gases opens up many possibilities for combating these problems, as well as taking effective preventive measures. The ability to prevent the hazards from developing becomes especially important as new and exotic materials become available.

This paper describes a model which allows one to predict the evolution of a fire in a room and the subsequent transport of the smoke and toxic gases which evolve from this fire. The numerical implementation improves on previous work, for a review see Jones [1], in particular by retaining the conservation laws in their full differential form and solving them as a set of coupled ordinary differential equations (ODEs). Such a formulation takes advantage of the effort which has gone into solving such systems of equations. The result is a numerical scheme which is considerably faster and much more 'rugged' than previous models.

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The model is assumed to be in a world of uniform temperature T_a and reference pressure P_a, with the outside of a wall at T_e which may not be the same as the ambient. The discussion is broken down into the basic structure and fundamental assumptions which go into the model, followed by a derivation of the predictive equations, a discussion of the source terms, the numerical implementation and some calculations and comparisons with experimental data. The notation is given in Appendix A. The numerical implementation of the model is modular and straightforward. It is designed to be transportable.

2. STRUCTURE OF THE MODEL

The primary element of the model is a compartment. The primary interest lies in the composition of the gas layers in each of these compartments. As such, the model is structured around fluid transport phenomena. In this context, the predictive equations for the gas layers in each compartment result from conservation of mass, momentum and energy together with an equation-of-state for each compartment. 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 being solved.

Each compartment is subdivided into one or more 'control volumes'. These control volumes will be of sufficient size that we will require only a few to describe any system of interest. The choice is based on the premise that the details which occur within such a volume do not concern us (at present), but their mutual interaction does. Each of these control volumes is called a zone. The rationale for such a choice arises from the experimental observation that when a fire spreads, the gas

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layers in the compartments actually stratify into two distinct zones. This is a compromise between a network model and a finite difference model. The former is computationally fast but yields no information on the internal structure whereas the latter yields a great deal of information but requires more computational resources than is warranted. The two zones are referred to as 'upper' and 'lower', respectively. The basic equations describe the mass, momentum and energy transfer from zone to zone in a fire driven environment. A schematic is shown in Fig. 1.

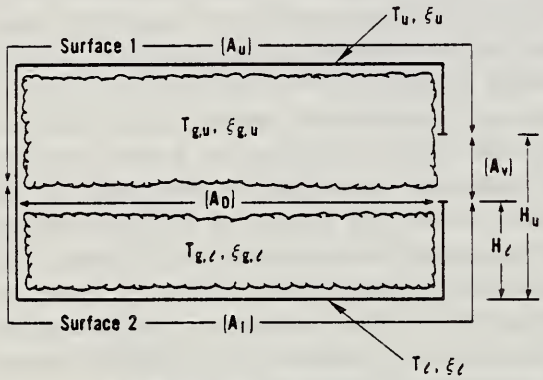

Fig. 1. A schematic of one compartment in the zone model concept. Two layers (u, l) and a single vent are shown.

In considering dynamic systems, it is necessary to solve a problem self-consistently. If such is not done, then some of the dynamics may be obscured or even lost. In particular, discussion of movement of the zone interfaces must be consistent.

The conservation equations for mass and energy can be written in the form

$$\frac{\mathrm{d}m}{\mathrm{d}t} = \sum_i \dot{m}_i \tag{1}$$

for mass and from the first law of thermodynamics we have

$$\frac{\mathrm{d}}{\mathrm{d}t}(EV) + p\frac{\mathrm{d}V}{\mathrm{d}t} = \dot{Q} + \dot{h} \tag{2}$$

together with an equation of state

$$P = \rho R T \tag{3}$$

which closes the set of equations, and with the definitions

$$E = c_v \rho (T - T_R)$$

$$\dot{h} = c_p \sum_i \dot{m}_{i,\,\mathrm{in}}(T - T_R) - c_p \sum_i \dot{m}_{i,\,\mathrm{out}}(T - T_R) + \sum_i h_{i,\,o}(T_R)$$

$\dot{Q} = \dot{Q}_f + \dot{Q}_R + \dot{Q}_c$ = net energy input

i = index of other compartments

($i \neq$ volume of interest).

The term $h_{i,\,o}(T_R)$ is relative to the temperature from which this mass parcel, $\dot{m}\mathrm{d}t$, came. It includes enthalpy of formation. The equation of state for an ideal gas is usually used for closure of the system. More correctly it should be written

$$P = P(\rho, T, \{i\}),\ \{i\} \equiv \text{set of species} \tag{4}$$

especially for applications to fire problems which are not ideal gas problems. However, for the case of an ideal gas, the derivations and discussion are simplified, and generalizations can be discussed later. The sign convention is that positive fluxes on the right-hand side of an equation will increase the quantity being calculated on the left-hand side, that is, transfer into a volume is indicated by a positive flux on the right-hand side.

The general form of the model is to divide each compartment into two zones: an upper zone which contains a hot layer, and a lower layer which is relatively cool. There may exist one or more fires and plumes in each compartment and these can usually be considered to be part of the upper zone. Mass and energy transfer between the zones is provided by the plumes, mixing at the vents, radiation between layers and flow along the walls. In general a plume, once created, simply transfers mass and energy from one zone to another. Another set of equations could be written for the plume, but as long as it is in quasi-steady equilibrium, considering it to be part of the upper zone is sufficient. Another way of looking at the plume is to consider it so small in mass, energy constant and volume that it can be ignored except as a transfer mechanism. For some problems, however, the plume must be considered a separate zone along with the concomitant conservation equations. An example would be when the rise time of the plume is of interest

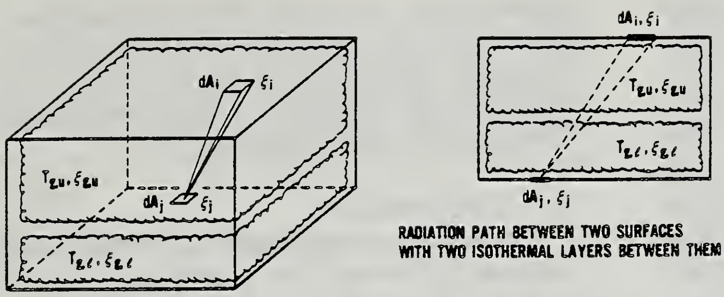

Fig. 2. Radiation transport scheme. Shown is the view factor calculation of surface 'i' as seen by surface 'j', transmitted through both layers.

or when the actual size and composition of the plume is important.

Since the conservation equations are written in terms of the volumes of these entities, a relationship between the height and the volume is needed, such as

$$V_u = \int_{Z_1}^{H_R} ZA(Z)\,dZ \qquad (5)$$

to calculate the layer depths. This removes the usual restriction that the compartments be rectangular parallelepipeds, and allows calculations for circular crosssections (aircraft) and trapezoids (atria).

The radiation transport scheme used is fairly simple and derives from the work of Siegel and Howell [2]. The view factors which are used in the calculation of solid angles are concomitant with surfaces which are planes or discs. The relationship is shown schematically in Fig. 2. The simplification used here and discussed in more detail by Jones [1] is retained, but the actual areas are used, and the exact view factors are used wherever possible [3]. For example, in calculating the area of the upper wall, allowance is made for any vents which exist by subtracting their area from the total wall area. In addition, ceiling and upper wall, lower wall and floor are treated separately (as pairs). This is necessitated by the possible use of different materials for the respective surfaces which may have different radiative properties, as well as the different types of convective flow which occur over each of these surfaces. More correctly, we should consider three surfaces, ceiling, wall and floor. This is under development. A problem arises in treating vertical convection as the layer depth tends to zero.

Actual closure of the model is obtained by assuming that the size of the compartment is fixed so that

$$V = V_u + V_l \qquad (6)$$

and that there is a single reference pressure

$$P_u = P_l \qquad (7)$$

at the boundary (interface) of the zones.

The set of equations which is necessary to describe fully such a physical system can be reduced by considering the physical impact of some of the terms. In particular, the pressure should be a general function of position, $P(X, Y, Z)$, in the compartment, which would require us to include a differential equation for the conservation of momentum explicitly. A general form for the perturbed pressure might be

$$\bar{P}(x, y, t) = P(t) - \int_0^z \rho(t)\,dz + \delta P(X, Y, Z, t) \qquad (8)$$

where P is a reference pressure and is usually the pressure at the base of the compartment. In the spirit of the 'control volume' formulation

$$\delta P \to 0$$

This implies that acoustic waves are filtered out and that internal momentum need not be calculated. The hydrostatic term is small in absolute value in comparison with the reference pressure, so it is not necessary to carry this calculation through the equation of state. Finally, the time dependent portion of the hydrostatic term deals with the movement of the interface, and thus can be ignored if we limit ourselves to problems where the momentum associated with the discontinuity (alternatively the velocity) is not significant. Dropping the momentum equation for internal waves increases the computational time step a great deal since we are not limited by the Courant time step criterion (time step α grid size/speed of sound). This prohibits us from considering problems such as deflagration waves and explosions. With these considerations in mind, we will assume

$$P_u = P_l = P \tag{9}$$

The pressure in eqn. (9) is the reference pressure at the floor. This simplification is carried through the conservation equations and greatly simplifies the resulting predictive equations. However, it is necessary to retain the hydrostatic term for the flow field calculations at vents. As we are considering only small changes in the absolute pressure, differences of these terms will be comparable to the hydrostatic pressure change, eqn. (8).

For example, for eqn. (22)

$$\delta P \sim 1 - 1000 \text{ Pa}$$

whereas

$$\int (\rho_1 T_1 - \rho_2 T_2)\, \mathrm{d}z \sim 100 \text{ Pa}$$

where the integration is over a vent opening. So the flow can be dominated by the hydrostatic term whereas the $\delta P/P < 1\%$.

3. DERIVATION OF THE CONSERVATION EQUATIONS

A zone model describes a physical situation in terms of integrals of extensive physical quantities. Thus we deal with total mass rather than mass density, total energy rather than energy density but temperature is used as before (an intensive quantity). The integrals are volume integrals whose boundary surfaces enclose the Euclidean space of interest. The space with which we are concerned usually is a compartment with zones including a hot upper gas, a cool (relatively) lower layer, objects, plumes and fires. The connections occur at the boundary of these zones. Examples of possible connections are the vents connecting compartments, the radiation from a fire to the compartment walls, etc. With this basis we can mold the conservation equations into a form which describes a fire in terms of the quantities which are appropriate to the control volume approach, intuitively understandable and lend themselves to measurement.

3.1. Fluid transport

The conservation equations for each compartment of a two layer model are

$$\frac{\mathrm{d}m_u}{\mathrm{d}t} = \sum_i \dot{m}_{u,i} \longrightarrow \dot{m}_u \tag{10}$$

$$\frac{\mathrm{d}m_l}{\mathrm{d}t} = \sum_i \dot{m}_{l,i} \longrightarrow \dot{m}_l \tag{11}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\{c_v m_u(T_u - T_R)\} - V_u \frac{\mathrm{d}P_u}{\mathrm{d}t} = \dot{Q}_u + \dot{h}_u \tag{12}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\{c_v m_l(T_l - T_R)\} - V_l \frac{\mathrm{d}P_l}{\mathrm{d}t} = \dot{Q}_l + \dot{h}_l \tag{13}$$

In writing these equations, we will make two assumptions. First, that the fire will not feed mass directly into the lower layer. Second, we will write the upper layer equation as if there is only one fire. If more than one fire exists, then a sum over such sources is necessary and if none are present, then this term vanishes. The source term $\dot{Q}$ includes all energy transfers due to radiation and convection and $\dot{h}$ includes the enthalpy flow. We can rewrite the energy conservation equations as predictive equations for temperature, in which case they become

$$m_u c_p \frac{\mathrm{d}T_u}{\mathrm{d}t} - V_u \frac{\mathrm{d}P_u}{\mathrm{d}t} = \dot{Q}_u + \dot{h}_u - c_p T_u \frac{\mathrm{d}m_u}{\mathrm{d}t} + c_v T_R \frac{\mathrm{d}m_u}{\mathrm{d}t} \longrightarrow \dot{E}_u \tag{14}$$

and

$$m_l c_p \frac{\mathrm{d}T_l}{\mathrm{d}t} - V_l \frac{\mathrm{d}P_l}{\mathrm{d}t} = \dot{Q}_l + \dot{h}_l - c_p T_l \frac{\mathrm{d}m_l}{\mathrm{d}t} + c_v T_R \frac{\mathrm{d}m_l}{\mathrm{d}t} \longrightarrow \dot{E}_l \tag{15}$$

The right-hand side of eqn. (14, 15) can be rewritten in a simpler form. The reference temperature (T_R) is chosen arbitrarily. If the only phase change occurs in pyrolysis of the fuel, then we can set the reference pressure to zero and include the pyrolysis energy as a sink term in the energy release rate. As $T_R \to 0$ we obtain

$$\dot{E}_u = \dot{Q}_f(u) + \dot{Q}_R(u) + \dot{Q}_c(u) - Q_p\dot{m}_f + c_p\dot{m}_p(T_v - T_u) + c_p\sum_i \dot{m}_{i,u}(T_i - T_u) \quad (16)$$

and

$$\dot{E}_l = \dot{Q}_f(l) + \dot{Q}_R(l) + \dot{Q}_c(l) + c_p\sum_i \dot{m}_{i,l}(T_i - T_l) \quad (17)$$

The equations and assumptions necessary to close this set are

$$P = \rho RT \quad (18)$$

$$\rho_u RT_u = \rho_l RT_l \quad (19)$$

with

$$m = \rho V \quad (20)$$

$$\text{and} \quad V = V_u + V_l = \text{constant} \quad (21)$$

The energy source terms $\{\dot{E}_l, \dot{E}_u\}$ are shown schematically in eqns. (16, 17) but can be much more complex and depend upon the configuration. Combining eqns. (10 - 11) and (14 - 17), together with the closure relations, we obtain

$$\frac{dP}{dt} = \frac{\dot{s}}{(\beta - 1)V} \quad (22)$$

$$\frac{dT_u}{dt} = \frac{1}{\beta}\left(\frac{T_u}{PV_u}\right)\left(\dot{E}_u + \frac{V_u}{(\beta - 1)V}\dot{s}\right) \quad (23)$$

$$\frac{dT_l}{dt} = \frac{1}{\beta}\left(\frac{T_l}{PV_l}\right)\left(\dot{E}_l + \frac{V_l}{(\beta - 1)V}\dot{s}\right) \quad (24)$$

$$\frac{dV_u}{dt} = \frac{1}{P\beta}\left(c_p\dot{m}_u T_u + \dot{E}_u - \frac{V_u}{V}\dot{s}\right) \quad (25)$$

where

$$\dot{s} = c_p\dot{m}_u T_u + c_p\dot{m}_l T_l + \dot{E}_u + \dot{E}_l \quad (26)$$

$$\text{and} \quad \beta = c_p/R = \gamma/(\gamma - 1) \quad (27)$$

It should be pointed out that the equations are written in this form for the sake of clarity and simplicity. In a numerical implementation there are better ways to express the source terms which minimize the problem of the small difference of large numbers.

4. SOURCE TERMS

Equations (22 - 25) are written so that physical phenomena which affect the environment are source terms and appear on the right-hand side. Sources which appear directly are:

1. radiation between the gas layers and walls, fires and other objects,
2. convective heating,
3. flow in plumes,
4. flow in vent jets,
5. mixing at vents.

Phenomena which are included but do not show up explicitly are:

1. radiation between objects,
2. conduction through walls and objects.

4.1. Source terms: radiation

In order to calculate the radiation absorbed in a zone, a heat balance must be done which includes all objects which radiate to the zone. Clearly, in order for this calculation to be done in a time commensurate with the other sources, some approximations are necessary.

The terms which contribute heat to an absorbing layer are the same (in form) for all layers. Essentially we assume that all zones in these models are similar, so we can discuss them in terms of a general layer contribution.

Radiation can leave a layer by going to another layer, to the walls, exiting through a vent, heating up an object or 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 will employ for the geometry is that used by Siegel and Howell [2] and is shown in Fig. 2. The radiative transfer can be done with a great deal of generality; however, as with most models we assume that zones and surfaces radiate and absorb like a grey-body with some constant emissivity ($\epsilon \leqslant 1$).

A further assumption consonant with the stratified zone assumption is that emission and absorption are constant throughout a gas layer. In application to a growing fire, a further assumption is made that the lower layer is mostly diathermous. Although not a necessary assumption, this reduces the computation time for this term by 50%. For smoke propagation some distance from the fire(s) such an assumption will not be valid, but the temperature will be so low that radiation will not be the dominant mechanism for heat loss. Flames, plumes, fires, objects and bounding surfaces have some average shape from which the view factors can be calculated. The walls of compartments are usually flat and rectangular. The gas layers are spheres with an equivalent radius of

$$L = 4V/A \tag{28}$$

and an effective emissivity of

$$\epsilon_g = 1 - \exp(-\alpha L). \tag{29}$$

The terms which contribute to heating of a layer are:

1. fires and plumes,
2. walls,
3. other layers,
4. vents (radiation from other compartments),
5. nonburning objects.

The radiation balance of items 2 - 5 can be dealt with using the following notation:

F_{jk} — geometrical view factor of surface (j) by surface (k)
σ — Stephen–Boltzman constant = 5.67 × 10^{-8} W/m^2 K^4
α — absorption coefficient of the upper gas layer m^{-1}
L — mean beam length of the equivalent sphere (m), defined in eqn. (28)
$\epsilon_{u,l}$ — emissivity of the upper/lower walls
ϵ_g — emissivity of the upper gas layer

Using the formalism of Siegel and Howell [2] we have

$$D = \{1 - (1 - \epsilon_u)(1 - \epsilon_g)F_{uu}\}\{1 - (1 - \epsilon_l)F_{ll}\} - \{(1 - \epsilon_u)(1 - \epsilon_l)(1 - \epsilon_g)^2 F_{ul}F_{lu}\} \tag{30a}$$

$$\Pi_u = [\{1 - (1 - \epsilon_g)F_{uu}\}\{1 - (1 - \epsilon_l)F_{ll}\} - \{(1 - \epsilon_l)(1 - \epsilon_g)^2 F_{ul}F_{lu}\}]\sigma T_{uw}^4 - (1 - \epsilon_g)F_{ul}\epsilon_l\sigma T_{lw}^4 - [1 + (1 - \epsilon_l) \times \{(1 - \epsilon_g)F_{ul}F_{lu} - F_{ll}\}]\epsilon_g\sigma T_g^4 \tag{30b}$$

$$\Pi_l = [\{1 - (1 - \epsilon_u)(1 - \epsilon_g)F_{uu}\}(1 - F_{ll}) - (1 - \epsilon_u)(1 - \epsilon_g)^2 F_{ul}F_{lu}]\sigma T_{lw}^4 - (1 - \epsilon_g)F_{lu}\epsilon_u\sigma T_{uw}^4 - [\{1 - (1 - \epsilon_u)(1 - \epsilon_g)F_{uu}F_{lu} + (1 - \epsilon_u)(1 - \epsilon_g)F_{lu}]\epsilon_g\sigma T_g^4 \tag{30c}$$

Finally,

$$\dot{Q}(\text{upper}) = A_u\epsilon_u\Pi_u/D$$

$$\dot{Q}(\text{lower}) = A_l\epsilon_l\Pi_l/D$$

To this must be added the energy radiated by the fire. A heat transfer balance with the fire is not necessary simply because the amount of heat radiated by the fire is usually much greater than that absorbed by the fire. In order to investigate flashover, however, this calculation must be generalized to include the fire and lower layer absorption in the radiative heat balance equation rather than relying on the postulate that superposition of the terms is sufficient.

A simple example of the results can be given for the case

$$\epsilon_u = \epsilon_l = 1,$$

for which we have

$$\dot{Q}_g = -\sigma[\epsilon_g T_u^4 A + (1 - \epsilon_g)T_{uw}^4(A_u + A_{uv}) - T_{uw}^4 A_u - \epsilon_g T_{lw}^4 A_d - T_a^4 A_{uv}] + F_f\dot{Q}_f \tag{31}$$

where

A_d = area of the upper/lower layer discontinuity

A_{uv} = area of vents which the gas layer 'sees'

A_u = area of the upper wall (including ceiling)

F_f = fraction of the fire which radiates times its view factor for the gas layer

$A = A_u + A_d$

4.2. Source terms: convective heating

Convection is the mechanism by which the gas layers lose (or gain) energy to walls or other objects. 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 here.

Convective heat flow is energy transfer across a thin boundary layer. The thickness of this layer is determined by the relative temperature between the gas zone and the wall or object surface, see Schlichting [4] and Turner [5]. We can write the heat flux term as

$$\dot{Q}_c = h_c(T_g - T_w)A_w \tag{32}$$

where the transfer coefficient can be written as

$$h_c = \frac{k}{l} C_v(\mathrm{Gr} \times \mathrm{Pr})^{1/3}$$

The terms are:

A_w = area of wall(s) in contact with the zone

Gr = Grashoff number = $gl^3|T_g - T_w|/\nu^2 T_g$

Pr = Prandtl number ≈ 0.7

k = thermal conductivity of the gas

$$= 2.7 \times 10^{-7}\left(\frac{T_g + T_w}{2}\right)^{4/5}$$

l = length scale ≃ $\sqrt{A_w}$

C_v = coefficient which depends on orientation [5]

Nu = Nusselt number

$$\nu = 7.18 \times 10^{-10}\left(\frac{T_g + T_w}{2}\right)^{7/4}$$

For the cases of interest

Orientation	*Coefficient*	*Condition*
Vertical	0.130	$\mathrm{Gr} \times \mathrm{Pr} > 10^8$
Horizontal	0.210	$T_g > T_w$
Horizontal	0.012	$T_g < T_w$

The coefficients for horizontal surfaces apply to a slab over the zone. For the inverse of this situation the coefficients should be reversed.

4.3. Source terms: plumes

A fire generates a plume which transports mass and energy from the fire into the upper layer. In addition, the plume entrains mass from the lower layer and transports it into the upper layer. The former generally increases the upper zone internal energy whereas the latter will have a cooling effect. For a fire which is consuming mass at a rate $\dot{m}_f$, heat addition will be

$$\dot{Q} \cong \chi_e \dot{m}_f \cdot H_c$$

Some fraction, χ_R, will exit the fire as radiation and the remainder will be left to drive the plume. We can empirically divide the heat transfer into actual combustion and simple gasification. The former, denoted by χ_c, is the relative fraction of pyrolysate which participates in the combustion. Also, once combustion occurs, a fraction of the energy leaves the fire as radiation ($\chi_R \dot{Q}$) and convective energy ($\{1 - \chi_R\}\dot{Q}$). The former is a function of such external effects as radiation, e.g., other fires, and vitiation. The latter efficiencies relate to sootiness and Froude number. The mass flow in a plume comes from a correlation of experimental data given by McCaffrey [6]. This correlation divides the flame/plume into three regions:

$$\left.\begin{aligned}
&\text{flaming:} \\
&\dot{m}_p = 0.011Q(Z/Q^{2/5})^{0.566} \qquad Z/Q^{2/5} < 0.08 \\
&\text{intermittent:} \\
&\dot{m}_p = 0.026Q(Z/Q^{2/5})^{0.909} \qquad 0.08 \leqslant Z/Q^{2/5} < 0.20 \\
&\text{plume:} \\
&\dot{m}_p = 0.124Q(Z/Q^{2/5})^{1.895} \qquad 0.20 \leqslant Z/Q^{2/5}
\end{aligned}\right\} \tag{33}$$

Entrainment in the intermittent region agrees with the work of Cetegen *et al.* [7] but yields greater entrainment in the other two regimes. This difference is particularly important for the initial fire as the upper layer is far removed from the fire. In this formulation, the total mass flow in the plume is given by the above correlation and the fuel pyrolysis is related to it by

$$\dot{m}_p + \dot{m}_v = f(mz, Q) \tag{34}$$

given above.

4.4. Source terms: door jets

Flow at vents is governed by the pressure difference across a vent. In the control volume approximation the general momentum equation for the zones is not solved. Instead, the momentum transfer at the zone boundaries is included by using Bernoulli's solution for forced flow. This solution is augmented for restricted openings by using 'flow coefficients'. The modification deals with the problem of constriction of velocity streamlines at an orifice.

There are two cases which apply to these models. The first, and most usually thought of in fire problems, is for 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 in the early stages of a fire. Rather than depending on density difference between two gases, the flow is forced, for example, by volumetric expansion when combustion occurs.

The results used for this model are those of Bodart and Jones [8] and will not be duplicated here. The notation used is:

S = smoke
A = air
ij = flow from compartment (i) to (j)
P = floor pressure (reference)

The order of the letters indicate the type of atmosphere from which the fluid is coming and to which it is going. As many as three neutral planes can exist for such flows. Two mixing phenomena which occur at vents are similar to entrainment by plumes. For the case when hot gas leaves a compartment and is driven by buoyancy into the upper layer of a second compartment, a door jet exists which is analogous to a normal plume. Mixing of this type occurs for flow

$SA_{ij} > 0$

and is discussed in detail by Cetegen *et al.* [7] and Tanaka [9]. The other is much like an inverse plume and causes contamination of the lower layer as cold gas from a compartment flows through a hot layer in a second compartment and is driven by buoyancy (negative) into the lower layer. Quintiere *et al.* [10] discuss this phenomena for the case of crib fires in a single room and deduce the relation

$$SA_i(\mathrm{u} \rightarrow \mathrm{l})/AS_{ji} = 0.5\left(\frac{T_{\mathrm{l}i}}{T_{\mathrm{u}i}}\right)\left(\frac{N - Z_i}{N}\right) \qquad (36)$$

This term is predicated on the Kelvin–Helmholz shear flow instability and requires shear flow between two separate fluids. The instability is enhanced if the fluids are of different density since the equilibration distance is proportional to $\nabla\rho$. A schematic of this type of flow is shown in Fig. 3. As can be seen, mixing into the lower layer of a room occurs under the same conditions for which the 'door-jet' mixing to the upper layer occurs.

4.5. Source terms: fire

Currently we can deal with two types of fires. The first is a specified fire. Then the mass pyrolysis rate is specified and the heat release rate becomes

$$\dot{Q}_{\mathrm{f}} = h_{\mathrm{c}}\dot{m}_{\mathrm{f}} - c_{\mathrm{p}}(T_{\mathrm{u}} - T_{\mathrm{f}})\dot{m}_{\mathrm{f}} - Q_{\mathrm{p}}\dot{m}_{\mathrm{f}} \qquad (37)$$

whereas the mass loss rate, $\dot{m}_{\mathrm{v}}$, is related to the pyrolysis rate by

$$\dot{m}_{\mathrm{v}} - \dot{m}_{\mathrm{f}} = (1 - \chi_{\mathrm{f}})\dot{m}_{\mathrm{v}}$$

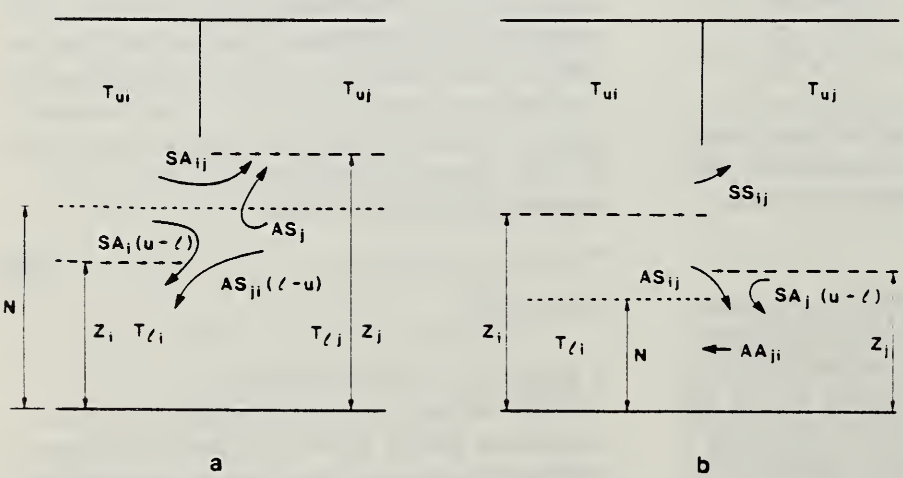

Fig. 3. Possible upper/lower mixing mechanisms which occur at vent jets.

As the burning efficiency becomes 100%, all of the volatiles are burned, and nothing remains for sooting. The heat release goes into radiation and enthalpy flux

$$\dot{Q}_R(\text{fire}) = \chi_R \dot{Q}_f$$

$$\dot{Q}_c(\text{fire}) = (1 - \chi_R)\dot{Q}_f$$

The term $\dot{Q}_c$(fire) then becomes the driving term in the plume flow equation (see eqns. (33, 34)).

This approach is extended for a pool fire. A pool fire is basically the same except that it is driven self-consistently by reradiation from the compartment and the flame itself. From Rockett [11] we have

$$\dot{Q}_f = \dot{Q}_R(\text{ext}) + \dot{Q}_{\text{flame}} - \dot{Q}_{RR} + \dot{Q}_{\text{conv}} - \dot{Q}_{\text{cond}} \tag{38}$$

where

$\dot{Q}_R$ = external radiation to the fuel source
$\dot{Q}_{\text{flame}}$ = radiation from the flame back to the fuel
$\dot{Q}_{RR}$ = fuel surface reradiation
$\dot{Q}_{\text{conv}}$ = enthalpy flux away from the fire
$\dot{Q}_{\text{cond}}$ = conductive heat loss from the fuel to the surroundings

4.6. Source terms: conduction

Conduction of heat through solids is not a source term in the sense mentioned 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, as well as heating of interior objects, the form of heat propagation in solids will be discussed here.

The equation which governs the heat transfer in solids is

$$\frac{\partial T}{\partial t} = \frac{k}{\rho c} \nabla^2 T \tag{39}$$

and is a linear parabolic equation [12]. As such, it must be solved by a different technique than is used for the ordinary differential equations which describe mass and enthalpy flux. 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 are decoupled as long as the time step used is short compared to the characteristic time scale for either set of equations. Wall temperatures change and the characteristic time for energy flux through a solid is characteristically on the order of minutes. By using a time step of no more than one second the applicability of time splitting is assured.

Currently the model assumes two walls, the upper wall (and ceiling) which is in contact with the upper layer, and the lower wall (and floor) which is in contact with the lower layer. A refinement will be to separate the ceiling and upper wall, and the lower wall and floor. This will be useful since walls are generally constructed of materials whose thermal properties are different than the ceiling and floor. A futher assumption is that conduction is one dimensional only. That is, the heat equation is

$$\frac{\partial T}{\partial t} = \frac{k}{\rho c} \frac{\partial^2 T}{\partial x^2} \tag{40}$$

and the solid behaves as an infinite slab in the other two space dimensions. A corollary to this is that the wall in contact with the gas layer changes temperature instantaneously as the layer interface moves up and down. Such a formulation is not entirely satisfactory as there is a finite equilibration time for the solid. An additional refinement will be to extend this equation to two dimensions to track the layer as it moves up and down. So far, the only zone model to attempt to include this effect is discussed by Jones [1] and Mitler and Emmons [13]. Even in this case the attempt was made only to include heat loss from the upper layer as it moves down and comes in contact with cool lower walls. However, the phenomenon is important, as is discussed by Quintiere *et al.* [14], 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 ($N + 1$ nodes). Then eqn. (40) is solved for each slice. The actual finite difference used is a time centered, implicit scheme which is symmetric about the nodes. For the interior nodes we have

$$T_i'[1+\eta] = \frac{\eta}{2}[T_{i+1}' + T_{i-1}'] + + \left\{T_i + \frac{\eta}{2}[T_{i+1} - 2T_i + T_{i-1}]\right\} \tag{41a}$$

where

$$\eta = \frac{\Delta t}{\Delta x}\frac{k}{\rho c}$$

and for the edge nodes

$$T_i'\left[1 + \frac{\eta}{2}\right] = \frac{\eta}{2}\left[T_{i+1}' \pm \frac{\dot{Q}_c}{k}\right] + + \left\{T_i + \frac{\eta}{2}\left[T_{i+1} - T_i \pm \frac{\dot{Q}_c}{k}\right]\right\} \tag{41b}$$

The temperature at the starting time at node 'i' is T_i and at time $t + \delta t$ it is T_i'. The number of nodes is chosen to reduce the residual error to some reasonable value, say less than 1%. Use of $N > 20$ will improve precision with no concomitant increase in accuracy. This technique would allow one to use different constituents for each slab, although such is not done in the current implementation. Each time step requires both an initial condition and one boundary condition. We start with the internal temperatures in each case, and the flux on the 'hot' side. The usual scheme is to set the far side boundary condition to zero heat flux (which allows heat build up in the interior) or to approximate the far side exterior as a constant temperature bath. Either technique is satisfactory unless this far side happens to be the interior boundary for another compartment.

5. NUMERICAL INTEGRATION

The problem of the spread of fire, smoke, etc. has been formulated as a set of differential equations. These equations are derived from the conservation of mass and energy. As a result, most of the equations are non-linear and first order ordinary differential equations (ODE). The exception to this rule is the heat conduction equation which is a linear parabolic equation, in one or two dimensions. The former can be solved using implicit predictor-corrector methods [15], and the latter by successive over-relaxation (SOR) [16].

In the numerical implementation, we have relied on the validity of a technique called time splitting. Simply stated, we have decoupled equations which have greatly differing relaxation times, that is

$$\frac{1}{n}\frac{dn}{dt} = L_n$$

where L_n varies by more than an order of magnitude for each process. Except for the driving program which invokes the hydrodynamics, species transport and thermal conductivity, the various modules which incorporate the physical processes are exercised separately and interact as source terms. This splitting technique is standard but the inherent assumptions should be checked when implementing a new numerical model. In addition, a check should be made at each time step to insure that the relevant stability criterion (similar to a Courant condition for fluid flow) is not violated.

For both types of equations the solution at each time step is found by an implicit scheme. The implicit method allows us to implement the numerical solution as a time centered algorithm. This insures reversibility in the physical phenomenon, at least for non-diffusive systems. A test of this assertion is to exclude thermal conduction, integrate from an initial condition to some final time, and subsequently, by changing the sign of the time step, we should be able to return to the starting position. A time reversal calculation is an important step in assuring ourselves that the integration scheme itself is not dissipative and thus will not relax to an incorrect final state. This is a real property in non-dissipative physical systems and should be mirrored as closely as possible in a numerical model. When conductivity is included, such reversibility ceases to be strictly valid, of course.

An additional virtue of the time centered scheme is avoiding the bifurcation which can occur in pure leapfrog schemes. The disadvantage is the one additional source calculation required at each time step. This time appears to be short, however, in comparison with the 'corrector' phase of the implicit scheme.

The order of the integration is as follows:

(1) Estimate the values for pressure, etc. at $t_0 + \delta t$.

(2) Find the source terms for eqns. (22 - 25) based on the time centered values ($t_0 + 1/2\delta t$).

(3) Integrate eqns. (22 - 25) using the source terms defined at the time centered positions.

(4) Repeat steps (2) and (3) until convergence is reached.

(5) Integrate the conduction equation using the SOR technique.

The following illustration shows where each of these time-step points is, in relation to steps (1 - 5):

(1) $t_0 \longrightarrow t_0 + \delta t$
estimate values at $(t_0 + \delta t)$

(2) $t_0 \longrightarrow x \longleftrightarrow t_0 + \delta t$
find sources at $(t_0 + \delta t)$

(3) $t_0 \longrightarrow t_0 + \delta t/2 \longrightarrow t_0 + \delta t$
integrate from (t_0) to $(t_0 + \delta t/2)$

(4) $t_0 \longrightarrow t_0 + \delta t$
repeat steps (2) and (3)

(5) $t_0 \longrightarrow t_0 + \delta t$
integrate conduction equation

Since each step is of at least second order accuracy, the overall scheme will also be second order accurate ($0(\delta t^3)$). The relative error allowed at each time step is $\sim 10^{-3}$. Thus the precision is greater than the precision of the computer being used (at least as long as these calculations are being done in single precision).

As for the integration scheme itself, it is derived from an Adam–Bashford backwards difference scheme [15], of order $k = 1$. This yields a single step predictor and second order corrector, $0(\delta t^3)$. These equations become 'stiff' if the individual source terms are large, which leads to a short time step, yet the total source function may be tightly coupled if the solution is being approached asymptotically. Another possibility is that the source terms for the various equations differ by more than an order of magnitude. In either case, the usual time step criterion would require a time step which is prohibitively short. It is possible to modify the Taylor expansion used in obtaining the predictor–corrector scheme to use the asymptotic nature of the equations to enhance the speed of the solver [17].

The general form of an equation is

$$\frac{dn}{dt} = q - ln \equiv f$$

Using the notation $n(0)$, $q(0)$, $l(0)$, $f(0)$ are the initial values at time (t_0), and $n(1)$, $q(1)$, $l(1)$, and $f(1)$ are the values at the new time $(t_0 + \delta t)$, we obtain first for the normal equations

$$\text{predictor } n(1) = n(0) + \frac{\delta t}{2} f(0) \tag{42a}$$

$$\text{corrector } n(1) = n(0) + \frac{\delta t}{2} (f(0) + f(1)) \tag{42b}$$

and for the stiff equations

$$\text{predictor } n(1) = n(0) + \frac{\delta t}{1 + \delta t l(0)} f(0) \tag{43a}$$

$$\text{corrector } n(1) = n(0) + \frac{2\delta t}{1 + \delta t\{l(0) + l(1)\}} \times \{f(0) + q(1) - l(1)n(0)\} \tag{43b}$$

The corrector must be iterated until some specified error criterion is reached. If the specified error cannot be reached in a small number of iterations, say two or three, then the time step must be reduced. It turns out to be advantageous to halve the time step for each instance that a reduction is required, and increase it by only 10% for each subinterval that the error criterion is satisfied.

One technique which has been used in previous work to reduce the solution time for these equations is to convert them to an algebraic form. The conversion is done by noting that the final state of the equations at each time step is a pseudo equilibrium. Thus the transient term can be dropped. For a number of reasons, simultaneous ODEs are generally easier to solve than the corresponding algebraic equations unless one is exceedingly close to the solution. Such an assertion is difficult to prove in the general case but two examples should suffice to indicate the difference in the nature of the root finding procedure. One of the simplest nonlinear algebraic equation is

$$AB = C$$

with A, B, and C being integers. Until recently this nonlinear decomposition was thought to be unsolvable (in finite time) for an arbitrary value of C. Also, a straight comparison of this method (embodied in a model) with other models using the algebraic scheme, has shown a reduction by at least a factor of ten in the time required for a given calculation. A detailed timing comparison of several models is given elsewhere [18].

6. COMPARISON WITH EXPERIMENTAL DATA

The series of tests which serve as a database for this analysis are based on a two-room fire scenario by Cooper *et al.* [19] and an ongoing series of full-scale validation tests at the National Bureau of Standards. The former was a two-room configuration, consisting of a burn (or fire) room and a corridor. It is referred to as the 'Nike Site' in later discussions. The latter is a three-room configuration with the additional room being a target room for testing high density occupancy, referred to as 'Building 205'. The geometry of each of these configurations is shown in Table 1.

Comparisons between the model and experimental data are for fires of 100 kW. Figures 4 and 5 show the comparison for the Nike Site tests for the upper layer temperatures in the burn room and corridor, and the interface height in the corridor. Figures 6 and 7 show a similar comparison to the current experiments in B205, a full scale facility at NBS. It is apparent from a comparison of Figs. 4 - 7 that plume entrainment is estimated very well but that the door jet entrainment is underestimated. We can see this from the good agreement between experiment and theory in any compartment which contains a primary plume whereas in other compartments the predicted temperature is too high and the layer depth too small in comparison with experimental values. This underestima-

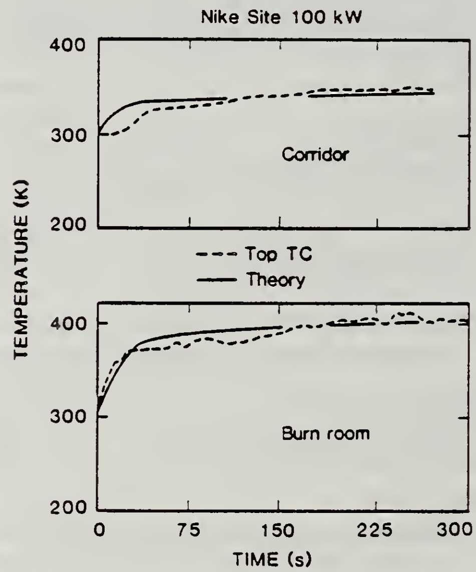

Fig. 4. Comparison of experimental and calculated temperature profiles for the upper layer in the burn room and corridor in the 'Nike Site' experiments (Table 1).

TABLE 1

Geometry data for validation calculation

		Burn	Vent	Corridor	Vent	Target
Nike Site	Depth*	4.3	—	11.1 - 20.2	—	
	Width	3.3	1.07	2.4	0.95	
	Height	2.3	2.00	2.3	0.15	
	Area	14.2	2.14	26.6 - 48.4	0.14	
	Volume	32.2	—	61.2 - 112.3	—	
Bldg. 205	Depth	2.3	—	12.2	—	2.3
	Width	2.3	1.0	2.4	1.0/1.0**	2.3
	Height	2.2	1.9	2.4	1.9/2.0	2.2
	Area	5.5	1.9	29.7	1.9/2.0	5.5
	Volume	11.8	—	72.6	—	11.8

*Lengths are in meters, areas in square meters and volumes in cubic meters.
**V1/V2: V1 is from corridor to target room and V2 is from corridor to the ambient.

tion occurs in the regions which McCaffrey [16] calls the flaming and far field regions. In the intermittent region, where the results of McCaffrey [6] and Cetegen *et al.* [7] agree, the entrainment rate appears to be correct.

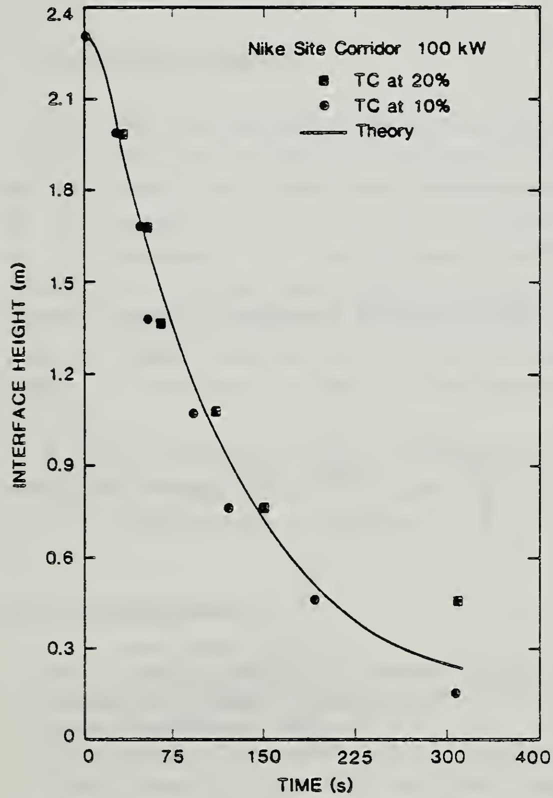

Fig. 5. Comparison of experimental and calculated interface height in the corridor of the 'Nike Site' experiments (Table 1). See refs. 14 and 19 for an explanation of the criteria (10%, 20%) used to determine the experimental interface height.

Another factor which gives rise to disparity between theory and experiment is the assumption, in the model, of known and uniform wall materials. In the experiments, walls consist of several materials in a composite such as calcium-silicate board over gypsum. Allowing for these factors, the agreement seems quite good. As research continues, these discrepancies will be resolved.

7. STABILITY AND COMPLETENESS

There are a number of phenomena which are either not included or need additional work. They are:

1. Wall effect — two dimensional, unsteady heat flow
2. Separation of flow — vents
3. Ceiling jet — transit time

The first refers to the finite thermal inertia of the wall as the hot layer moves down (or possibly up). There will be a two dimensional thermocline in the wall which differs from that in the compartment. Although this has only a small direct effect, it can lead to flow along the walls which can subsequently contribute to contamination of the lower layer. Such effects become particularly important as the smoke travels further from the fire source and temperature differentials become small.

The second problem is quite important for asymptotic predictions, especially near the room of fire origin. Currently we assume that hot gas mixes with hot gas or cold with cold

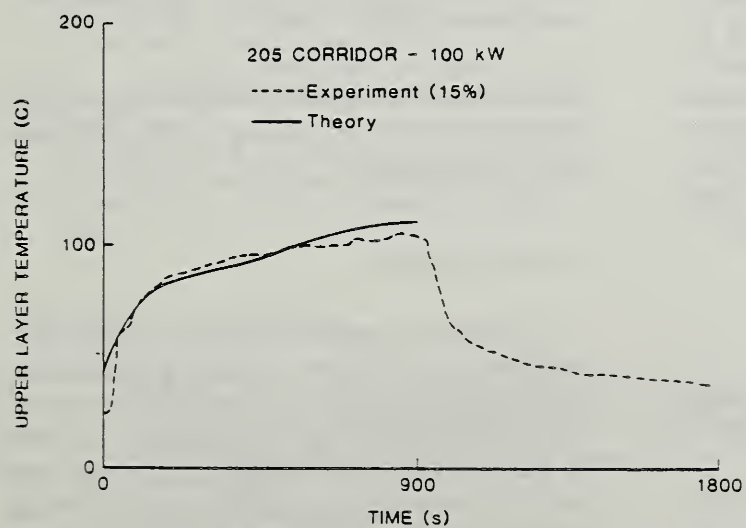

Fig. 6. Comparison of experimental and calculated upper layer temperature in the corridor of 'B205' experiments (Table 1).

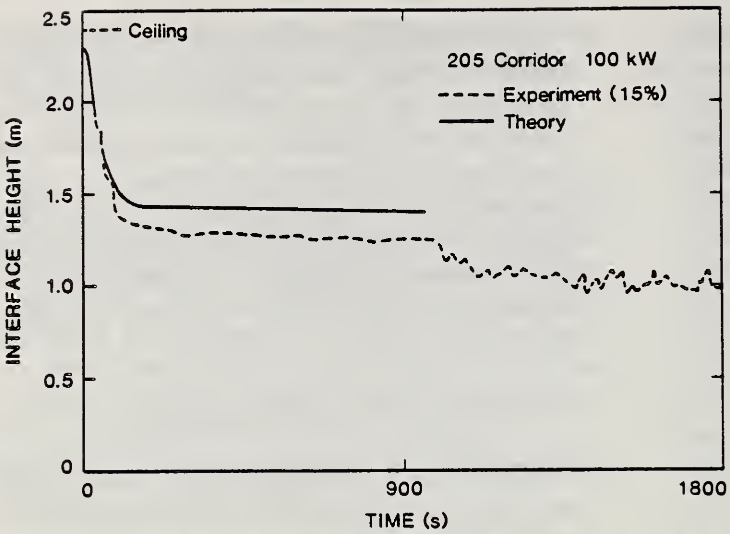

Fig. 7. Comparison of experimental and calculated interface height in the 'B205' experiment (Table 1).

gas as it traverses a vent. This was a reasonable approximation while the lower layer was assumed to be ambient. Now that we calculate the lower layer temperature, we find that the recirculating gas may have a temperature of the order of the lower layer of the room into which it enters. A particular example will demonstrate the effect. In a two-compartment calculation, Jones and Quintiere [20] found that the layer outside of the burn room is lower than that in the compartment of fire origin. As there is no source of heat in this second compartment and cooling occurs due to mixing, the upper layer in this adjacent space is cool relative to the upper layer in the fire room, and even comparable in temperature with the lower layer. Currently we assume all of the hot gas in the adjacent room, which flows into the fire room, will be deposited in the fire room upper layer. As can be seen in Fig. 8 (Evans [21]), this assumption leads to discrepancies in prediction versus experiment. A better approach is to divide the incoming flow into two components: for flow into compartment (i) from compartment (j), we have a component into the upper layer

$$= \left(\frac{T_{uj} - T_{li}}{T_{ui} - T_{li}}\right)\dot{m}_{j \to i},$$

with the remainder going into the lower layer. This occurs only after an interface discontinuity has been established.

The third problem will only be important for very long corridors (20 m) or very tall compartments or shafts. Also, it is only a

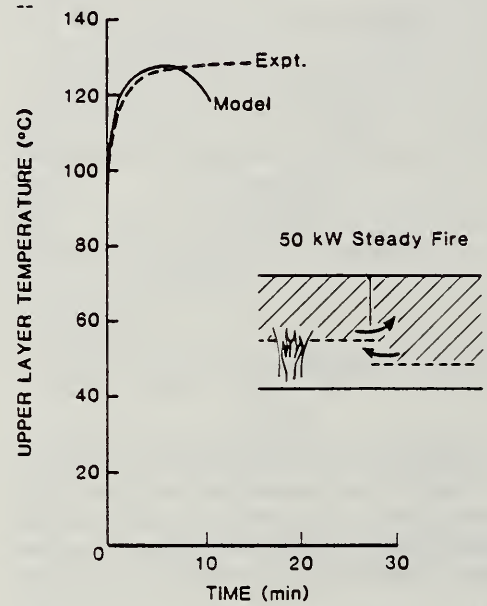

Fig. 8. An example of the upper layer separation which occurs in actual flows.

transient phenomenon. For purposes of siting smoke detectors, for example, this transient may be important.

8. CONCLUSIONS

The fire and smoke transport model, as described in this paper, is quite detailed and complete as far as our current understanding of fire phenomenology is concerned. It draws on a great deal of the research into fires which have occurred over the past ten years, pulling together much of the best work which has been done in the field. The numerical implementation is of particular interest because it is extremely durable. The problems discussed in Section 7 'Stability and Completeness' need to be addressed if we are to carry this work further, such as to fires in high rise hotels or on aircraft carriers.

ACKNOWLEDGEMENTS

Two NBS cooperative students, Alicia Fadell and Charles DeWitt have contributed to this effort. Ms. Fadell was instrumental in implementating the 'BUILD' program which generates the configuration and description files for the 'FAST' model. Mr. DeWitt is responsible for 'FASTPLOT', a routine which enables one to analyze rather easily the extensive output available from 'FAST'.

A machine readable copy of the model is available through NTIS. The tape includes the data file listed in the appendices.

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APPENDIX A — NOTATION

A	area (m^2); A_u, A_l, A_d are the upper and lower compartment surface areas in contact with the upper and lower gas layer, Fig. 1, respectively. A_d is the interface area between the upper and lower layers. In Section 4.4, 'A' is used as a variable in the flow equations to indicate air.
B	width of a vent (m)
C, C'	flow coefficient $\simeq 0.6$ - 0.7 for both smoke and air
c	specific heat — c_p, c_v (J/kgK)

$\dot{E}$	energy release rate (J/s)
E	internal energy of the gases — see eqn. (2)
F_{ij}	view factor — relative area of 'i' as seen by 'j' (dimensionless)
g	acceleration of gravity (9.8 m/s^2)
H	height (m), H_u, H_l, are the upper and lower limits of a vent — Fig. 1
h	enthalpy (J/kgK)
h_c	heat of combustion — theoretical (J/kg)
i, j	compartment indices
k	thermal conductivity (J/smK)
L	mean beam length (m) equivalent opaque sphere
m	mass (kg)
$\dot{m}$	mass flow (kg/s):
	$\dot{m}_v$ — rate of release of volatiles
	$\dot{m}_e$ — entrained into a plume
	$\dot{m}_f$ — fuel burning rate = $\chi_e \dot{m}_v$
	$\dot{m}_{ij}$ — mass entering room 'i' from room 'j'
	$\dot{m}_p$ — flow rate in plume ($\dot{m}_p = \dot{m}_v \div \dot{m}_e$)
N	height of the neutral plane (m)
P	pressure (Pa):
	$\bar{P} \to P$ — floor reference pressure
	P_a — outside ambient pressure
$\dot{Q}$	rate heat is added or lost (J/s):
	$\dot{Q}_u$, $\dot{Q}_l$ — upper, lower zones, respectively
	$\dot{Q}_f$ — fire ($h_c \dot{m}_v$)
	$\dot{Q}_o$ — objects
	$\dot{Q}_R$ — radiation
	$\dot{Q}_c$ — convection by walls
	$\dot{Q}_g$ — radiation added to upper gas layer
	$\dot{Q}_k$ — radiation from surface 'k'
	$\dot{Q}_p$ — combustion energy lost by formation of volatiles
R	gas constant for specific mixture
S	smoke — Section 4.4
t	time (s)
T	temperature (K):
	T_a — ambient
	T_c — external wall
	T_u — upper wall
	T_l — lower wall
	T_R — reference temperature for enthalpy flow
	T_g — upper zone temperature
	T_v — pyrolysis temperature
V	volume (m^3)
Z	layer thickness (m) — Z_i = interface height in compartment (i)
α	absorption coefficient of upper gas layer (m^{-1}), thermal diffusivity (m^2/s)
γ	ratio of specific heat (c_p/c_v)
ϵ	emissivity (dimensionless):
	ϵ_i — surface 'i'
	ϵ_g — upper gas layer
	ϵ_u — upper compartment surface
	ϵ_l — lower compartment surface
ρ	mass density (kg/m^3); ρ_{ui} — density of the lower layer in compartment (i)
κ	thermal conductivity (J/msK)
δ_{ij}	Kronecker delta = 0 $i \neq j$
	= 1 $i = j$

Δt time step (s)
Δx spatial discretization

Subscripts — In general 'u' and 'l' indicate upper and lower gas layer, respectively. For area and emissivity variables, reference is to the compartment itself.

APPENDIX B

Shown in Table 2 is a sample input for FAST. The organization is that control is at the beginning, followed by component information, connections, wall properties, a description of the fire, species generation information and finally file descriptors for graphics and the dump file.

TABLE 2

```
VERSION 16 Toxic hazard evaluation
Timesteps   600  120  000    0    0
NFLOR     1 NUMBER OF FLOORS IN THE CALCULATION
NROOM     4 TOTAL NUMBER OF ROOMS
NMXOP     1
TAMB  300.
HI/F    0.0  0.C  0.0  0.0
WIDTH   3.3  2.4  2.9  2.4
DEPTH   4.3 18.8  9.9  9.9
HEIGH   2.3  2.3  2.3  2.3
HVENT     1    2       1.07  2.0  0.0
HVENT     2    3       1.07  2.0  0.0
HVENT     3    5       0.95  .15  0.0
HVENT     2    4       1.07  2.0  0.0
HVENT     4    5       .95  .10   0.0
WALLS     2
COND  .0012  .0012  .0012  .0012
SPHT  .840   .840   .840   .840
DNSTY 2000.  2000.  2000.  2000.
THICK 0.50   0.50   0.50   0.50
EMISS 0.8    0.8    0.8    0.8
COND  .0012  .0012  .0012  .0012
SPHT  .840   .840   .840   .840
DNSTY 2000.  2000.  2000.  2000.
THICK 0.50   0.50   0.50   0.50
EMISS 0.8    0.8    0.8    0.8
LFBO      1 ROOM OF FIRE ORIGIN
LFBT      1 TYPE OF FIRE (GAS BURNER)
LFMAX     6 NUMBER OF INTERVALS OF FIRE GROWTH
LFPOS     1 POSITION OF THE FIRE (CENTER)
        1.0  0.0       .750 .250  .00      49758 300.    .0
FMASS  .002 .002 .002 .002 .002 .002 .002
FAREA    .5   .5   .5   .5   .5   .5   .5
FHIGH    .0   .0   .0   .0   .0   .0   .0
FTIME    60.  60.  60.  60.  60.  60.
SPECI   3 1.0    1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0
SPECI   7 1.0    .025 .025 .025 .025 .025 .025 .025 .025
SPECI   9 3500. .02  .02  .02  .02  .02  .02  .02  .02
SPECI  10 31.2    1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0
ENDSP
```

In general, the first word in each line is a key word and must be included. The explanation of this file will be by example:

Line	*Meaning*
1	version and title
2	time step information 600 → number of seconds for the calculation 120 → print interval

	120 → dump interval (requires files)
	1 → graphics interval (requires files)
	0 → hard copy counter
3	Number of floors — not used with this version, but retained for compatibility
4	Total number of compartments
5	Maximum number of openings between compartments (≤ 4)
6	ambient temperature,
7 - 10	compartment geometry, $W \times L \times H \times$ Floor (1 → NROOM)
11 - 16	connection configuration (outside is compartment NROOM + 1)
17	number of walls used in the calculation[1]
18 - 27	thermophysical properties of the upper and lower walls respectively (units are SI except energy (kJ) and power (kW).
28	which compartment the fire is in
29	type of fire (currently only a gas burner is allowed)
30	number of intervals for production rate[2]
31	interior position of the fire to establish entrainment rate (1 → center)
32	fuel properties necessary for partial combustion
	1.0 → fraction of pyrolysis which burns
	0.0 → fraction of water in the fuel
	0.750 → fraction of carbon in fuel by weight
	0.25 → fraction of hydrogen in fuel by weight
	0.00 → fraction of oxygen in fuel by weight
	49758 heat release rate (kJ/kg)
	300.0 fuel inlet temperature
	0.0 fraction of heat which exits the fire plume in the lower layer as radiation
33	mass loss rate at each end point (kg/s), LFMAX + 1_e
34	area of the fire at each end point (m^2)
35	height of the base of the flame (m)
36	duration of each time interval (LFMAX)
37 - 40	fractional production rate of species 3, 7, 9 and 10[3]
	first number is species (1 → 12)
	second number is a conversion factor
	third through LFMAX + 3 are fractional production rates[4]
41	termination label (required)
42 - 44	file descriptors
	DISFG = plan view[5]
	CONFG = layer information[5]
	DUMPR = dump file for FASTPLOT

There are two primary output files for the model. The first is binary (UNIT = 9) and is used by the routine 'FASTPLOT' described in Appendix D. The other is an ASCII file (UNIT = 6) and usually is displayed on the printer. Units are SI (MKS) except for energy which is in kJ. The meanings of the symbols, in the order which they appear, are:

---

[1] Currently an upper and lower wall are used. This will change shortly to four walls to reflect the physical difference among the ceiling, walls and floor.

[2] Figure 9 shows a sample fire production curve.

[3] Species 1 - 12 are N_2, O_2, CO_2, CO, HCN, HCL, ThHC, H_2O, smoke density, total % LC_{50}, smoke number density and HCL number density.

[4] Fraction of the mass burning rate at the corresponding endpoint (see line 33 and Fig. 9).

[5] Format for the graphics files is given in the NBSIR by Jones and Fadell [22].

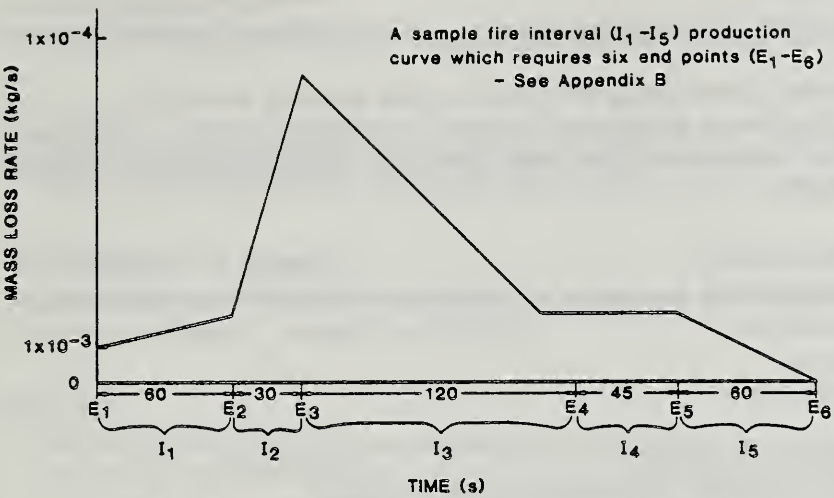

Fig. 9. An example of fire size specification through mass loss data.

Initial	— reiterate the input parameter, generally in the order of input
Timestep output	—
TIME	— simulated time (s)
U. TEMP	— upper layer temperature (K)
L. TEMP	— lower layer temperature (K)
U. VOLUM	— upper layer volume (m^3)
U. DEPTH	— vertical thickness of the upper layer (m)
C. TEMP	— ceiling temperature at the surface (K)
F. TEMP	— floor temperature (K)
EMS	— flow into the upper layer from the plume (kg/s)
EMP	— pyrolysis rate (kg/s)
ADS	— area of the fire (m^2)
QF	— enthalpy release rate of the fire (kW) to the upper and lower layer
QR	— total radiant energy to the upper and lower layers (kW)
QC	— total convective heating of the upper and lower layers (kW)
Pres	— floor reference pressure (Pa)
mass	— vent flow from $i \rightarrow j$ (kg/s) - sec (Section 4.4)

Species concentrations listed by species:

mass	— total mass of that species in the layer (kg)
M/V	— mass per unit volume multiplied by the conversion factor shown in line 37 - 40 of the input fuel. Unity leaves this value in (kg/m^3) [6].
PPM	— parts per million of the total molecules present
PPM-M	— dosage which is an integral of (PPM) over time (PPM — minutes)

APPENDIX C

The program BUILD is used to construct data files for configuration display. These files can then be used by FAST to display a decision tree either interactively or as a graphics streaming file. Both the configuration file for display as well as information on position and type of display for the decision tree are built by this program. The commands are:

[6]This conversion factor allows the user to convert this output to an optical density, LC_{50} or whatever.

ADD [VERTEX, EDGE, POLYGON] (default = VERTEX)

add vertex	— create vertices by specifying three (x, y, z) coordinates; add vertices to the work file
add edge	— create edges by specifying two vertices; add edges to work file
add polygon	— create polygons by correcting vertices. A minimum of three vertices are required to define a polygon, and there is an internal maximum specified by NPVERT.

DELETE [VERTEX, EDGE, POLYGON] (default = VERTEX)

delete vertex	— delete vertices and any edges or polygons which are connected to the deleted vertices
delete edge	— delete edges
delete polygon	— delete polygons

DISPLAY [ALL, VERTEX, EDGE, POLYGON] (default = ALL)

display all	— display all edges and polygons in graphics mode
display vertex	— display all vertices and their line numbers in graphics mode
display edge	— display all edges in graphics mode
display polygon	— display all polygons in graphics mode

DUPLICATE

Duplicate a polygon at another location — asks for a displacement vector.

END

End the program.

ERASE

Erase the display screen.

GET [filename] (default = INFILE)

Open an existing file and assign the filename to INFILE; the elements of this file make up the new work file.

HELP

List all the BUILD commands, their corresponding options, and the default values.

LIST [VERTEX, EDGE, POLYGON] (default = VERTEX)

list vertex	— list the world coordinates, window coordinates, and the vertices of the work file on the display screen
list edge	— list the edges of the work file on the display
list polygon	— screen list work file's polygons on the display screen

MOVE [VERTEX, POLYGON] (default = VERTEX)

move vertex	— move a vertex from its present location to a new location — asks for a displacement vector
move polygon	— move a polygon from its present location to a new location — asks for a displacement vector

PRINT [ALL, VERTEX, EDGE, POLYGON] (default = ALL)

print all	— list the work file's world and window coordinates, vertices, edges, and polygons on the printer
print vertex	— list the world coordinates, window coordinates, and vertices of the work file on the printer
print edge	— list the work file's edges on the printer
print polygon	— list the polygons of the work file on the printer

SAVE [filename] (default = OUTFILE)
Save the current file under the specified filename; assign the filename to OUTFILE.

STATUS
List the filenames stored in INFILE and OUTFILE; indicate the current number of vertices, edges, and polygons and the maximum number of each element allowed.

WINDOW
Create the work file's window space by specifying minimum and maximum x and y coordinates for display. Defaults to WORLD.

WORLD
Create the work file's three-dimensional world space by specifying x, y, and z coordinates. All structures must be contained in this cartesian coordinate system.

APPENDIX D

FASTPLOT is a data analysis program which runs in conjunction with 'FAST'. The results for 'FAST' are dumped to a data file after each prescribed desired time step. FASTPLOT has the capability to form a list of variables, read in their values at each time interval, list out the values in tabular form, graph the values (hard copy or screen), and save the variables in a file for future reference.

The FAST model models a fire in one of several compartments, or rooms, and follows smoke and toxic gases from one compartment to another. We are concerned with variables in both the upper and lower layers.

The list of variables presently available through FASTPLOT are:

AREA	burning area of the fire (m^2)
CONCENTRATION	species density in parts per million
CONVECTIVE	heat loss from layer to solid surface due to convection (kW/m^2)
DOORJET	buoyant mass flow through a vent (kg/sec)
DOSE	species concentration integrated over time (ppm-min)
ENTRAINED	mass entrained by a plume (from lower layer to the upper layer)
INTERFACE	height of the two-zone discontinuity (m)
MASS	mass density in a layer (kg/m^3)
MDOTFIRE	mass loss rate of the fire source (kg/sec)
NEUTRAL 1 / NEUTRAL 2 / NEUTRAL 3	neutral planes (maximum of three) for each vent
PLUME	total mass flow into the plume (kg/sec)
PRESSURE	reference pressure at the floor of the compartment (Pa)
QC	total convective heat gain by a layer
QF	total enthalpy increase from the fire source
QR	total radiative heat gain by a layer
RADIATION	heat loss from layer due to radiation (kW/m^2)
TEMPERATURE	temperature of the layer (C)
VENTFLOW	mass flow through a vent (kg/sec) — bidirectional
VOLUME	volume of the upper zone (m^3)
WALLTEMP	temperature of the wall (C)

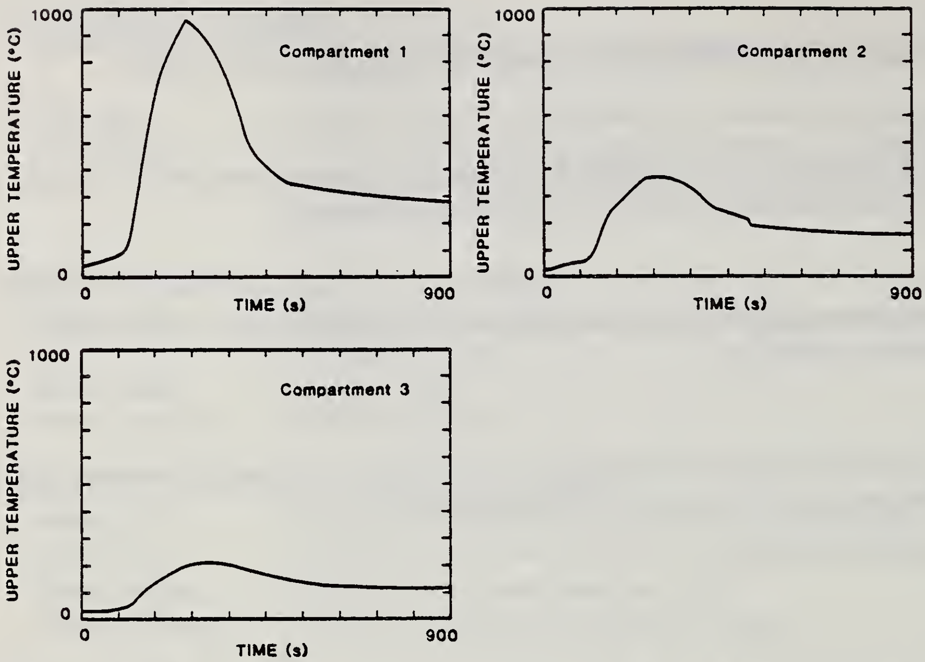

Fig. 10. Sample output from 'FASTPLOT'. Shown is one of the 100 kW calculations for the 'B205' experiments in the three compartment configuration.

The CONCENTRATION, DOSE, and MASS also have associated with them a species number.

The main control of the program is carried out in the subroutine WHICHONE. It does the actual building of a list and the processing of the options. The possible options available to the user are:

ADD
CHANGE
CLEAR
DEFAULT
DELETE
END
HELP
LIST
PLOT
REVIEW
SAVE

Upon running the program, the first input encountered will be that of the dump file generated by FAST. Most of them will be of the form:

filename.DMP

Next, the user will be asked to input the option which he wishes to have performed. The following is a description of each of the options available. They are in the order that they usually will be encountered. However, some may be executed before the others without any problems. The minimum number of characters required to recognize an option is enclosed in the parenthesis at the beginning of each word.

1. (DE)FAULT
   This enables the user to set his own default parameters for the following:

   COMPARTMENT #
   VENTFLOW DESTINATION
   LAYER

SPECIES #
CHARACTER SET FOR PLOTTING

This option may be done at any time and if it is not done the defaults are set to '1, 2, upper, 9, and 4' respectively. The purpose of this option is to change the defaults available for other commands and data input.

2. (VA)RIABLES
The purpose of this option is to allow the user to recall the possible variables that are available for use. They will be listed on the screen.

3. (AD)D
This command is used to build a list of variables. When an option is requested ADD may be entered by itself or together with a list of variables that are to be added. If it is entered alone a message will be printed asking for the variables that are to be added to the list. For example:

⟩ ADD
— INPUT VARIABLES TO BE ADDED ⟩
or
⟩ ADD TEMP, PRES, ...

For each variable selected there is a series of questions that will be asked as to the type of that variable wanted. Questions asked about all variables are:

WHICH COMPARTMENT? —⟩
WHICH LAYER? —⟩

If VENTFLOW is chosen the compartment origin and destination will be requested; if CONCENTRATION, MASS, or DOSE are selected the species number of each will be requested.

The maximum number of variables allowed on the list at any one time is 25. If the list is full or the variable is presently on the list the addition will be disallowed and another option requested.

4. (DEL)ETE
When this option is entered the present list of variables will be printed out to the screen and the user will be asked to input the variables to delete by the number associated with them on the list. They must be entered on a single line separated by commas or blanks.

If the variable number that is input does not correspond to one that is currently on the list it will be skipped. After the deletions have been processed a new list is presented and another option requested. If the list is presently empty then that fact will be stated in an error message.

5. (HE)LP
This command may be input at any time that the user is asked for an option. Its purpose is to simply list out to the console a list of the available commands and a brief explanation after which another option will be asked for.

6. (RE)VIEW
At times the user may wish to see what is presently on his list before entering a command. This may be done with the REVIEW command. It will print out the current list along with the compartment number, species, and layer of each of the variables. After the printing of the entire list the option request is again displayed.

7. (LI)ST
After variables have been added to the list and their data values read in, the user may list out the values of any of the variables on the list to either the printer or the console. The user will input the device number (5 = CONSOLE, 6 = PRINTER), and the list of variables presently on the list will be displayed. He will then be asked to input the corresponding number(s) of the variable(s) to be listed out. They must be entered on a single line separated by commas or blanks. The maximum number of variables able to be listed at one time is 8 for the printer and 5 for the console.

8. (PL)OT

This option is central to the data analysis. After entering this command the current list of variables will be displayed along with their numbers. The user will be asked to input the number of the variable(s) to be plotted from the list. They should be entered in a string separated by a comma or a blank space. For example:

ENTER VARIABLES TO BE PLOTTED —› 1,2,3,4
or
ENTER VARIABLES TO BE PLOTTED —› 1 2 3 4

After entering the variable numbers, the number of the device which the graph is to be plotted on will be asked for.

The possible devices are:

1. CALCOMP
2. PRINTER
3. LEXIDATA
4. SCREEN

The maximum number of plots per call to PLOT is limited to 4. They will be printed in the following order on the device depending on the number of graphs per page:

```
 -------          -------
|  1  2 |        |  1  2 |
|  3  4 |        |    3  |
 -------          -------
  FOUR             THREE

 -----            -----
|  1  |          |  1  |
|  2  |          |     |
 -----            -----
  TWO              ONE
```

If more than 4 variables are input only the first four will be accepted and the remaining ones disregarded. If a variable number not on the list is entered, an error message will appear, the list will be reprinted and the input will be asked for again. This will continue until all variables entered are currently on the list.

Before the graphing is done the user is given the opportunity to change the range of the X and Y axes. The maximum and minimum values of the X and Y axes will be displayed, followed by a request for a change in each, which will be of the form:

CHANGE (X or Y) AXIS TO? —›

If no change is desired simply enter a ‹RETURN› and the next axis change will be displayed. If a change is made the value will be entered and the same change request will be made again. This will be repeated until a ‹RETURN› is entered.

When all the changes have been made, if any, the graph of that particular variable will be plotted. After it has been completed the next variable's maximum and minimum will appear and their changes input as before.

After the final graph has been completed the option request will be displayed and a new option may be entered.

9. (SA)VE

This option allows the user to save the values of the variables on the list in a file. The format used will make the data compatible with an experimental data processing program designed for handling of data in the Center for Fire Research.

The user will be asked for the name to be used for the file. A check will be made to see whether that file presently exists or not. If it does the user will be asked if he wants to write over the old file with this new data. If his answer is NO, nothing will be placed in the file and another option requested. If, however, he does want the file rewritten, or the file does not already exist, the new file will be created and the data stored in it.

Each variable on the list will be dumped with the following format at the beginning of each block of data:

I6,I6,A6, * ---------- COMMENT ----------

The first I6 will be for the number of data points for that variable, the next I6 is for the number given to that variable on the list, and the A6 is for the actual variable name. Everything after the * is a comment block and will be filled with information relevant to that particular variable, such things as species number, compartment number, layer, etc. The actual numerical data will be dumped using the format 7E11.5.

10. (CL)EAR
The input of this command empties the variable list.

11. (CH)ANGE
This option restarts the program by asking for a new file and resetting all variable lists.

12. (EN)D
This function terminates the execution of the FASTPLOT program.

APPENDIX B

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EXITT - A SIMULATION MODEL OF OCCUPANT DECISIONS AND ACTIONS IN RESIDENTIAL FIRES: USERS GUIDE AND PROGRAM DESCRIPTION

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July 1987

U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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EXITT - A Simulation Model of Occupant Decisions and Actions in Residential Fires: Users Guide and Program Description

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ABSTRACT

EXITT is a computer model that simulates the decisions and actions of occupants in a residence. This model can be used to determine the locations of the occupants during the progress of a given fire. The rules for the action choices of the occupants are based largely on studies of residential fires and to a lesser extent on relevant controlled experiments. These rules involve consideration of the smoke conditions, and the characteristics, capabilities and locations of the occupants. EXITT can be run on a personal computer and does not require user training--the user controls the model by answering simple questions that appear on the screen. It can be run with pre-selected scenarios and, also, with buildings, fires and occupants selected by the user.

1. INTRODUCTION

The EXITT model simulates occupant decisions and actions in fire emergencies in small residential buildings. In assigning decisions to an occupant, the computer considers such factors as: age of occupant; sex; whether occupant is asleep; smoke conditions; whether smoke detector is sounding and how loud it sounds; whether occupant needs help in moving; and location, capabilities, condition and status of the occupants. This version of the model does not consider the heat or toxic components of the smoke. The permitted actions include: investigate the fire; alert others; awake others; rescue others; and evacuate/escape. Actions not permitted in the current version include: telephoning fire department from within the building; fighting the fire; and re-entering the building to make a second rescue.

The simulation is currently being developed as a series of progressively more sophisticated models. This report describes an early interactive version of the model.

The next Chapter of this report describes the EXITT model, with emphasis on the rules used in determining the simulated decisions and actions of the occupants. The casual user, who is familiar with personal computers, may wish to read only the first two chapters of this report. The remaining chapters are designed to be reference material plus some guidance for the computer novice to help him get started (see Section 3.2).

Chapters 3 and 4 of this report serve as a users manual and computer program documentation, respectively. The program is written to be sufficiently user friendly that it should not be necessary to read the users manual in Chapter 3. Chapter 4 also contains details about the program that are not in the general description of Chapter 2.

This simulation program is designed to run on the IBM-PC computer (and similar microcomputers using the MS-DOS operating system) using the BASICA programming language.[1] To run the model the user must load BASICA into the computer and run the program EXITT. The program is sufficiently user friendly that the user can run and understand the program from the comments, questions and information appearing on the screen. Descriptions of the full set of the various options given to the user are provided in Section 3.3.

The necessary input data for running the model are: a description of the building, the smoke characteristics of the fire, and the characteristics of the occupants. The user can provide his own input data or select from three buildings, nine fires and eight occupant sets "stored" in the computer program. While the layout of a building stored in the program will be displayed on the screen, the user may find it important to have a copy of the building layout available in hard copy. See Figures 1a-1d for copies of the layouts of the three buildings used.

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

. DESCRIPTION OF THE MODEL

2.1 Introduction.

The EXITT model simulates occupant decisions and actions during fire emergencies in small residential buildings. Buildings are represented in the model as nodes that represent rooms, exits and secondary locations within rooms; and links or distances between adjacent nodes. The occupants move from node to node at a speed that is a function of their assigned normal travel speed, the smoke conditions, and whether or not they are assisting another occupant.

The user controls the model through the keyboard by answering simple questions that appear on the screen. (A "batch" version of the model, that does not require or permit user interaction during the running of the model, is also available in the FORTRAN programming language: the decision rules in this paper apply also to the batch version.) The decisions of the occupants are reported on the screen and on the printer. The movements of the occupants are displayed graphically on the screen, reported on the printer, and stored in a data file. The user can suppress outputs on the printer and on the screen.

All the decision rules programmed in the computer model are designed to make the decisions as similar as possible to those that building occupants would make. The decision rules are based on: 1. a limited number of controlled experiments; 2. case studies of occupant actions in residential fires; and 3. the judgment of the author. Whenever the rules are based directly on data in the literature or specific case studies, reference is made to such data. Otherwise, the rules are based on the author's judgment.

Imbedded in the decisions rules are parameters that can be easily changed. Developing improved values for these parameters is a major part of the future development of the model.

The fires, buildings and occupants that are modelled can come from three sources: 1. three buildings--each with two or more fires and two or more sets of occupants--are stored in the computer programs and associated data files; 2. the user can substitute a new building, fire and/or set of occupants by answering a large number of simple questions appearing on the screen; 3. the user can substitute a new building, fire, and/or set of occupants by changing the program and/or providing a new data file using the guidance provided in Chapter 6.

2.2. Input Variables and Parameters.

2.2.1. Building. The building is represented within the computer by nodes that represent rooms, exits and secondary locations within rooms; and by links or distances between adjacent nodes. The major data used to define a building are: the number of rooms, nodes and exits; the height of each room; the room location of each node; nature of each exit (door or window); and the distances between adjacent nodes. Windows that cannot or would not be used in a fire are not entered into the computer as exits, e.g., those with a window air conditioner installed.

2.2.2. Smoke. The program is designed to use the output of the FAST model--or any other similar model--for distributing smoke throughout the building over time [Jones, 1984].[2] 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, e.g., every five seconds.

The measure of optical density for which the model is being calibrated is the one used by Jin in his studies of human behavior in smoke.

$$OD = \ln (L_0/L)$$

where L_0 is the initial light intensity which reduced to a value of L over a path of one meter. This measure is consistent with the well recognized fact that when people perceive a physical stimulus, the perceived intensity tends to vary directly with the log of the physical intensity of the stimulus.

One important factor in making action choices in a residential fire is the properties of the smoke in the occupant's room. A measure of the psychological impact of smoke is determined as follows:

$S = 2 * OD * D / H$ where,

S is the psychological impact of the smoke.
OD is the optical density of the smoke in the upper layer,
D is the depth of the upper layer, and
H is the height of the room.

This expression is based on the assumption that the impact varies directly with the optical density (i.e., the log of the amount of smoke in the upper layer) and with the depth of the upper layer relative to the height of the room. The formula is an arbitrary representation of this assumption.

Some of the decision rules and definitions that involve S include:

> Sometimes the response to smoke is largely a function of the height of the lower layer, which can be presumed to be relatively clear. For example, occupants will escape through a room containing any density of smoke provided there is sufficient clear space for crawling, say, 1.2 meters.
>
> Occupants will not move to a node where S>0.5 unless the depth of the lower layer (H-D) is at least 1.2 meters.
>
> Occupants will not move to a room where S>0.4 unless the depth of the lower layer is at least 1.2 meters.

---

[2] Items in brackets refer to references at end of report.

Occupants will increase their travel speed by 30% after encountering a room where S>0.1.

Occupants will terminate an investigation if they are in a room where S>0.05. They will terminate their investigation before entering a room where S>0.1.

Once an occupant is in a room where S>0.1, the decision rules are modified, e.g., in the text below these changes are referred to as consequences of believing the fire to be serious.

When S>0.4 there are prohibitions and penalties: these are referred to below as consequences of encountering "bad smoke."

Each of the above mentioned thresholds is an input parameter and can be easily changed as we continually improve the calibration of the model, i.e., modify the model to correspond better to behavior in real fire emergencies. Although the values selected are consistent with a conservative interpretation of Jin's data [1976], these values will be reconsidered as part of the further development of the model.

2.2.3. Noise and Alarm. The background noise level in a room affects the ability of an occupant to hear the alarm, both in real fires and in the model. The background noise is preset at 35 decibels. The user can easily override this value, on a room by room basis, by entering a larger value when defining the fire scenario.

Another input, related to a specific fire scenario, is the loudness of each smoke detector in each room, including the room in which it is located--it is a function of distances and of which doors are open. The impact of the alarm is a function of the difference between the signal intensity of the alarm and the background noise.

2.2.4. Characteristics of the Occupants. The user has an opportunity either to define or modify the characteristics of the occupants through the keyboard. 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. Some of these additional parameters are described in Section 2.5, Delays, Pauses and Action Times.

2.3. Decision Rules.

2.3.1. Introduction. There are two types of occupants: those who are fully capable when awake and those who need assistance in moving. The decision rules apply only to those who are capable when awake. Those who need assistance moving make no decisions and their movements are determined by their "rescuer".

At the beginning of the simulation, all occupants are unaware of the fire and the potential danger. Actions and decisions are assigned, in part, based on the smoke conditions in each room at the beginning of the appropriate time period.

The following paragraphs describe the sequential steps the computer follows in determining the decisions and actions of one occupant for one time period. The computer goes through these steps for each capable occupant for the first time period and then repeats the process for each subsequent time period, in turn, until all the occupants are either out of the building or trapped by the fire. (For each step, the computer considers all occupants before proceeding to the next step.)

2.3.2. Aware of Fire. The first step in determining the actions of an occupant is to determine if and when an occupant is sufficiently aware of the fire cues (i.e., smoke, sound of alarm and visible flame) to undertake an action. If the occupant became aware of the fire cues in a previous time period, he will remain aware of the fire cues for this and all subsequent time periods. An occupant becomes aware of the fire when the fire cues are sufficiently strong. 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. (Visible flame can be used, if desired, as input data: if it is used, it will be an additional fire cue.) If the weighted sum of the intensities of the cues reach a prescribed threshold, the occupant will be flagged as being aware of the fire cues. (If the fire cues are of borderline intensity, the occupant will become awake and aware after an assigned delay.) If the fire cues are not sufficiently strong for the occupant to become aware of the fire during the current time period, the consideration of this occupant for the time period is completed.

The following basic equation, for determining if and when an occupant will start to respond to the fire cues, was suggested by the empirical results of Nober et al.[1981]. While Nober studied only the response of the smoke detector alarm, his results were generalized for the odor of smoke, and the sight of smoke.

$T = 70 - 4(C-20)$ and

$C = (A-N)+X1+X2+X3+X4$ where,

T is the delay time, in seconds, before the occupant will start his first action;

C is the sum of the sensory impacts on the occupant;

A is the sound intensity of the smoke detector as heard by the occupant;
N is the background noise;

X1 is impact of an awake occupant seeing flame. It is set sufficiently high to assure a rapid response whenever an awake occupant is in the same room as a visible flame; and set equal to zero if the occupant is asleep or if the location of the flame is not entered into the computer;

X2 is impact of an occupant smelling smoke--it is a function of the smoke density and smoke depth and applies to both sleeping and awake occupants. It varies directly with S, the psychological impact of smoke when the smoke remains above 1.2 meters. However, its value dramatically increases when the upper smoke level gets down to the height of a person in a bed;

X3 is impact of an awake occupant seeing smoke--it is a function of the product of the smoke density and smoke depth in the upper layer and also varies directly with S; and

X4=0 if the (typical) occupant is asleep and X4=15 if the occupant is awake. This reflects the fact that more stimuli are required to awake than to alert an occupant. The value of 15 is based on the data in Nober [Nober et al, 1981]. Occupants who have difficulty waking could be assigned negative values of X4.

Subject to the restrictions:

A-N cannot be less than zero. If N>A let A-N = 0;

If C < 20 then T = infinity (i.e., 99999 in the computer). This restriction is based on Nober's data where occupants usually either responded within 70 seconds or remained asleep for the remainder of the test period;

X1 and X3 equal zero if the occupant is asleep.

The model as described above assumes that the response is a function of the sum of the impacts of different sensory cues. This assumes that the relevant aspects of the perceptual processing of olfactory, visual and auditory cues are similar. There does seem to be a surprisingly consistent perceptual observation (Fechner's Law) that the intensity of a perception varies directly with the log of the physical stimulus. (While Fechner's Law has broad applicability, it is not universal and only approximate [Boring, 1950].) Since our measure of the psychological impact of all the cues are based on the log of a physical measure, the impacts to the three types of cues can be assumed to be roughly comparable. The decision to sum the impacts of the three cues is based on the assumption that simple behavioral rules are better than complicated ones when there is no technical reason to select a complicated one. Furthermore, simple summing is consistent with the results of Fletcher and Munson who found that a tone heard binaurally seems twice as loud as the same tone heard monaurally [Licklider, 1951].

The physical measure of each fire cue is measured in different units and they must be converted to a single measure of sensory impact. The cue most easy to quantify, and the one for which we have the most data, is the sound of the smoke alarm which is measured in decibels. It was decided to use "equivalent decibels" as the single measure of sensory impact. The impacts of the other sensory cues are "converted" to equivalent decibels, i.e., the values of X2 and X3 are transformed to the number of decibels that would approximate an equivalent impact in alerting occupants. (When the flame is visible to an awake occupant, the value of X1 is set sufficiently high to ensure a rapid response.) The transformation factors are input parameters: their values will be the subject of future research and analysis.

While occupants respond more quickly to strong fire cues, there is a minimum duration of time required to awaken or become aware of the fire cues, select an action, and perform preparatory actions. These minimum times range from 1 to 10 seconds depending on whether the occupant is asleep and the amount of smoke. (See Section 2.5.5.)

For each occupant, a time to start his actions is computed independently at each time period until the occupant starts his first action: that is, a different time to start his actions will be computed each time period. He will start his action at the earliest time among those computed.

2.3.3. Assigning Actions to Occupants Who Are Aware of Fire. If an occupant has been assigned an action in a previous time period, he will be given an opportunity to complete that action before any consideration is made regarding additional actions.

2.3.4. Investigation Top Priority. The normal first action is to investigate the fire cues to determine the nature of the hazard. However, there are a number of exceptions, i.e., situations that would make investigation either a lower priority or an unreasonable choice. [Levin, 1985] If the computer determines that none of these exceptions applies, the computer assigns the room with the most smoke as the GOAL, labels the occupant as investigating, and assigns him the task of going to the room with the most smoke.

One special situation that would cause investigation to be a low priority arises when an adult female occupant is in the same building as a baby--in a case study provided by Keating and Loftus a mother rescued her baby before determining if it was necessary. [Keating and Loftus, 1984]

Investigation is not permitted: if the occupant has already completed an investigation; if the occupant has been in a room with moderate or bad smoke; or if the occupant has been awakened or alerted by an occupant for whom investigation is not permitted.

If the exceptions do apply, the computer considers the following alternative actions 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 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 ten functions as an adult, that is, they follow the priority list presented above for adults.

A child who is 8,9, or 10 will rescue any occupant in the same room and will go to another room to awaken or alert another occupant. However, he will not go to another room for the purpose of rescuing an occupant. Children 7 and younger do not assist others out of the building but will wake or alert other occupants who are older. A child is considered to be a baby if his age is equal to or less than the parameter BABY: babies do not initiate any actions. The tentative value of BABY is 3.

The general rationale for the above priority order is to determine if there is a need for positive action, to assist those known to require help, and then to assist those who might require help. (When it is unknown if a sleeping occupant has awakened, he can be considered as someone who might require help.) If two people are known to require help, provide help to the one needing more limited help, that is, a sleeping but otherwise capable occupant. The rule that supercedes all others is to help someone in the same room before helping an occupant in different room.

2.4. Travel Within the Building.

Occupants move within the building from node to node. The path assigned is determined by finding the shortest path to an exit based on a shortest path algorithm which contains an option for assigning penalties for going through bad smoke and for leaving through windows.

The route to be taken to a designated room, the best exit, or another designated node is determined by a shortest path algorithm. The shortest path algorithm used is described by Levin and Hedetniemi [1963]. Normally when the occupant is investigating or going to assist another occupant, a straightforward shortest distance is determined.

If the occupant wishes to egress or evacuate the building, or if the occupant had encountered too much smoke when going to assist another occupant, then the path with the lowest number of demerits is selected. 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 the occupant is escaping, the route out of the building with the least demerits is selected. If all escape routes are also blocked, he will be considered trapped. (See section on Smoke in Section 2.2 for decision rules regarding moving or not moving through bad smoke.)

As an occupant attempts to move, whenever he encounters an intolerable amount of smoke based on the criteria in Section 2.2, he will stop moving and the computer will redetermine his best route to his destination, i.e., the route with the fewest demerits. If the shortest path algorithm fails to find an acceptable path, the computer will look for the best route out of the building. If all exit routes are blocked by smoke, the occupant is considered trapped.

2.5. Delays, Pauses, and Action Times.

2.5.1. Introduction. The time consuming activities of an occupant can be classified into three categories.

> Movement from one node to another. He travels the shortest path at the speed defined below.
>
> Delays and pauses. These activities include time to awaken, time to make decisions, and time to prepare for action.
>
> Assisting actions, i.e., waking another occupant and preparing another occupant for egress.

2.5.2. Speed. The travel speed of each occupant is set at:

> 1.3 meters per second for normal conditions;
>
> 1.69 m/s (30% faster than normal) if an occupant should consider the fire to be serious (e.g., he has been in a room with heavy smoke);
>
> 0.65 m/s (50% of normal) if the occupant is assisting another occupant, or 0.845 m/s if the occupant also considers the fire to be serious;
>
> 0.78 m/s (60% of normal) if the smoke is bad (i.e., S>0.4) and if the depth of the lower layer is less than 1.5 meters, i.e. if the occupant has to "crawl" under the smoke. (0.52 m/s if the occupant is also assisting another occupant.)

The normal travel speed and all the modification factors are parameters that can be set by the user. While these values will be reconsidered as part of further model development, they are similar to those reported by Jin [1976].

Whenever an occupant moves, his actions are printed on the screen and on the printer, recorded in a data file, and graphically represented on the screen. (Printing on the screen or on the printer can be suppressed.)

2.5.3. Delay Times. The delay time, the decision time, and the time to perform assisting actions (hereafter, collectively called Delay Times) depend on the occupant characteristics, the fire characteristics and the impact of the fire cues on the occupant. The length of these Delay Times are determined by a set of decision rules as described below. These Delay Times can be changed rather easily and all assigned values should be considered as tentative.

2.5.4. Minimum Response Time. The normal (i.e., smoke is not bad) minimum response (delay) time is 6 seconds for awake occupants: this includes decision and preparation time. The normal minimum response time for sleeping occupants is 10 seconds: this also includes decision and response times. These values are based on the work of Nober [Nober et al, 1981]. The status of sleeping occupants is changed to awake status whenever the remaining response time is 6 seconds or less.

2.5.5. TPAUSE. An occupant is assigned normally 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 seconds.

2.5.6. Decrease in Preparation Time Due to Heavy Smoke. When an occupant is subjected to normal fire stimuli, a ten second response Delay Time is assigned to a sleeping occupant and six seconds to an awake occupant. (Note the response time will be greater if the fire stimuli are not sufficiently strong for an immediate response.) However, if the occupant believes the fire to be serious, the maximum Delay Time for the occupant becomes four seconds and if the smoke in the room is bad, the maximum Delay Time becomes 1 second.

2.5.7. Hesitation Due to Not Being Alone. Research by Latane and Darley [Latane and Darley, 1968] has shown that when the fire cues are noticed but not immediately compelling, adults will hesitate in their responses if other capable adults are in the same room. A simple explanation is that there is a failure to respond due to a feeling of shared responsibility. The computer program accounts for this by delaying responses by one time period for each time period where: there is no one that needs to be rescued, alerted, or roused; there is a second capable occupant in the room; the smoke detectors are not sounding; and the sum of the psychological impacts of the fire cues is less than 30, i.e., if $C<30$ then $T=99999$, where C and T are defined in Section 2.2. (The threshold for this hesitancy is 30 rather than 20 to reflect that more stimuli or cues than the "minimum for response" are required to prevent the "hesitation due to not being alone.")

2.5.8. Time Required to Alert, Wake or Prepare for Evacuation. Whenever one occupant assists another, time for providing or receiving the service must be assigned. The following times are assigned:

If Occupant J is alerting a fully capable and awake adult, he moves to the node of the other occupant. Once he arrives at that node, Occupant J starts his next action with no delay or decision time charged. The occupant being alerted is assigned a Delay Time of five seconds or 2.5 seconds 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 five seconds for the occupant doing the waking. For the occupant who is being awakened the delay is ten seconds--5 seconds for waking plus 5 seconds 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 seconds and the total Delay Time for the previously sleeping occupant would be 5 seconds.

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 seconds if the disabled occupant is awake and 12 seconds 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 seconds ((2+4)/2).

2.6. Smoke Detectors.

The building may have up to three smoke detectors. These smoke detectors are independent and are not interconnected in any way. It is necessary to provide the locations of the smoke detectors and how loud each detector would sound in each room of the building. A smoke detector will sound if the smoke density of the upper layer smoke is at least .015, and the depth of the upper layer is .15 meters or greater.

An option in the program is to consider the smoke detectors as broken. It is, therefore, easy to determine the effect of smoke detectors by running the program twice with the same fire and occupants, once with smoke detectors working and once with them broken.

A third option is for the user to preset the time for each detector to sound.

2.7. Current Limitations and Future Development.

The model as described in this paper is a preliminary version of a model under development. The development, improvement and expansion of the model is a continuing activity. The user should be aware of the limitations of the current model. These limitations include:

1. The model is deterministic. Only typical behavior is modelled: aberrant behavior is not permitted.

2. Improved calibration is required to upgrade its validity. Calibration means changing parameter values in the model based on: a. analyses of data in the technical literature; b. judgments of a panel of experts; c. analyses of in depth interviews of survivors of residential fires; and, d. attempts to simulate behavior in real fire emergencies for which we have information. An intensive effort to improve the calibration of the model, is scheduled for the next year.

3 Some typical actions are not included, especially, fighting the fire, phoning the fire department from within the residence, reentering the building.

4. Occupants respond to smoke conditions but not to heat conditions.

The current development program is designed to overcome and eliminate these limitations. The program can be made probabilistic, and heat will be added as a factor in decision making and route selection,

The model permits the user at the keyboard to override a very limited set of the occupant decisions assigned by the computer. Within the next few months, the user will be given the opportunity to override most, if not all, of these assigned decisions. This will permit the model to be used in studying the effect on safety of alternative decisions by the occupants.

3 USING THE MODEL.

3.1 Introduction.

The program is written in the BASICA programming language for the IBM-PC computer. Other computers can be used if: they can accept programs written for the IBM-PC; and there is available a version of BASICA (or BASIC) compatible with BASICA for the IBM-PC. It is very user friendly in that it requires very little knowledge about the program--and no knowledge about programming--to use. It is designed to be sufficiently easy to use that it should not be necessary to refer to this chapter in order to run the model. However, this chapter is valuable as the source of information for the following purposes:

> To assist users to get started if they have no knowledge of the Disk Operating System (DOS):
>
> To obtain a better understanding of the options given the user when running the program;

Since much of this chapter is designed to be used as reference material, many of the sections are written as reference material rather than as descriptive narrative.

The simulation normally displays the building layout and the location of the occupants on the monitor screen (i,e., the "TV" screen). This feature requires the computer to have a "graphics board" that enables the computer to handle the graphics instructions in programming language BASICA. The computer will ask if the computer has an IBM graphics board or one that works like it. If the computer does not have the proper graphics board, answer NO, and the program will not display the floor layouts and the location of the resident on the screen.

There are nine fire scenarios available for use in the version being distributed. (It is possible to add a fire scenario of the users choice but adding a completely new scenario requires a considerable amount of effort to input all the data that is needed.) Making changes to the fire characteristics and to the occupants is relatively easy. Making minor changes to the characteristics of the building is also easy but some changes require a working knowledge of the BASIC programming language (but not an expert knowledge). More information on this will be given later.

While it is not necessary to know anything about programming to use this simulation, it is, of course, necessary, to know enough about your computer to start the running of a BASIC program and to understand the limited computer terminology in this introduction.

The simulation is provided on one floppy disk. This floppy disk contains a number of different programs and data files. These programs must work together for the simulation to work properly. If all these programs and data files remain together in a single disk drive (and directory), the computer will switch or chain from one program to the other automatically. The user must tell the computer in which disk drive the program is available by answering a question which will appear on the monitor or screen.

The program has a number of options. The user selects the options he wants by answering questions. The number of such options might overwhelm the first time user. One question is "IS THIS YOUR FIRST EXPERIENCE WITH THIS PROGRAM?" A YES answer directs the computer to select a fire scenario and to limit the number of options for the novice.

There are three different building layouts permanently available to the user. (It is possible for the sophisticated user to add a fourth building of his/her own design. Instructions for doing this are in Chapter 6, Describing a New Building, Its Occupants and the Fire.) One option is to load the characteristics of a building of the user's choice through the keyboard by answering a series of questions. When you define a building through the keyboard you lose the option of having a graphical representation of the building layout on the monitor screen. To gain an understanding of the input data that affects the simulation, it is suggested that you enter the characteristics of a very small building, its occupants and a fire, through the keyboard. (Such a small building might be only two rooms and a hallway.) However, use of the stored scenarios and buildings are recommended for use by the novice as he experiments with the model and learns its characteristics.

3.2 How to Start and Run the Program.

To run the simulation model the user must load BASICA into his computer and then load and run the program EXITT. If all the provided programs and data files are available on the default disk drive, no other actions are needed to run the simulation model. However, if you have fancy options on your computer, you may have to program your computer to perform like a standard IBM-PC.

The following describes, for the novice, one way to set up a computer to do this if the simulation is being run as a self contained model. If the simulation is being run in conjunction with other models, such as is done with the Hazard Assessment Methodology [Bukowski, 1987], procedures and instructions that permit the models to work together will supercede the recommendations below.

Whether or not your computer has a hard or fixed disk drive will determine how the program is loaded into the computer. The following discussion is for users with a standard IBM-PC personal computer (or compatible computer) and very limited knowledge of the disk operating system for their computer.

> If your computer has one or two floppy disk drives and no hard disk drives, place a disk with MS DOS (DISK OPERATING SYSTEM) into disk drive A, close the "door" of the disk drive and turn the computer on. (When you turn on the computer, the disk operating system will automatically load into the computer--If you have problems, you probably put the disk in the wrong disk drive.) At the A> prompt--i.e., when A> appears on

the screen--type BASICA and press the return key. This will load the BASICA programming language into your computer. (If you do not have an IBM computer, you may have to replace the MS DOS disk with a disk containing BASICA before typing BASICA.)

Once the programming language BASICA has been loaded into the computer, you will receive a prompt, Ok, from the computer. At the Ok prompt, replace the MS DOS DISK with the disk containing all the programs for the simulation, close the door, type the expression RUN "EXITT" and press return. This statement will load the simulation into the computer and start the program.

If your computer has a hard disk drive and you wish to copy the simulation onto the hard disk, use the following instructions: (It is assumed that the computer has the root directory on the hard disk as the available directory. Unless the computer has been programed to do otherwise, you have this situation when you turn on the computer.)

Place the disk containing all the programs for the simulation in drive A and close the door.

At the C> prompt type COPY A:EXITT and press return. (This will load a program that will make it easier to start the program.)

At the C> prompt, type MD EXIT. (This will make a new directory in which we will store the simulation programs on your hard disk.)

Type CD\EXIT. (This will tell the hard disk to refer to the EXIT directory.)

Type COPY A: *.* and press return. (This will copy the contents of the programs and data files on the simulation disk onto the hard disk.)

Remove the simulation disk from drive A and replace it with the MS DOS disk. (If you do not have an IBM computer, use whatever disk has your copy of BASICA.) At the C> prompt, type COPY A:BASICA.* and press return. (This will copy BASICA onto the hard disk in the simulation directory.)

> Note: This step can be omitted if you can access BASICA from this directory. You can test for this by typing BASICA and pressing the return key before starting this step. If BASICA appears on the screen, you can omit this step. You can get out of BASICA by typing SYSTEM and pressing the return key.

To start the program when you are using a hard disk, type EXITT and press the return key. (You can do this if you are in either the root directory or the EXIT subdirectory.) This will start a program that will change to the proper directory; load BASICA; load program EXITT; and tell the computer to start running the EXITT program.

To control the running of the program, the user answers the questions posed by the computer on the monitor screen (i.e. the "TV screen"). To answer these questions it is not necessary to have any knowledge of computers, programming or the characteristics of this computer simulation.

> Exception: the user should know if his computer has an IBM graphics board (or one that works like one). If the user does not know, he should assume his computer has the proper board. If the program stops running immediately after he answers YES to the question about the graphics board, he can assume he does not have the proper board (or the board in his computer is not currently programmed to act like an IBM graphics board).

3.3 Description of the Options.

The options are presented as questions and are self explanatory. However, some of the effects of the option choices are not obvious. While it is not necessary to know these effects to use the program, they are described below.

> DO YOU WANT TO USE YOUR PRINTER? A negative response will suppress all printer output. If your computer does not have a printer, the program may not work unless you give a negative response. If you give an affirmative response, a record of the simulation results will be printed.
>
> IN WHICH DISK DRIVE IS YOUR PROGRAM: A, B, OR C? Since some users may have stored the program on a hard disk (drive C) and others may have the program stored on a floppy disk (drive A or B), this option gives users the flexibility to use any of these disk drives.
>
> DOES YOUR COMPUTER HAVE A COLOR MONITOR (TV SCREEN)? Color displays on the screen often cannot be seen on black and white screens. This option permits the computer to use color displays on color monitors and monochrome displays on monochrome monitors. Type 1 if you have a color monitor or 2 if you have a monochrome monitor. (Note there will be color displays only when you use building 1.)
>
> It is not necessary to ask the user this question when he is using an IBM-PC. Instead he should change the instructions in statement 971 of program EXITT to X=1. When X=1, the program will direct an IBM computer to determine for itself whether it is attached to a monochrome or color monitor.
>
> DO YOU WANT TO DEFINE YOUR OWN BUILDING? The normal mode of running this simulation program is to use one of the available fire scenarios, including scenarios you have "programmed". If you do, the characteristics of the building are preset. If you choose to define your own building, you must also enter the characteristics of the smoke and of the building occupants through the keyboard. Entering the characteristics of the building, smoke spread and occupants is very easy but time consuming because of the amount of data that must be entered.

If you define your own building through the keyboard, the graphics part of the output is suppressed.

ARE YOU IN A HURRY--THAT IS, WOULD YOU LIKE TO BYPASS SOME OF THE REPETITIVE INFORMATION THAT CAN BE PRINTED ON THE SCREEN? This option is self explanatory. It also applies to output from the printer if the printer is working. The most important sets of data that are not displayed, if you respond affirmatively, are the smoke conditions. It is recommended that you answer YES to this question unless you have a special reason to answer NO.

IN THIS SIMULATION THE COMPUTER WILL MAKE DECISIONS FOR THE BUILDING OCCUPANTS SUCH AS WHETHER TO INVESTIGATE THE FIRE OR ESCAPE. DO YOU WANT THE ABILITY TO OVERRULE SOME OF THE OCCUPANT DECISIONS AS GENERATED BY THE COMPUTER? The current version of the program gives the user a limited capability to make changes. Future versions will give the user additional capability. An affirmative answer gives the user an opportunity to change the cycle time if the user is entering the smoke characteristics through the keyboard. An affirmative response gives the user the opportunity to answer the following questions about the smoke detectors.

ARE THE SMOKE DETECTORS BROKEN? The simulation is based on the assumption that there is one, two or three independent single station detectors in the building. The available fire scenarios all include working detectors. This option gives the user the capability of disabling all the defined detectors. <u>If the user defines his own scenario that does not include operating smoke detectors, he must answer yes to this question.</u> (He must also respond YES to the question <u>DO YOU WANT THE ABILITY TO OVERRULE SOME OF THE OCCUPANT DECISIONS AS GENERATED BY THE COMPUTER</u>? in order to get to this option.) If the smoke detectors are not functional, the initial response to the simulated fire may be delayed, just as in real life.

DO YOU WANT TO PRESET WHEN THE SMOKE DETECTOR WILL SOUND? The simulation will normally determine when a smoke detector will sound based on the smoke conditions in the room in which the specific smoke detector is located. If the user chooses to have the ability to overrule some the occupant decisions, he will be presented with this option. If he answers affirmatively, he will be directed to preset the time of sounding for each of the smoke detectors in the building.

DO YOU WANT TO CONTROL THE DENSITY AND THICKNESS OF THE UPPER SMOKE LAYER? If the user is using one of the available fire scenarios, the spread of the smoke is normally controlled by the computer. However, if this question is answered affirmatively, the computer will ask the user to input the smoke conditions each time period. (To minimize the effort required, only changes in the smoke conditions from the previous time period need to be entered.) If you are defining your own building through the keyboard, you must, of course, provide the smoke densities through the keyboard. The computer will give the user an opportunity to change smoke densities, height of upper layer, and whether or not a flame is visible at the beginning of each separate time cycle. Note: if the simulation program contains smoke data for X time cycles and the simulations runs for X+1 time cycles, at the X+1 time cycle, the program will switch to this option.

DO YOU WANT TO RUN AN ADVANCED VERSION OF THIS PROGRAM? The "advanced" features relate to the ability to make and store changes in the input data and the program parameters. Specifically, an affirmative response to this question will automatically give the user the opportunity to make changes in the input data and some of the parameter values (unless the user is defining his own building through the keyboard.) If a negative response is chosen, the user will be given the opportunity to make changes only in the characteristics of the occupants.

DO YOU WANT TO SAVE THE INPUT DATA FROM THIS RUNNING OF THIS PROGRAM? An affirmative answer to this question directs the computer to save all the input data and parameter values used in the current running of the program. The purpose of saving these values is to use them in a subsequent running of the model. It should be noted that if no changes are made, the future running of the model will give the same output as the current run. However, the user will have ample opportunity to make changes when he runs the model with the saved data.

DO YOU WANT TO USE THE INPUT DATA FROM A PREVIOUS TIME YOU RAN THIS SIMULATION? An affirmative response permits the user to use the input data saved from a previous run. See comments under previous option.

WE WILL USE THE INPUT DATA AND PARAMETERS IN A COMPUTER FILENAME 'DATA.SAV'. DO YOU WANT TO USE A DIFFERENT FILE? The program contains some error checks when renaming files--however, failure to follow the rules for naming files might cause the running of the program to terminate.

THE RESULTS OF THIS RUN WILL BE STORED IN A COMPUTER FILE NAMED 'DATA.SAV'. DO YOU WANT THE FILE TO HAVE A DIFFERENT FILENAME? These two options permit the saving and reusing of many sets of input data and parameter values.

THE RESULTS OF THIS RUN WILL BE STORED IN A COMPUTER FILE NAMED 'RERUN. EVA'. DO YOU WANT THE FILE TO HAVE A DIFFERENT NAME? The data being saved contains the arrival time of each occupant as he arrives at a node. It is used by Program TENAB which calculates the toxic smoke exposure of each occupant [Bukowski, 1987]. Although the suggested name may differ, the user is always given an opportunity to assign the name he prefers. Therefore, the user can easily save the results of an unlimited number of runs.

DO YOU WANT THE COMPUTER TO PLACE OCCUPANTS IN THE BUILDING? If the user is using one of the available fire scenarios, the location and characteristics of the occupants are normally preset. However, if the user answers this question affirmatively, the computer will ask a series of questions that permits the user to define the characteristics of the occupants. In any event, the user is given the opportunity, at a later point in the program, to modify the characteristics of the occupants.

3.4 Description of Input Data.

3.4.1 Introduction. In order to run this model it is necessary to define the characteristics of the building, the building occupants and the fire. These input data can be defined in one of three ways:

> The user can enter the characteristics through the keyboard. He does this by answering a very long series of questions. The user activates this option by giving an affirmative respond properly to the question: DO YOU WANT TO DEFINE YOUR OWN BUILDING? (If he answers negatively, the user will be asked to choose among the three buildings stored in the computer programs and data files.)
>
> The characteristics of three buildings, nine fires and eight sets of occupants are stored in subroutines and data files. These subroutines and data files will be automatically called, as needed, if the user responds properly to the questions:
>
> > DO YOU WANT TO DEFINE YOUR OWN BUILDING?
> >
> > DO YOU WANT TO CONTROL THE DENSITY AND THICKNESS OF THE UPPER SMOKE LAYER? and
> >
> > DO YOU WANT THE COMPUTER TO PLACE OCCUPANTS IN THE BUILDING?
>
> The user will be asked to select among the three buildings, the two or more fires for that building, and the two or more sets of occupants for that building. (It is possible to change these inputs by modifying the appropriate subroutines and data files: information that will assist the user in making these modifications is contained in Chapter 6.) The user will be given an opportunity to change the characteristics of the occupants through the keyboard. He also will be given the opportunity to change the characteristics of the building and the fire by answering affirmatively to the question: DO YOU WANT TO RUN AN ADVANCED VERSION OF THIS PROGRAM?
>
> The characteristics used in a previous run can be used. The user selects these data if he answers affirmatively to the questions: DO YOU WANT TO RUN AN ADVANCED VERSION OF THIS PROGRAM? and DO YOU WANT TO USE THE INPUT DATA FROM A PREVIOUS TIME YOU RAN THIS SIMULATION? Note that if you use the same input data, you will get the same output. Therefore, the user will be given ample opportunity to make changes.

3.4.2 Occupant Characteristics

3.4.2.1 Introduction: The user will always have an opportunity to either define or modify the characteristics of the occupants. The characteristics that can be defined or modified by the user are: age, sex, 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. These characteristics are used in the decision rules of the simulation.

3.4.2.2 Age. The age of an occupant is most important if the occupant is a child. An infant is defined as being age 0. Very young children will not respond to a fire and should be labeled as needing assistance.

The computer may assign capable children different actions than it assigns adults in the same situation. An occupant over the age of ten functions as an adult. Young children (i.e., seven or younger) respond differently than children eight or older, e.g., young capable children will not be assigned to assist someone out of the building. Younger persons who need assistance are rescued before older persons in the same room.

3.4.2.3 Sex. The sex of the occupant plays a significant role only if the occupant is over twenty and young children are in the building. A male adult may investigate a fire before he attempts to rescue his children, while a female occupant, twenty years of age or older, will always rescue a baby first.

3.4.2.4 Help. Whether or not an occupant needs help in evacuating plays a large role in the simulation. An adult who needs help evacuating cannot investigate a fire and cannot leave unless another occupant over the age of ten can assist him. It is assumed that it does not require much strength to assist an occupant out of the building: e.g. carry a baby, assist an elderly occupant, lead a mentally retarded occupant.

When an occupant is being helped to evacuate, the travel speed of the rescuer is decreased.

An occupant cannot need partial help; he is either capable or incapable of egressing the building. An occupant, over the age of ten, who does not need help evacuating, is assumed to be able to help any other occupant who does need help.

Very young children are automatically defined as needing help. If the age of the child is equal to or less than the assigned value of the parameter BABY,the child is labelled as needing help.

3.4.2.5 Sleep. An occupant who is asleep cannot respond to the fire until after he awakes. The fire cues or stimuli must total at least TH (the response threshold) or the occupant will remain asleep until awaken by another occupant. His state of consciousness (i.e., asleep or awake) is important in determining the total length of time it will take for that occupant to react to a given set of fire cues.

> SELECT A SLEEPING PENALTY FOR PERSON J. The sleeping penalty is an extra amount of fire cues or stimuli needed to awaken a sleeping occupant. A sleeping penalty of zero is normal. The higher the number, the heavier a sleeper the occupant is: a high value may prevent the

occupant from awakening without help. (Entering a negative value for the sleeping penalty will indicate that the person is a light sleeper--e.g. parent of a baby.) An occupant who is in a relatively deep sleep will have a sleeping penalty of around five to ten and will require a greater intensity of fire stimuli before awakening: an intoxicated occupant may be assigned a much larger sleeping penalty, depending upon how much alcohol he has consumed. A person with a minor hearing loss should normally be assigned a sleeping penalty equal to his hearing loss in decibels.

3.4.2.6 Room. This item is self explanatory. The occupant must be in a room and not at an exit node at the start of the program. His room location is defined when his other characteristics are defined and can be changed whenever the user is given the opportunity to change the characteristics of the occupants. The occupant is automatically placed at the node that is the same as his assigned room number, e.g., if an occupant is placed in room 2, the computer will place him at node 2.

3.4.3 Building Characteristics

3.4.3.1 Introduction. The user will have the opportunity either to define or modify the characteristics of the building if he selects the correct options--see Section 3.4.1. The characteristics of the building are: number of rooms, number of exits, number of nodes, room location of each node, distances between nodes, background noise in each room, and information about smoke detectors and how loud they sound in each room.

The simulation has three subroutines that each contain the input data that describe one building, giving the user easy access to three different buildings. It is possible to write a fourth subroutine that contains the input for a building of your choice, but it is very time consuming to write. Procedures for creating a fourth building or for changing the stored values of the building characteristics, will be described in Chapter 6. Changes that can be made through the keyboard by answering questions will be discussed in this section. Data for the three buildings includes floor plans based on common layouts.

3.4.3.2 Description of the three buildings.

Ranch House. This is a three bedroom, two bathroom, one level ranch house. It includes a living/dining room and a kitchen as well. This building layout is the simplest of the three in that there is only one story. See Figure 1a.

Two-story Townhouse. On the first floor there is a living/dining room off of the kitchen, a foyer, a family room directly off of the kitchen, a bathroom, and a broom closet that houses the hot water heater. The second floor includes three bedrooms and two bathrooms. There is a central hallway on each of the levels. The most important difference between the townhouse and the ranch house is that the townhouse has two stories and, therefore, has a staircase leading to its second floor. See Figure 1b.

Two-story Detached House. The first floor features a separate living and dining room, family room, kitchen, and bathroom. The second floor has three bedrooms, two bathrooms and an extra room (bedroom, study or office). At the front door is a foyer and a hallway leading to the family area. The rest of the first floor rooms can be separated from adjacent rooms by doors. The second floor has a central hallway that leads to all of the bedrooms and one of the bathrooms. See Figure 1c.

Limitations. This program is limited to 12 rooms and a total of 35 nodes. The program that distributes the smoke throughout the building is limited to a smaller number of rooms. To keep the number of rooms small, in the two story houses, not every room is necessarily treated as aa separate "room". In the town house, the kitchen and family area constitute one room as opposed to two separate rooms: the only bathroom that is counted as a separate room is the one in the master bedroom. In the two-story detached house, none of the bathrooms are treated as a separate room. Although the kitchen has been assigned a node, it is considered to be in the same room as the family area (i.e., the smoke conditions in the entire area are similar). Room five includes the stairs and the second floor hallway, and room three includes the living room and the foyer. Room numbers are assigned to be consistent with the program from which the smoke data is obtained, i.e., FAST.

3.4.3.3 Nodes, Rooms and Exits.

Number of Rooms. This program is limited to 12 rooms.

Number of Exits. Exits include doors to the outside and windows that can and might be used to exit the building. Windows that are not usable (e.g. painted shut or with a window air conditioner) or near a door, would not be considered to be exits.

Number of Nodes. Each room contains at least one node: the node number of the most central node is the same as the corresponding room number. Each exit is considered a node. In addition, additional nodes may be assigned within any room. These extra nodes are usually assigned at choice points along paths between rooms/nodes: for example, in Figure 1a, node 15 is a choice point on all routes starting at room one and ending elsewhere in the building such as the route between node 1 and node 2 and the route between node 1 and node 7.

Distances Between Nodes. If the normal route between two nodes is direct--i.e., not by way of a third node--then the distance (the length of the link) between the two nodes should be an input variable. It is necessary to define the distance in one direction only--either direction is acceptable. The unit of measure is meters.

3.4.3.4 Background Noise. The background noise level in a room will affect the ability of an occupant to hear the alarm. There is a minimum of 35 decibels of background noise--even if there is no background noise, the computer will consider the background noise to be 35 decibels. The white noise generated by an air conditioner will result in approximately 50 decibels of background noise. A loud stereo will result in even more background noise. If the background noise is louder than the smoke detector (i.e. if the background noise is greater in decibels than the alarm), the occupant in that room will not hear the smoke detector. The loudness of the alarm can also be changed (see below).

3.4.3.5 Input Variables for One Story Buildings. A building is treated as one story building when the parameter NB1=1. (A building with only one story could be treated as a two story building but the converse is not true.) In "one story" buildings there is only one smoke detector and it is defined as being in the hall. It is necessary to set the loudness of the detector in the hall and the door position (open or closed) of the doors between the hall and the other rooms. The loudness of the alarm in each room is computed using the following rule: 12 decibels are lost as the sound passes into a room with an open door and 24 decibels are lost as the sound passes into a room with a closed door. The minimum background noise is 35 decibels.

Whether or not a door is open or closed will affect two aspects of the simulation. A closed door will result in a decrease in loudness of the alarm signal in that room. Secondly, smoke movement will be restricted. For example, little or no smoke may enter a room with a closed door, depending on how the leakage through the door is defined. Because of this, the response time of an occupant in a room with a closed door--other than the room of fire origin--may be greatly delayed, both in the simulation and in real life.

3.4.3.6 Input Variables for Two Story Buildings. A building is treated as a multiple story building when parameter NB1=2. (A building with only one story could be treated as a two story building but the reverse is not true.) In one story buildings the computer computes, for each room, the loudness or signal intensity of the one smoke detector. In larger buildings there may be more than one detector and the geometry of the building is such that it is easier to enter the loudness of each detector for each room than to enter data that permits the computer to compute these values. Therefore, the user must enter the loudness of each detector for each room. (If the loudness is 35 decibels or less, the value of value 35 should be entered: lower values will be automatically increased to 35.) It should be noted that in the current version of the model, whenever the user defines the building through the keyboard, he is restricted to using a one story building, i.e. NB1=1. (If NB1=2, there is neither the need nor the opportunity for the user to set the door positions when running the EXITT model.)

3.4.3.7 Smoke Detectors. There are several opportunities in the program to alter different aspects of the smoke detectors by answering questions through the keyboard. Those aspects that can be changed will affect the responsiveness of an occupant to the fire cues.

Broken Smoke Detectors. The user will get a chance to "break" the smoke detectors if he answers affirmatively to the question, DO YOU WANT THE OPPORTUNITY TO OVERRULE SOME OF THE OCCUPANT DECISIONS AS GENERATED BY THE COMPUTER? A broken smoke detector will never work. It is equivalent to not having a smoke detector at all--one way to model a building with no smoke detectors is to define the detector(s) as broken. (Another way is to set the smoke detectors to activate at a time after all occupants are certain to be safe or dead--see option DO YOU WANT TO PRESET WHEN THE SMOKE DETECTORS WILL SOUND in Section 3.3). Occupants in a building where the smoke detectors do not work are dependent solely upon the other fire cues (e.g., smoke) to determine that there is a fire. This may greatly increase the amount of time necessary to respond to the fire.

Loudness. The loudness or signal intensity of a smoke detector alarm is important in determining if a person will hear the alarm or, if sleeping, if he will awaken. The normal signal intensity for a smoke detectors alarms in the hall of a one story building is 85 decibels, but it can have a range from 75 to 141 decibels when the user defines his own building through the keyboard. Locations more remote from the alarm will have lower signal intensities.

Presetting Smoke Alarm. The smoke detector will sound if the smoke density exceeds a prescribed level, and the depth of the smoke in the upper layer is at least .15 meters. The user will be given the opportunity to override this automatic feature and preset the time when the smoke alarms will sound. Whether the smoke detector activation is controlled by the program or is preset, the alarm will sound only at the beginning of a time period.

(The minimum smoke density that will activate a smoke detector is the parameter TOL(5): it is set equal to .15. The user will get a chance to change this value if he responds affirmatively to the question: DO YOU WANT TO RUN AN ADVANCED VERSION OF THIS PROGRAM?)

3.5 Making Changes in the Program.

Much of the information in the following chapters is designed to permit the user to make changes in the program. The casual user is unlikely to want to make such changes. However, there are some changes that the serious user may want to make. Some examples are:

The user may want to add an additional building of his own design to the available set of buildings.

The user may want to change some of the parameter values that cannot be changed through the keyboard for a given run.

The user may want to change default values of parameters that can be changed through the keyboard for a given run.

The user making such changes should be aware that program DEC3 is too large to run within the 64k bytes of memory available in BASICA. To make it small enough, it has been compressed. The compressed program is called COMP4. To make changes in DEC3, the user must have access to a program to compress the modified version of DEC3 or the user must make the changes directly in program COMP4. (The program used to compress DEC3 is copyrighted and cannot be provided as part of the simulation disk.)

4. DESCRIPTION OF COMPUTER PROGRAM.

4.1 Introduction.

EXITT is programed in the BASICA programming language for an IBM PC computer with 128k bytes of random access memory. It can be run without modification on similar computers of other companies. DOS 2.1 or later is required.

For the most part the program is written in a simple style. Emphasis was given to making the model easy to modify and expand rather than to minimizing computer running time.

This Chapter presents information about the computer program. While the general description of the model in presented in Chapter 2, additional details about the model are included in this chapter.

4.2 Structure of the Program. Because of the characteristics and limitations of the BASICA programming language, the computer instructions are contained in 10 separate programs. One of the programs, DEC3, contains the basic simulation model. Since program DEC3 does not fit into the maximum space permitted by BASICA, it has been compressed and the shorter version is called COMP4. (The difference between the two programs is that COMP4 contains no comment statements and two or more short statements in DEC3 may be combined into one long statement in COMP4.) All the other programs are concerned with: defining the building, fire and occupants; defining the parameters; and input and output. The program switches from one program to another through the CHAIN instruction. These programs are:

EXITT. The EXITT program contains: an alphabetic list and very brief description of all parameters and variables; the dimension statements; and the statements that give the user an opportunity to select some of the options. It chains to program DEC1. (A brief description of all parameters and variables is in Appendix A of this report.)

DEC1. The main function of DEC1 is to control the input of the desired fire scenario, including the characteristics of the building, fire and occupants. Based on options selected by the user, the program will:

> Give the user the opportunity to enter the fire scenario (i.e., the characteristics of the occupants, the building, and the fire) through the keyboard;
>
> Call other programs (using the CHAIN statement) that will provide the fire scenario;
>
> Provide an opportunity to modify the fire scenario and many of the program parameters;
>
> Combinations of the above.

DEC1 also contains additional statements that give the user an opportunity to select options.

There is a package of programs that contains: 1. programs with the characteristics of three buildings; two or more set of occupants for each building; and two or more fires for each building; and 2. a program for saving, retrieving and modifying the input data of a run. DEC1 calls these programs (i.e., CHAINS to them), as needed, to obtain the desired information. These programs are:

OCC1. OCC1 is the program that contains the information about the characteristics of the occupants. This program chains back to the DEC1 program.

BLDG. BLDG1 is the program that contains the information about the characteristics of building 1, a ranch house. (See Figure 1a.) BLDG2 contains the information about building 2, a townhouse. (See Figure 1b.) BLDG3 contains the information about building 3, a two story detached house. (See Figures 1c and 1d.) BLDG4 is reserved for a building designed by the user. These programs chain either to another BLDG program or back to the DEC1 program.

SMOKE9. The smoke characteristics of each fire is stored in a data file with a name containing the word SMOKE followed by one or two digits and the suffix SMK. The first digit indicates the building in which the fire is located. The second digit, if any, is used to distinguish between fires in the same building. (For example, SMOKE11.SMK is the file for one of the fires in building 1.) Program SMOKE9 inputs data from the selected data file. SMOKE9 also contains (and inputs) data for other aspects of the fire scenario such as background noise and the location and characteristics of the smoke detectors. Program SMOKE9 chains to the DEC1 program.

AGAIN. AGAIN is a program that stores the input data from a run so that it can be used again and that retrieves these data in a subsequent run. If the data were used unmodified in a second run, the run would be identical and the results would be identical: therefore, AGAIN provides the user with an opportunity to change one or more of the input datum, including many of the parameter values.

4.3 Description of the Fire.

4.3.1 General Description. The fire characteristics within room I at a given time are fully described by three variables:

SDUL(I). The simulation model is based on a two zone smoke spread model with a layer of smoke at the top of the room and a lower layer of non defined density. SDUL(I) is the density of the upper layer.

SDLL(I). SDLL(I) is the height of the lower layer. If there is no smoke in a room, then SDLL(I) is defined equal to the height of the room.

FLAME(I). FLAME(I)=0 if there is no visible flame, FLAME(I)=999 if there is visible flame in room I, and FLAME(I)=1 if there is no visible flame in room I but flame in another room can be seen from room I. It is not necessary to input values of FLAME(I) and little will be lost if, at ignition, no occupant is awake in the room with the flame. The program is normally run without inputting flame characteristics, i.e., FLAME(I)=0 for all rooms. In future versions flame may have a more important role.

4.3.2 HF(I). To decrease the number of rooms in a computer run of a smoke spread model, rooms may be consolidated. A "room" could contain a stairway and a upstairs hallway. The height of the floor at a node in the hallway would be above the height of the bottom of the room, i.e., the bottom of the stairs. This difference is the variable HF(I). It is used in determining the impact of the smoke. If this problem does not arise, ignore this variable, it will be automatically be given the default value of zero and the program will operate correctly. Note: the value of HR(I), the height of the room at node I, will be the distance from the floor to the ceiling at node I.

4.3.3 SMOKE. The impact of smoke is a function of the density of the upper smoke layer and its thickness. The generally used measure of this impact in a room is the variable SMOKE. It is computed in subroutine 3090-3098 of program DEC3. (It is twice the product of SDUL(I) and the ratio of the thickness of the upper layer to the height of the room--see Section 2.2).

4.4 Awareness of Fire.

4.4.1 The Basic Algorithm. The 5000 series of instructions in program DEC3 contains the decision rules for determining if and when an occupant will respond to the fire cues. The basic equation (which is statement 5250 of program DEC3) is:

TRESP(J) = 70 - 4(AWARE(J)-TH), subject to the following restrictions:

TRESP(J) is unchanged if TH>AWARE(J); and

TRESP(J) >= a minimum value based on the smoke conditions and whether the occupant is awake or asleep, where:

AWARE(J) is the sum of the impacts of all the fire cues;

TRESP(J) is the time until occupant J starts his action; and

TH is the threshold for response, i.e., the minimum value of AWARE(J) necessary for a response. Its value is set in statement 1008 of program DEC1 and can be modified through the keyboard in program AGAIN if the appropriate options are selected. It value must be greater than 15 unless instruction 5125 of DEC3 is modified. That is, TH must be greater than X4.

The basic equation for computing AWARE(J) is:

AWARE(J) = ALEFF + X1 + X2 + X3 + X4, where:

> ALEFF is the difference between the loudness of the alarm and the background noise;
>
> X1 is impact of an awake occupant seeing flame;
>
> X2 is impact of an occupant smelling smoke;
>
> X3 is impact of an awake occupant seeing smoke; and
>
> X4 is bonus for being awake or (penalty for being asleep).

4.4.2 Detectors. Detectors sound at a signal intensity of LROOM(I,II) where I is the room number and II is the detector number. The units are decibels. In two story buildings, these values are input variables. In one story buildings, the values are computed using the rule that 12 decibels are lost as the sound enters a room with the door open and 24 decibels are lost as the sound enters a room with the door closed. See instructions 5055, 5155, 5255 or 5355 of program SMOKE9 (and subroutine 4250 of program DEC1 when user is defining his own building and subroutine 5400 of program DEC1 when the user is changing or correcting the door settings from open to closed or vice versa).

The volume of the detector alarm in the room containing the alarm is the parameter LALARM. Its value is set in statements 1400-1428 of program DEC1 when the user defines the building through the keyboard. Otherwise, it is defined in statement 20 of program SMOKE9.

4.4.3 Measures of Fire Cue Impact. Each of the fire cues is measured in different units. The units for the loudness of the smoke alarm is decibels (dB). All the other units are "converted" to decibels, i.e., the values are transformed to the number of decibels that would approximate an equivalent impact in alerting occupants.

Sound. ALEFF is the difference between the loudness of the alarm and the background noise. This is computed in statements 5010 to 5115 of program DEC3. The first step in computing ALEFF is to determine if the smoke detectors are sounding. One of the options is to preset when the detectors will sound. If the detectors are preset, statement 5026 will flag a detector as sounding. If the detectors are not preset, statement 5031 will flag a detector as sounding if there is sufficient smoke in the room/hall containing the detector.

X1. X1 is the impact of an awake occupant seeing flame. It is the product of SLP, CFIRE and FLAME(I). (See statement 5116 of program DEC3.) Since both SLP AND FLAME(I) are either zero or >=1, X1 will be either zero or >=CFIRE.

> SLP. If the occupant J is asleep (i.e., if SLEEP(J)=1), then SLP=1. Otherwise, SLP=0. (See instruction 5010.)

FLAME(I). FLAME(I)=999 or 1 if flame is in or near room I. Otherwise, FLAME(I)=0. Note: the program normally runs well if FLAME=0 throughout the running of the program because the smoke conditions provide sufficient information about the fire.

CFIRE. CFIRE is a parameter that defines the magnitude of the impact of seeing a fire on becoming aware of the fire. Its value is set in statement 1005 of program DEC1 and can be modified through the keyboard in program AGAIN if the appropriate options have been selected (see statement 4325 of program AGAIN).

X2. X2 represents the impact of the odor and irritability of smoke. Its value is the product of SMOKE and COLF where:

SMOKE is a measure of the impact of smoke and is described in Section 4.4.3.

COLF is a parameter that determines the importance of the odor of smoke in alerting an occupant to the fire cues. It is the multiplier used to modify a measure of smoke so that is can be combined with a measure of sound. Its value is set in statement 1005 of program DEC1 and can be modified through the keyboard in program AGAIN if the appropriate options have been selected (see statement 4355 of program AGAIN).

Exception 1. If the occupant is asleep and the lower smoke layer is between 1 and 1.2 meters in depth, then X2=5*(SDUL(I)). (See statement 5119 of program DEC3).

Exception 2. If the occupant is asleep and the lower smoke layer is 1 meter in depth or less, then X2=10*(SDUL(I)). (See statement 5120 of program DEC3.)

X3. X3 represent the impact of seeing smoke. It is the product of SLP, CSMK, and SMOKE where SLP and SMOKE have the properties described above. CSMK is analogous to COLF but relates to the importance of seeing smoke.

Note: if the occupant is sleeping, SLP=0 and, therefore, X3=0.

X4. X4 reflects the phenomenon that awake occupants will require less impacting cues to be alerted. If the occupant is awake, X4=15 (see statement 5125 of program DEC3). If the occupant is asleep, X4=-CSLP(J).

CSLP(J) is a measure of the extra amount of fire cues or stimuli needed to awaken a sleeping occupant who has difficulty waking. It is called a sleeping penalty. A sleeping penalty of zero is normal, i.e., no extra cues are needed. The higher the number, the heavier a sleeper the occupant is: a high value may prevent the occupant from awakening without help. An occupant who is in a relatively deep sleep may have a sleeping penalty of ten or more and will require a greater intensity of fire stimuli before awakening. An intoxicated occupant may be assigned a much larger sleeping penalty, depending upon how much alcohol he has consumed. A person with a minor hearing loss should normally be assigned a sleeping penalty equal to his hearing loss in decibels if it is expected the fire alarm will sound.

Entering a negative value for the sleeping penalty will indicate that the person is a light sleeper--e.g., a parent of a baby. If the value of the sleeping penalty were negative 15, the intensity of the fire cues necessary for response would be the same as when the occupant is awake--see value of 15 given X4 in statement 5125 of program DEC1. Therefore, CSLP(J) should not be given a large negative value.

The values for CSLP(J) are defined in the appropriate subroutine of program OCC1 (and in statement 5292 of program DEC1 when the characteristics of the occupants are being entered or modified through the keyboard).

4.4.4 Minimum Response Times. While occupants respond more quickly to strong fire cues, there is a minimum amount of time required to awaken, if necessary, select an action, and perform preparatory actions. If the occupant is asleep, the minimum time is 10 seconds, (see statement 5258 of program DEC3). If the occupant is awake, the minimum time is 6 seconds, (see statement 5257).

Exception 1. If the smoke is bad (i.e., SMOKE>TOL(3)), the minimum is 4 seconds. (See statement 5263.)

Exception 2. If the smoke is very bad (i.e., SMOKE>TOL(2), the minimum is 1 second. (See statement 5265.)

For each occupant a time to start his actions is computed 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.

4.5 Choice of Actions.

4.5.1 Permitted Responses. Once a capable occupant has decided to respond or has completed an action, he has a choice of responses or actions. Several common responses are not available in this version of the simulation: phoning the fire department; fighting the fire; reentering the building, and assisting or escorting more than one occupant out of the building . The available responses for capable adults in order of priority are listed below. The order of items 2-7 is determined by instructions 7800-7806 and 7900-7906 (or 7820-7829 and 7920-7922 for children). It should be noted that the priority list of items 2-10 is also followed when an action choice is made upon arrival at a room.

1. Investigate the fire--there are a number of conditions that will make this action an unacceptable or lower priority choice. See Section 2.3.4 and statements 7120-7129 of program DEC3.

2. In the unlikely event that there is a capable and awake adult in the same room who is not aware of the fire cues, alert that occupant. See statements 7450-7469.

3. Wake a sleeping but otherwise capable occupant in the same room (see statements 7500-7516 and 7400-7429 of program DEC3).

4. Rescue an occupant in the same room (see statements 7500-7548). Sleeping occupants are considered first in subroutine 7500: if there are no sleeping occupants that need rescue, awake occupants will be considered in subroutine 7530.

5. Go to the room of a capable awake adult (age between 18 and 60) who is unaware that there may be a fire (response delay of more than 10 seconds) and alert him. (See instructions 7700-7708).

6. Go to the room of an occupant needing rescue (see instructions 7560-7574).

7. Go to the room of an occupant who is asleep (see instructions 7580-7599).

8. Alert an awake and capable occupant, whose response delay is greater than 10 seconds, that there is a need to respond or hurry (see instructions 7710-7718).

9. Investigate the fire if investigation is a permitted choice (see instructions 7200-7202).

10. Egress the building (see instruction 7216).

The available responses for competent children (age 10 years or less) are listed below in order of priority. Competent children are those who don't need assistance in evacuating, i.e., ACT(J) is not equal to 1, 11 or 21.

In this version of the model, an occupant over the age of ten functions as an adult, that is, they follow the priority list presented above for adults. (See statements 7142 and 7160 of program DEC3 for the branching statements.) Young children (i.e., seven or younger) respond differently than children eight or older. (See statements 7129 and 7820 of program DEC3.)

1. Investigate the fire--there are a number of conditions that will make this action an unacceptable or lower priority choice as discussed below. In this version of the model, the rules for older children are the same as for adults. Capable children 7 or younger will not investigate (see statement 7129).

2. In the unlikely event that there is a capable and awake adult in the same room who is not aware of the fire cues, alert that occupant. See statements 7450-7469.

3. Wake a sleeping but otherwise capable occupant in the same room. (See statements 7500-7516 of program DEC3 for children eight and older and statements 7400-7429 for younger capable children. See statement 7820 for the statement with the branching instruction).

4. If the child is 8, 9, or 10 years of age, rescue an occupant in the same room. (See statements 7500-7548.)

5. Go to room of an unaware (or sleeping) but capable adult (age between 13 and 70). (See instructions 7720-7728.)

6. Go to room of an unaware (or sleeping) but capable occupant who is older, i.e., a child will awake or alert another child in another room who is older than he is. (See instructions 7480-7499.)

Note that a child who is 8,9, or 10 will rescue any occupant in the same room but will not go to another room for the purpose of rescuing an occupant. Children 7 and younger neither investigate nor assist others out of the building.

4.5.2 <u>Reasons for Investigation Being Low priority or Not Permitted.</u> Investigation is the most likely action or response unless one of the following conditions apply:

1. If the occupant is a female at least 20 years old and there is a baby who has not yet been assigned to a rescuer, then rescue, waking and alerting have a higher priority than investigation for that female occupant (see instructions 7120-7124 of program DEC3). A child is considered to be a baby if his age is equal to or less than the parameter BABY.

2. Investigation is a permitted action for occupant J only when ACT1(J)> equals zero.

4.5.3 <u>Criteria for Setting ACT1(J)=1.</u> Investigation cannot be selected as an action for occupant J whenever ACT1(J)> is one or two. The criteria for setting ACT1(J) equal to two is described below in the section, "Criteria for the Fire to be Considered Serious". In addition ACT1(J) is set equal to one by any of the following instructions in program DEC3. (Note: none of these apply when ACT1(J)=2):

6844. Occupant is in room with a smoke density of TOL(4) or greater.

6971. Occupant was alerted to the fire emergency by another occupant for whom investigation was not a permitted action.

7127. Same as in instruction 6844.

7678. Occupant was awakened or alerted by another occupant for whom investigation was not a permitted action.

4.5.4 Criteria for Fire to be Considered Serious. A fire is considered to be serious by Occupant J if ACT1(J)=2; occupant J being any capable occupant in the building. ACT1(J) can be set equal to two by any of the following instructions:

6845. Occupant is in a room where the smoke density is at TOL(3) or greater, or in a room where flame is visible.

6937. Occupant is in the same room as another occupant who considers the fire to be serious. (In this early version of the model, this statement is reached only under special circumstances.)

6971. Occupant is being alerted to the fire emergency by another occupant who considers the fire to be serious.

7128. Same as in instruction 6845.

7678. Occupant is being awakened by another occupant. If the other occupant considers the fire to be serious, then the occupant being awakened will also consider it to be serious.

8150. Occupant has completed his investigation.

8488. Occupant cannot reach his goal (i.e., cannot successfully complete his action because of heavy smoke).

4.6 Finding Shortest Path.

4.6.1 Shortest Path Algorithm. The shortest path algorithm is adapted from Levin and Hedetniemi [1963]. All routes are considered to be composed of nodes along the route and links between the nodes. The basic approach is to develop a tree of nodes and links representing the shortest routes from the origin node to all other nodes. Each time a shorter route is found to any node, that route is tested to determine if it can be used (or extended) as the first n-1 nodes of an n node route to another node. Much of the computer code is concerned with the bookkeeping: to assure that all routes that should be considered for extension are, in fact, tested; and to record the tentative shortest routes.

4.6.2 Handling Obstacles. There are two versions of the subroutine for finding the shortest path. Statements 6100-6199 comprise a subroutine that is a straightforward application of the shortest path algorithm.

Statements 6200-6399 comprise a subroutine that considers obstacles such as smoke and windows. The approach of the second subroutine is to find the route with the fewest demerits where demerits are assigned as follows:

One demerit is assigned for each meter to be travelled. Fractional demerits are assigned. (See statements 6219 and 6257.)

One hundred demerits are assigned for leaving by a window. This is a sufficient penalty to assure that an unobstructed exit path through a door is considered superior to an exit path through a window. (See statements 6219 and 6257.)

Two hundred demerits are assigned for reaching a node that is in a room where the value of SMOKE is between TOL(2) and TOL(1) at the time the subroutine is being run. (See statements 6232 and 6237.)

A link is considered blocked if:

The destination node of the link is in a room where the value of SMOKE is TOL(1) or greater. (See statements 6227 and 6236.)

The destination node of the link is in a different room than the origin node of the link, and the destination node is in a room where the value of SMOKE is TOL(2) or greater. (See statements 6222 & 6227 and 6260 & 6236.)

Exception. If lower smoke layer has depth of at least 1.2 meters, The route is considered passible. (See statements 6221 and 6259.)

Note that a link that may be passible, when the shortest path routine is run, and it may be blocked later, when the occupant attempts to travel the link.

4.6.3 <u>Choice of Exit</u>. When searching for the route out of the building, the subroutine that considers obstacles is used, i.e., the subroutine starting at statement 6200. This subroutine finds the route out of the building with the fewest demerits.

The subroutine uses a two step approach. The routine first finds the best path to the front door. In running this subroutine the computer finds all "shortest" paths to other nodes that are "shorter" than the distance to the front door; that is, all paths that have fewer demerits. (A blocked path is considered to have an infinite number of demerits.) After the best path to the front door is found, the computer selects the path out of the building with the fewest demerits as the best egress route. (See statements 8210-8224.)

4.6.4 <u>Choice of Shortest Path Subroutine</u>. In brief, the straightforward subroutine is called when the occupant has not had an opportunity to learn much about the fire. The subroutine that considers smoke is called when the occupant has learned about the fire or is attempting to leave the building.

When the occupant is investigating the fire cues, the straightforward subroutine is called. (See instruction 8110.)

When the occupant is leaving the building, the subroutine that considers smoke and windows is called. (See statement 8209.)

When the occupant is going to another room to alert, awaken or rescue another occupant, the straightforward subroutine is used. Exception: if the occupant has just been blocked by smoke in his attempt to go to a room or to investigate--that is ACT2(J)=93--the subroutine that considers smoke is called. (See statement 8418.)

4.7 Moving the Occupants.

4.7.1 Introduction. Statements 6800-6999 comprise the one set of instructions that moves all occupants along the path selected by the shortest path programs described in Section 4.6.

4.7.2 Speed. SPEED(J) is the normal travel speed of occupant J. SPD is a parameter which is set at 1.3 meters per second (i.e., almost 3 miles per hour) in statement 1006 of program DEC1. SPEED(J) can be set in three ways:

If the characteristics of the occupants are entered through the keyboard, an occupant's speed is entered in response to a question. (See 5270-5276 of program DEC1.)

If the characteristics of the occupants are entered when running program OCC1, the values of SPEED(J) can be defined with the other characteristics.

If the characteristics of the occupants are entered when running program OCC1, and if the value of any SPEED(J) is not defined with the other characteristics, the value of that SPEED(J) is set equal to SPD. (See statements 1910-1919 of program OCC1.)

The following modifications to the travel speed do not apply to occupants who are investigating.

If an occupant J should consider the fire to be serious, as described in Sections 2.2.2 and 4.5.4--that is, if ACT1(J)=2--then the travel speed would be multiplied by SPD1. SPD1 is set equal to 1.3 in statement 1006 of program DEC1. Therefore, the travel speed of occupant J would be increased by 30% if ACT1(J)=2. (See statements 6809 and 6962 of program DEC3.)

If occupant J is assisting another occupant out of the building, his travel speed usually is cut in half. (See instruction 6808 and 6961.) Note that if he considers the fire to be serious, it is the increased travel speed that is cut in half.

Travel speed to the next node is set as follows when the occupant needs to crawl or bend very low. He is deemed crawling if SMOKE at the next node is at least the average of TOL(2) and TOL(3) and if the depth of the lower smoke layer is less than 1.5 meters. (See statements 6847 and 6848.)

If he is assisting another occupant out of the building, their speed will be .4(SPEED(J)).

If he is not assisting another occupant out of the building, his speed will be .6(SPEED(J)). (See statement 6945.)

4.7.3 Available Time. In this model, the computer must know the location of each occupant. It does this by recording the node at which the occupant is located and the time he started his current action. In this context the "action" could be moving or making a decision. If the occupant cannot complete his movement to the next node in the current time period, the movement is deferred to the next time period.

There are three quantities of interest: distance, travel speed and time. To see if an occupant can complete a movement to a node in the time period, it is necessary to either convert the length of the link to a travel time or convert the available travel time to a travel distance. In this version, the program converts the available travel time to a distance that can be traveled in that time. This new variable is called DT. (See statement 6810.) It is then possible to compare DT with the distance between nodes (statement 6825) and to subtract the distance between nodes from DT to get a new value of DT (statement 6950). By cycling back to statement 6815, the new DT can be used to see if the occupant can move to another node in this time period.

4.7.4 Criteria for Branching out of Subroutine. Whenever the distance to the next node exceeds DT, the program branches out of this subroutine. (See statements 6825-6832.) The program also branches out when: 1. SHORT(J)=0, i.e., the shortest path has not yet been determined (see 6805); 2. route is blocked by smoke (see 6868); 3. occupant reached an exit node (see 6919 and 6929); 4. occupant reached goal, i.e., arrived at destination node (see 6976); and 5. occupant terminated his investigation because he encountered heavy smoke (see 6889).

4.7.5 Smoke. An occupant cannot move to the next node if it requires that he pass through intolerable smoke. Also, if he is investigating the fire cues, he will not move through unpleasant smoke. When SMOKE exceeds TOL(2) and the lower smoke layer is less than 1.2 meters in depth, the smoke is too bad to enter that room. When SMOKE exceeds TOL(1) and the lower layer is less than 1.2 meters, the smoke is too bad to go from one node to another in the same room. Note that the smoke is never so bad as to prevent an occupant from leaving a room if the next node is in a location with an acceptable level of smoke. (See instructions 6850-6855)

When an occupant is investigating, he will:

> Terminate (i.e., complete) his investigation when he arrives at a node where SMOKE>=TOL(4) or flame is visible (see especially statements 6844, 6845, 6930, and 6932);
>
> Terminate (i.e., complete) his investigation without additional movement when the next node on his path is in a room with bad smoke, i.e. SMOKE>=TOL(3) and the lower smoke layer is less than 1.8 meters in depth (see statements 6847 and 6848); and
>
> Complete his investigation if he arrives at his goal, i.e., node GOALJ(J) (see instruction 6948.)

Whenever an occupant moves, his actions are printed on the screen, may be printed on the printer, and may be graphically represented on the screen. Many of the statements in this subroutine are concerned with printing this information. They are straightforward and obvious and are not described in this report.

4.7.6 Assisting Other Occupants to Escape. When an occupant is assisting another occupant to escape, the following is done whenever the first occupant moves to a different node. The program branches to a set of statements that: 1. describes the action on the screen; 2. prints similar information on the printer; and 3. resets the node location of the disabled occupant. (See statements 6988-6991 and 6920-6929.)

5. PARAMETER VALUES

5.1 Introduction. There are a number of numerical constants, imbedded in the decision rules, that the user might wish to change. The value of each of these constants can be changed by making a simple change in the program itself. To provide the user with greater flexibility and control, some of these constants are described below and information necessary to modify them is provided. Usually, the change is so simple and obvious that a brief description of the function of the constant and the location of the statement assigning the constant its value, is all the information provided.

An attempt has been made to make it easy for the user to change some of these values. These constants are assigned parameter names, and the parameter names, rather than the numerical value, are used in the decision rules. These constants will be called parameters. They can be changed by redefining their values in the computer program. Also, some of them can be changed through the keyboard when the user responds affirmatively to the question DO YOU WANT TO RUN AN ADVANCED VERSION OF THIS PROGRAM?

A number of these constants appear as numerical values in the computer statements that set delay times. These values can be changed only by changing the appropriate program statement.

5.2 Parameters.

BABY. BABY is the upper limit of the age at which a child is considered to be too young to perform productive actions in a fire emergency. It is set equal to 3.0 in instruction 1005 of program DEC1.

CFIRE. CFIRE is the scaling factor for seeing flame when summing the impacts of the fire cues. It is set equal to 100 in statement 1005 of program DEC1. The impact of seeing the fire is equivalent to awake person hearing an alarm of CFIRE decibels. Any assigned value above TH+15 will result in the same rapid response.

COLF. COLF is the scaling factor for smoke odor and irritability when summing the impacts of the fire cues. It is set equal to 50 in statement 1005 of program DEC1.

Obviously, the impact of smoke odor is important for awakening and alerting sleeping occupants. However, it appears to have only a mild effect when the smoke conditions are not severe [Kahn, 1984]. The impact on sleeping occupants depends on: smoke density, the irritability of the smoke components and, the location of the head in relation to the upper smoke layer. This model disregards variations in the irritability of the smoke components. If the sleeping occupant's head is in the upper layer, i.e., the depth of the lower layer is less than 1 meter, the impact is similar to a sound of COLF*10*(SDUL(I)) decibels. (See instructions 5118-5123 of program DEC3).

CSMK. CSMK is the scaling factor for awake occupants noticing smoke when summing the impacts of the fire cues. It is set equal to 1000 in statement

1005 of program DEC1. When the upper and lower smoke level depths are equal, the impact is similar to a alarm of CSMK*SDUL(I) decibels. (More precisely, it is the impact of CSMK*S decibels, where S is defined in Section 2.2.2.) Note that for awake occupants, this factor dominates the impact of smoke odor/irritability.

<u>LALARM</u>. LALARM is the loudness or volume of the smoke detector alarm in the hall of a one floor ranch house. Depending on the options selected, it is assigned a value by the user in response to a question or in statement 1105 of program BLDG1, In this version, LALARM is not used for two story houses.

<u>SPD</u>. In program DEC1, SPD is the <u>normal</u> speed of typical capable occupants as they move through the building. It is set equal to 1.3 meters per second (2.9 miles per hour) in instruction 1006 of program DEC1. As described in Section 4.7.2, the normal travel speed of each individual, SPEED(J), can be set equal to SPD or to a value provided by the user, depending on the options selected by the user. Once the values of SPEED(J) are set for all occupants, SPD can then used in program DEC3 for the <u>actual</u> speed of the current occupant being considered. Occupant J refers to any of the occupants in the building.

<u>SPD1</u>. When occupant J considers the fire to be serious (i.e., ACT1(J)=2), he increases his travel speed. This increase is accomplished by multiplying his normal speed by the parameter SPD1. It is set equal to 1.3 in instruction 1006 of program DEC1. This value of SPD1 increases travel speed by 30%.

<u>TCYCLE</u>. TCYCLE is the number of seconds in one time period. It is set equal to 5.0 in statement 1050 of program DEC1 and this value can be superceded through the keyboard if the appropriate options are selected after choosing to use an "advanced" features of the program. If the fire is loaded into the computer by running program SMOKE9, TCYCLE could be assigned a value by a statement in the SMOKE9 program: this would supercede the value assigned in statement 1050 of program DEC1 but not the value assigned through the keyboard.

<u>TH</u>. TH is the threshold for an occupant to respond. The sum of the impact of all fire cues or fire stimuli must equal TH units for any occupant to respond: otherwise he will ignore the fire stimuli. The value of TH is set equal to 20.0 in instruction 1008 of program DEC1.

> Awake occupants are given an extra 15 units when computing the sum of the impacts of the fire cues. This is mathematically equivalent to decreasing TH by 15 for awake occupants. These 15 extra units are given in instruction 5125 of program DEC3: it is the value assigned to X4. The value assigned TH in statement 1008 of program DEC1 must be greater than the value assigned to X4 in statement 5125 of program DEC3.

<u>TOL(I)</u>. There are five levels of smoke tolerance used in this simulation. Their values are set in instruction 1007 of program DEC1. In applying four of these parameters, TOL(1) through TOL(4), the measure of the impact of the smoke is called SMOKE. SMOKE is twice the product of two factors: 1. the optical density of the smoke and 2. the ratio of the depth of the upper smoke layer to the height of the room. That is, it is the optical density of the

smoke in the upper layer (SDUL(I)) if the room is half filled with smoke. (See discussion of S in Section 2.2.2 and instruction 3095 of program DEC3.)

TOL(1) is the threshold for stopping action. It is set equal to 0.5. If an occupant tries to reach a node with this level of smoke, he will cease all action, unless the lower layer of cleaner air is greater than 1.2 meters (3.9 feet) in depth; that is, he will stop movement unless he can crawl under the smoke.

TOL(2) is the threshold for not entering a room. It should be noted that an occupant will not be assigned a route that involves entering a room with smoke density greater than TOL(2) unless the lower layer of cleaner air is greater than 1.2 meters. It is set equal to 0.4.

TOL(3) is the threshold for quickening the pace of an occupant's actions. It is set equal to 0.1. If Occupant J encounters this much smoke, ACT1(J) is set equal to two. When ACT1(J)=2, travel speed is increased by 30% and some response (delay) times are less (See Section 4.3. Delays and Pauses, and the above description of SPD in this section).

TOL(4) is the threshold for terminating an investigation or deciding an investigation is not necessary. When SMOKE>=TOL(4), there is enough smoke for an occupant to realize that egress is necessary. It is set equal to 0.05.

TOL(5) is the threshold for activating a smoke detector. If the upper or smoke layer has optical density greater than or equal to TOL(5) and if the depth of the smoke layer is greater than .15 meters, a smoke detector will sound. TOL(5) is set at 0.015 per meter. The depth of .15 meters is set in instruction 5031 of program DEC3.

TPAUSE. TPAUSE is the time allotted for an occupant to spend between completion of an action and the start of the next action. It basically accounts for decision time. TPAUSE is set equal to 3.0 in instruction 1009 of program DEC1. It is used after completing an investigation and after finding that a path is blocked by smoke.

5.3 Delays and Action Times.

5.3.1 Introduction.

The time consuming activities of an occupant can be classified into three categories.

Movement from one node to another. (This section is not concerned with these actions.)

Delays and pauses. These activities include time to awaken, time to make decisions, and time to prepare for action.

Assisting actions. These activities include awaking another occupant and preparing another occupant for egress.

The delay time, the decision time, and time to perform the assisting actions (hereafter called Delay Times) depend on the fire characteristics and the impact of the fire cues on the occupant. In this section, the times assigned to these actions will be presented and, also, information will be provided that will permit the user to change these assigned times by making changes to statements in program DEC3. (The time to move from one node to another and the time to become aware of the fire cues will not be discussed in this section: those times are treated differently and they have been amply discussed in earlier sections.)

The numerical value of most Delay Times is specified in a program statement as a number rather than as a parameter. Therefore, to change its value, i.e., the time duration, the number in the statement must be changed. To permit the user to change these Delay Times, the relevant statement is identified. One exception is the decision time after completing some of the actions: see discussion of TPAUSE in Sections 5.2 and 5.3.2.

The normal (i.e., smoke is not bad) minimum response (delay) time is 6 seconds for awake occupants. This includes decision and preparation time. It is based on the work of Nober [Nober et al, 1981]. It is set in statement 5257 of program DEC3. A new value can be selected by substituting the new value for the number 6 both times it appears. If the smoke is bad, this can drop to 4 seconds (if SMOKE>=TOL(3)) or to 1 second (if SMOKE>=TOL(2). (See statements 5263 and 5265 where TRESP(J) is the response time for occupant J.)

5.3.2 TPAUSE. When an occupant completes his action (e.g., reaches his goal) or terminates his action (e.g. blocked by smoke), he is assigned a delay time of TPAUSE seconds. (See TPAUSE in Section 4.2 for the assigned value of TPAUSE.) This delay includes the time required to choose a new action. There are times, however, when the usual delay time is not assigned.

Exception 1. There is no Delay Time assigned when the completed action is to alert an able and awake adult to the fire emergency.

Exception 2. There is no Delay Time assigned when the occupant arrives at the room of someone needing assistance.

Exception 3. When the action is to wake a sleeping occupant, the rules in Section 5.3.5 apply.

There are currently four cases where the Delay Time of TPAUSE seconds is assigned.

Suppose an occupant is moving towards another occupant in order to alert, awaken, or assist that person. If for some reason the second person awakens, becomes alerted to the fire, or is being actively assisted by a third occupant before the first occupant arrives, the first occupant will change his action, i.e., change his decision in mid-route and be assigned a Delay Time of TPAUSE (decision time for choosing another course of action). See statement 2134 of program DEC3..

If the chosen route is found to be blocked by smoke, the occupant will stop and select another route or action. The time taken to decide on another course of action will be accounted for in the assigned Delay Time of TPAUSE. See statement 6868.

After seeing sufficient smoke or fire to stop the investigation, the occupant will decide on another course of action. After a Delay Time of TPAUSE, he will start his next action. See statement 6886.

After arriving at the end point of the investigation--the room with the most smoke or with visible flame--the occupant will decide on another course of action and be assigned a Delay Time of TPAUSE accordingly. The occupant will then start his next action after the Delay Time has elapsed. See statement 6973.

5.3.3 Decrease in Preparation Time Due to Heavy Smoke. When an occupant is subjected to normal fire stimuli, a ten second response delay time is assigned to a sleeping occupant and six seconds to an awake occupant. (See instructions 5257-5258.) (Note the response time will be greater if the fire stimuli are not sufficiently strong for a timely response--See Section 4.5.1.)

Exception. If the fire cues are sufficiently strong or long lasting such that the occupant is scheduled to respond within 10 seconds, the maximum remaining delay time of the occupant is: four seconds if SMOKE=>TOL(4); or one second if SMOKE=>TOL(3). These delay times can be changed by changing the values related to TRESP(J) in instructions 5263 and 5265. (Note the need for two changes in each instruction.)

5.3.4 Hesitation Due to Not Being Alone. Research by Latane and Darley [Latane and Darley, 1968] has shown that when the fire cues are noticed but not immediately compelling, adults will hesitate in their responses if other capable adults are in the same room. A simple explanation is that there is a failure to respond due to a feeling of shared responsibility. The computer program accounts for this by delaying responses by one time period for each time period when all of the following conditions apply:

1. There is no one that needs to be rescued, alerted, or roused (see instruction 7225 of program DEC3);

2. There is another fully capable adult occupant in the same room (see instructions 7332-7344);

3. None of the smoke detectors is sounding (see instructions 7345-7347);

4. There is no visible flame (see instruction 7348);

5. The fire cues are noticed but are not taken very seriously by the occupant(s) i.e., AWARE(J)>=TH and AWARE(J)<TH+10--see instruction 7350.

5.3.5 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 five seconds or 2.5 seconds depending on whether the alerting occupant believes the fire to be serious (i.e., ACT1(J)=2). These delay times can be altered by changing values of TRESP(JK) in statement 6971. (See Section 4.6.4, Criterion for Fire to be Considered 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 five seconds for the occupant doing the waking. (See value of ZZZ in statement 7642 for assigned waking time. See statement 7676 for the adjustment of TCR(J)--time remaining in the time period. In statement 7676, Y is the time, if any, required to travel within the room to the node of the occupant needing assistance--see statements 7636-7639.) For the occupant who is being awakened, the delay is ten seconds. His remaining time in the time period is the amount assigned the person waking him plus 5 seconds--i.e., plus ZZZ seconds--decision and preparation time. (See statement 7684.)

> Exception: if the assisting occupant believes the fire to be serious (i.e., ACT(J)=2) the value of ZZZ would be halved (see instruction 7670). Therefore, his time devoted to waking would be only 2.5 seconds and the total delay time for the previously sleeping occupant would be 5 seconds . (See Section 3.6.4, Criteria for Fire to be Considered Serious.)

If an occupant needs help moving, the Delay Time (starting at the time the assisting occupant arrives at the location of the other occupant) is 10 seconds if the disabled occupant is awake and 12 seconds if he is asleep. (See value of ZZZ in statement 7643.)

> Exception 1. If the disabled occupant is a baby (i.e., AGE(JK)<=BABY), the Time Delay in seconds is the baby's age plus 4. (See value of ZZZ in statement 7646.)

> Exception 2. If the capable occupant believes the fire to be serious (i.e. ACT(J)=2), the previously determined Delay Time is halved. (See value of ZZZ in statement 7647.)

Note: if you wish to make a change in the Delay Time in statements 7642 or 7643, change the values of ZZZ but do not change the values of Z.

6.0 DESCRIBING A NEW BUILDING, ITS OCCUPANTS AND THE FIRE

6.1 Introduction.

There are three ways of entering input data when running the simulation:

Enter input data through the keyboard by answering questions;

Enter input data saved from a previous run;

Enter input data by chaining to programs that contain data in DATA statements and LET statements and that call data files. These programs will be called INPUT PROGRAMS.

In this chapter we will discuss; the structure of the INPUT PROGRAMS; the format of the data files; and the structure of the subroutines in programs DEC1 and DEC3 that draw the building layout.

This section is written for a user who is familiar with the BASICA programming language. It is recommended that you not attempt to make alterations in the input programs unless you have a knowledge of BASICA.

Warning!! Do not make changes in the program before you have made copies of the original disk.

The set of computer programs and data files comprising this simulation contains the characteristics of three buildings, nine fires and eight different sets of occupants. The information is stored in the form of computer instructions in a number of separate programs and data files.

There are three programs that contain the characteristics of the three buildings, one program for each building. They are called BLDG1, BLDG2 and BLDG3.

There are nine data files that contain the characteristics of the nine fires, each containing the characteristics of one fire. They are called SMOKE1.SMK, SMOKE2.SMK, etc. One program, called SMOKE9, contains information about the loudness of the smoke detectors and about the position of the bedroom doors in the one story building. Program SMOKE9 also calls the appropriate data file containing information about smoke conditions.

One program, called OCC1, contains the characteristics of all eight sets of occupants.

One additional program, BLDG4, is also provided. It is only half written and can be completed by the user as he defines a building of his own selection. Together with additions to programs DEC1, DEC3/COMP4, SMOKE9 and OCC1, the user can add another building of the user's choice.

In this section, we will discuss how to add an additional building, fire and set of occupants. This discussion will also provide sufficient information to permit the user to modify the characteristics of the other buildings, occupants, and fires, although the focus of the discussion will be on adding a completely new building, fire, and set of occupants.

If the user wishes to add a second new building after defining the first one, it is recommended that he add it on a separate disk, starting with the original set of programs and using BLDG4. Similarly, if the user changes the characteristics of a building, he should do it on a separate disk and save the original disk.

If the user adds a new building, he must also add: 1. new occupants by modifying or expanding program OCC1, and 2. new fire data by modifying program SMOKE9 and providing a new data file for smoke characteristics.

6.2 Describing the Building.

6.2.1 Introduction. The characteristics of the new building will be contained in program BLDG4. A substantial part of program BLDG4 is devoted to locating nodes and occupants on the building layout on the screen. That part of the program is discussed below in Section 6.5, Layout of New Building.

Note in program BLDG1, most of the input data is in the 1000 series of statements; in BLDG2, the 2000 series; in BLDG3, the 3000 series; and BLDG4, the 4000 series: but the last three digits of the statement numbers are comparable for similar instructions in the four programs. Similarly, different series of instructions are used in the different programs that contain the smoke characteristics and within the program that contains the occupant characteristics.

6.2.2 Number of Nodes, Rooms, and Exits. The number of nodes, rooms and exits are entered as variables into the program in the form of LET statements. The number of nodes is variable NN, the number of rooms is NR, and the number of exits is NE. Statement 4010 of programs BLDG4 is reserved for entering the values of these parameters. Variable NB1 tells the computer what graphics mode to use: it is given the value of 2 in statement 4005 which directs the computer to use high resolution graphics.

6.2.3 Lengths of Links Between Nodes. The distance, in meters, between two nodes is stored in the matrix DIST(I,II). Initial values are defined as 999 meters in subroutine 500. The distance DIST(I,I) is defined equal to .01. because the shortest path routine would not work if it were zero: any positive value could have been assigned to DIST(I,II). When the link between the two nodes, node I and node II, is X meters, the length of the link is entered as a LET statement in the form DIST(I,II)=X. A separate entry is made for each link. The distance from node I to node II is normally the same as the distance from node II to node I: it is necessary to define the link only once, using either direction. Statements 4030 to 4039 of program BLDG4 are reserved for these entries. You may enter more than one DIST parameter per line, if you separate each statement with a colon. For example:

```
4030 DIST(1,12)=2: DIST(1,15)=3.5: DIST(2,13)=1.5
```

6.2.4 Defining Windows. If an exit node X is a window that can be used as an exit, set WINDO(X)=1 in instruction 4040. (Do not place a node at a window unless it can be used as an exit: an unusable window can be shown in the graphical representation of the building on the screen but it should not considered as a node and it must not be defined as an exit node.) The values WINDO(I) should be defined in instruction 4040 of program BLDG4. For example:

```
4041 WINDO(11)=1: WINDO(12)=1: WINDO(18)=1: FRONT=3
```

When determining the desirability of a path, 100*(WINDO(I)) demerits are given if the egress path involves going out window I. Note that exiting by window II could be given fewer or greater than 100 demerits by assigning WINDO(II) a value less or more than one, respectively.

6.2.5 Front Door. The number of the exit node for the front door is entered in instruction 4040 of program BLDG4 as the value of the variable FRONT. (See above example.)

6.2.6 Room Location of Nodes. If there are NR rooms, each of the first NR nodes are assigned to a room of the same number (e.g. node 1 is in room 1). This assignment is made automatically by statements 4064-4068 of program BLDG4. The exit nodes are not considered to be in any room. If there are additional nodes, it is necessary to inform the computer in which room they are located. This information is stored in parameter RMNOD(I). If node Y is in room X, then RMNOD(Y)=X. This information is entered in instructions 4060-4063 of program BLDG4. For example:

```
4062 RMNOD(15)=7: RMNOD(16)=4: RMNOD(17)=4
```

6.2.7 Height of Rooms. The heights of all the rooms in the other buildings is set at 2.4 meters, i.e., as close as we can get to 8 feet using two significant digits. The heights are set in instructions 4130-4134. The user can change the heights, if he wishes, by a simple change in these instructions. Note that parameter HR(I) is the height of room I. If there is a staircase in your building, and the staircase is a room, double the height of the room and add the thickness of the floor/ceiling construction. Line 4140 is reserved for this type of modification. Also note that the default or "no smoke" value of SDLL(I), the height of the lower smoke layer, must be set equal to the height of the room in this instruction. (The reason for this is explained in the next section.) For example:

```
4132 HR(I)=2.4: SDLL(I)=HR(I)   '--existing instruction
4132 HR(I)=2.3: SDLL(I)=HR(I)   '--new instruction if we want to change
the room heights
4140 HR(4)=4.7: SDLL(I)=HR(I)    '--room 4 is stairs
```

If a computer model is used to provide the characteristics of the spreading smoke, it must use the same room heights as the EXITT model.

6.2.8 Combining Rooms. This set of computer programs can model a building with up to 12 rooms. The programs that distribute the smoke (i.e. programs that provide input to the EXITT model) also have limits on the number of rooms that can be modelled. To keep the number of rooms within the prescribed limits, it is sometimes necessary to treat several rooms as a single room.

Normally one would consider the hall or foyer at the bottom of a stairs, the stairs, and the upstairs hallway as three separate rooms. However, it may be desirable to treat the foyer, the stairs, and the upstairs hallway as three (or more) nodes of one room. If this is done, the smoke conditions of the three areas should be treated differently because the psychological and physiological impact of the smoke in the three areas are different. This is handled by treating the combined area as one smoke compartment with different heights of the floors and ceilings for the various nodes in the compartment. The height of the ceiling, i.e., HR(I), in relation to the bottom of the smoke compartment, must be defined for each node.

Similarly, the height of the floor--HF(I)--in relation to the bottom of the smoke compartment must be defined for each node. Since the usual value of HF(I) is zero, and HF(I) is automatically assigned a value of zero, nothing needs to be done unless we combine a stairway with the upstairs hallway. Similarly, the program assigns the same value of HR(I) for all rooms and nodes and nothing needs to be unless we combine the stairway with a portion of the downstairs. The special values of HR(I) and HF(I), if any, can be specified in statement 4145 and 4146

6.3 Smoke Characteristics.

6.3.1 Introduction. Each fire is stored in a separate data file with a name that starts with the word SMOKE. The next character is the building number: an additional digit may be used to distinguish among different fires for the same building. The suffix is .SMK. The data file name reserved for the first fire in the new building, building 4, is SMOKE4.SMK

Statements 5000-5090 in program SMOKE9 contains information about one fire scenario. Each of the eight succeeding blocks of 100 statements contains information about another fire scenario. The block of statements from 5900-5990 is reserved for a new fire scenario. The organization of the data in the nine blocks of statements are similar.

6.3.2 Smoke Characteristics. The current version of this simulation is based on the assumption that there are two layers of air in each room--an upper layer contaminated with smoke particles and a lower layer that is practically clear. The two characteristics of smoke that are used are: 1. the optical density of the upper layer with smoke; and 2. the depth of the lower clear layer (i.e., the distance from the floor to the upper (or smoke) layer). Before a fire takes place, the depth or height of the lower "smoke" layer is equal to the height of the room. This is because there is no smoke in the room. If the room were to become completely filled with smoke, the depth of the lower layer would be equal to zero because there would be no more clear air left in the room.

The two sets of smoke characteristics for each room for a single time period are stored in the data file whose name is stored in the string XX$. For a fire in the new building, XX$ is defined as SMOKE4.SMK in statement 14118. However, the user will be given the opportunity to change this data file through the keyboard (see subroutine 7000 of program SMOKE9).

In the data file, each data entry is a separate data record. If there are N rooms, there will be (2*N)+1 entries for each time period. The first N entries will be the optical densities of the N rooms in sequential order of the room number (i.e., the smoke density of room one will be first). The second N entries will be the depth or height of the lower clear layer in each room, again in sequential order of room number. The last entry will be 999. The computer will accept any value for the smoke densities and height of the lower layer but will check to see if there are 2*N entries between the 999 entries. The height of the lower layer should not exceed the height of the room (but it may exceed the height of a foyer if the foyer is in the same room as the stairs).

If the data file contains data in a different format, statements 7100-7170 can be modified to accept the new format.

6.3.3 <u>Number of Time Periods</u>. The current version of the program can input from a data file smoke conditions for 102 time periods. (The limit comes from one of the dimensions of the matrix of smoke values.) The actual number of time periods for which smoke data is obtained from a data file is NZ and the value of NZ should be entered in instruction 14116 of program SMOKE9. If the simulation is run for more than NZ time cycles, then smoke conditions for the NZth time period can serve as the smoke conditions for the remainder of the simulation. However, if the simulation is run for more than NZ time periods, the user will have an opportunity to change the smoke conditions in all time periods following the NZth period.

6.3.4 <u>Description of the Fire</u>. Statements 14110-14111 are reserved for a brief description of the fire. The description can be either a comment statement or the part in quotes of a print statement. Remember to put an apostrophe before the comment to avoid a syntax error.

6.3.5 <u>Smoke Detectors</u>. The building may have up to three smoke detectors. (Building 1, i.e., NB=1, can have only one detector. Also, since NB=1 for buildings defined through the keyboard, they also have only one detector.) These smoke detectors are independent and are not interconnected in any way. It is necessary for the user to provide the characteristics of the smoke detectors and how loud each detector would sound in each room of the building for any new fire scenario. Statements 14120-14130 of program SMOKE9 are reserved for these entries. The following parameters should be defined. NSD is the number of smoke detectors. DET(I) is the room (or node) where detector I is located. LROOM(N,I) is how loud (decibels) detector I will sound in room N: all combinations of rooms and detectors should be entered. (Note that detectors usually sound about 85 decibels in the room in which they are located, and they sound about 12-15 decibels less in an adjoining room if the door is open and about 24-30 decibels less if the door is closed.) See statements 5620-5628 for an example.

(If you are using statements 5000-5300 as a guide in making changes in a building stored in the computer, you should note that in building 1 the smoke detectors are treated differently. Because of the simplicity of the building, there would normally be only one smoke detector and it is possible to let the computer compute the loudness of the detector in each room. However, it is necessary to input information about the bedroom doors that are closed--default position is open. An example of the instructions for doing this are located in statements 5140-5159 of program SMOKE9.)

6.3.6 Background Noise. The background noise in each room is set as 35 decibels in statements 4082-4086 of program BLDG4. If any room has a greater amount of background noise, this information can be entered in statement 4088 of program BLDG4. If the background noise in room I is X decibels, then NOISE(I)=X.

6.4 Occupant Characteristics.

6.4.1 Introduction. The characteristics of all occupants are in program OCC1. The space reserved for the occupants of the new building is the 3000 series of instructions. The OCC1 program will not accept the new set of occupants until statement 400 is changed to read: 400 GOTO 3000

As you enter the characteristics of the occupants, be sure to keep statement 3000 as an instruction or comment statement.

The 3000 series of statements, when constructed as described in this section, will be similar to the nine series of statements starting with statement 2000. They can be used as examples.

6.4.2 Number of Occupants. Set the parameter NP equal to the number of occupants in statement 3005.

6.4.3 Age. Set the parameter AGE(J) equal to the age, in years, of occupant J in statement 3010. A separate LET statement is needed for each occupant: they should be separated by colons.

6.4.4 Disabilities. An occupant either is fully capable when awake or is in need of assistance to evacuate. The actions of capable children are limited solely as a function of age, e.g., they may be too young to rescue others. If ACT(J)=1 or AGE(J)<=BABY, then occupant J is treated as one who needs assistance escaping. Setting ACT(J)=1 is the only way of flagging an occupant of age BABY+1 or older as needing assistance in moving. This should be done in statement 3011. (To avoid careless errors, you may wish to set ACT(J)=0 for the capable occupants.)

6.4.5 Sex. When SEX(J)=1, occupant J is a male. When SEX(J)=0, occupant J is a female. The sex of the occupants should be defined in statement 3015.

6.4.6 Location of Occupants. The parameter RP(J) signifies the room number in which occupant J is currently located. The initial room locations should be defined in statement 3020.

6.4.7 Sleep. When SLEEP(J)=0, occupant J is asleep. When SLEEP(J)=1, occupant J is awake. The initial sleep status of each occupant should be defined in instruction 3030.

Some occupants are deep sleepers and require more stimuli than the average in order to awaken from sleep. The deviation from the norm is indicated by the value of the parameter CSLP(J). When CSLP(J)=0, occupant J requires the normal amount of stimuli to awaken. As a general guideline in setting the value of CSLP(J), consider the units as additional decibels required to awaken the occupant. Note the parent of an infant is likely to awaken more easily than most people and might be assigned a small (say less than 8) negative value for CSLP(J). Values of CSLP(J) are defined in statement 3035.

6.4.8 Travel Speed. The parameter SPD is the normal travel speed of the occupants. It is set in statement 1006 of program DEC1. In subroutine 1910 of program OCC1, the speed of all occupants is set as SPD. The speed of occupant J is stored in parameter SPEED(J). If you wish to set the normal speed of any occupant to be different than the value of SPD, you can override the speed set in subroutine 1910 by defining a new value for SPEED(J) in statement 3091.

6.5 Output to TENAB.

When this model is being used as part of the Hazard Assessment Methodology, it provides a data file specifying all movements of the occupants. TENAB is a model that determines the physiological impact of the toxic gases and heat on the occupants. It uses as input the data file specifying all movements of the occupants. The name of the data file must have the suffix .EVA. The name of the file for the fire in the new building is given in statement 14105. The user will be given the opportunity to change the name through the keyboard. The name given by the program can also be changed by changing statement 14105.

6.6 Layout of New Building.

6.6.1 Introduction. The simulation is designed for use at the computer with the results being displayed on the screen. It includes displaying the floor layouts, and the movements of the occupants in the building: the layout is displayed on the monitor screen using the computer graphics of BASICA.

The simulation program contains the layouts of three buildings: a ranch house; a townhouse; and a detached house. The model is designed to print the appropriate layout on the monitor screen during the running of the model. The user may add a fourth building of his choice. To add the layout of the new building, it is necessary to develop a set of instructions that will draw the floor layouts and that locates nodes on the layout. While this is relatively easy, it can be very time consuming, especially if you show details of the layout in the graphics.

6.6.2 <u>How to Skip the Graphics</u>. You can run the program without developing the instructions that draw the layout by either of the following methods:

1. Answer the question "DO YOU HAVE AN IBM GRAPHICS BOARD?" negatively each time you run the simulation with that building; or

2. In the program SMOKE9, add the instruction: 5 OWN$="Y"

   Do not forget to delete this instruction when you want to run the program with the graphics.

6.6.3 <u>How to Draw the Building.</u> The complete set of instructions for drawing the new building must be included in both the DEC1 and the DEC3/COMP4 programs. The first statement must be number 14110 and the last statement must be less than 14199. (These restrictions apply to both the DEC1 and DEC3/COMP4 programs.)

The following instructions are for drawing the building in the high resolution graphics mode. The programs are written with the assumption that the layout for the additional building will be in the high resolution graphics. High resolution graphics are used when NB1=2.

The screen is composed of 640 horizontal points and 200 vertical points. (Numbering starts from the upper left corner of the screen.) All of the horizontal range may be used but only some of the vertical range is available: the remainder of the screen is reserved for text describing the actions and decisions of the occupants. The vertical range reserved for the graphical representation of the building is 61 to 181.

Detailed descriptions of the instructions used for drawing the building can be found in the IBM BASIC MANUAL. It explains the use of the PSET and DRAW functions used in the BASICA language. It is not necessary to draw the building in the style (e.g., level of detail) used in drawing the other buildings stored in this set of computer programs. It is important, however, to stay in the vertical range defined above.

The general approach used in drawing the other buildings is to start at line 61 using the PSET instruction. (The horizontal coordinate should be selected so that the final drawing is reasonably centered on the screen.)

In drawing the other buildings stored in this set of computer programs, the simulation used diagonal lines to represent doors and gaps to represent windows. In drawing the building the following features of BASIC should be noted:

1. The length of a diagonal line is longer than a vertical or horizontal line of the same number of units,

2. On typical monitors, five vertical units are the same length on the screen as twelve horizontal units (high resolution mode).

3. Retracing a line does not affect its characteristics.

When drawing the buildings, select a scale so that the drawing will be in proportion to the actual dimensions. Two scales should be made: one for the vertical and one for the horizontal dimensions. The reason for two scales is because of feature 2 noted above. Remember that the vertical dimension should not exceed 120 units.

The 12000 and the 13000 series of statements of programs DEC1 and DEC3 are examples.

6.6.4 Labelling Nodes. It should be noted that the coordinate system for locating alphanumeric characters on the screen is different from that for locating lines on the screen. In the high resolution graphics there are 80 horizontal positions and 24 vertical ones, again counting from the upper left corner.

In the graphics mode, the LOCATE instruction can be used to place an alphanumeric character on the screen. The LOCATE instruction requires a pair of coordinates to define the desired location on the screen. If you give the computer the coordinates for the location of each node on the floor layout, the computer will show the location of those nodes (and the location of the occupants who are at that node). These coordinates are stored in matrix G(I,J). G(I,1) is the vertical coordinate of node I and G(I,2) is the horizontal coordinate of the same node. Sometimes there will be more than one occupant at a node. The parameters G(I,3) and G(I,4) are for use when more than one occupant is at node I. They tell the computer where to place the second occupant in relation to the first.

When there are two occupants at node I:

1. If occupant 2 is to be shown below occupant 1, then

   G(I,3)=1 and G(I,4)=0;

2. If occupant 2 is to be shown above occupant 1, then

   G(I,3)=-1 and G(I,4)=0;

3. If occupant 2 is to be shown to the right of occupant 1, then

   G(I,3)=0 and G(I,4)=1, etc.

The values of G(I,J) are stored in instructions 4900-4998 of program BLDG4 as DATA statements. It is suggested that instruction 4901 be used for node 1, instruction 4902 for node 2, etc. Each instruction should be a DATA statement with five numbers. The first four numbers should be G(I,1), G(I,2), G(I,3) and G(I,4) respectively. The fifth and last number must be 999. The first data statement will contain the data for node 1, the second for node 2, etc. For example in program BLDG1, the positions of the nodes for the Ranch house are entered as:

```
1901 DATA 9,10,1,0,999
1902 DATA 18,11,1,0,999
```

```
1903 DATA 18,17,1,0,999
etc.
```

The line number 1901 is the data for node 1, 1902 is the data for node 2, etc. Using statement numbers starting with 4901, enter the data values that define the node/occupant locations to suit your own building. (You may wish to use program DEC1 to print the layout on the monitor screen, interrupt the running of DEC1, and move the cursor across the layout on the screen to determine the desired coordinates of the nodes.)

7 OUTPUTS

The program provides outputs in three formats:

1. A description of the decisions and movements of the occupants is printed on the screen as the simulation progresses. There will be frequent pauses to permit the user to read the text on the screen: the user can end each pause and permit the simulation to continue by pressing the RETURN key. The pauses and graphics can be suppressed by selecting the appropriate options.

2. A description of the decisions and movements of the occupants can be printed of the printer. Once the program starts, the first question posed to the user is, "DO YOU WANT TO USE YOUR PRINTER?"

3. A record of the movements of the occupants will be stored on hard disk drive if the program is run from the hard disk. The information recorded on the disk is designed to be used as input to program TENAB which determines the hazard for each occupant according to the room conditions encountered along the escape route. [Bukowski, Chapter 6.] The model provides this output only when the program is in the C disc drive, that is, on the hard disc.

When the movements of the occupants are stored on the hard disc, the information is stored in the following order:

1. Number of rooms, number of exits, total number of nodes, number of occupants, and length of one time cycle in seconds.

2a. Occupant number, initial room location of occupant, time in seconds (i.e., zero if it is the initial location).

2b. Height of floor at node in relation to lowest level in "room".

2c. Node number.

2d. Height of separation between lower and upper smoke layers.

2e. Smoke density of the upper layer.

3. Repeat steps 2a to 2e for each occupant

4. Repeat steps 2a to 2e each time an occupant arrives at a node. (Modify step 2a to reflect that we are not recording an initial location.)

The arrival time is recorded as an integer: it is obtained by dropping the fractional portion of the number. That is, there are no fractional seconds in this output although there are fractional seconds in the other outputs.

The name of the data file used to store these results is defined in program SMOKE9. The file name is a function of the fire scenario and is defined at the time the fire scenario is defined. See statements 5005, 5105, 5205, 5305, etc.

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APPENDIX A
DEFINITIONS AND DESCRIPTIONS OF PARAMETERS AND VARIABLES

ACT(J) is the current action choice of Occupant J. The choices are:

0. Initial setting. The choice of preferred action has not yet been addressed by the simulation.
1. Needs rescue. This is the choice if Occupant J has been classified as needing help in evacuation (see, for example, instruction 5266 of program DEC1).
3. Go to occupant (in other room) who needs rescue.
4. Investigate. Go towards room with greatest smoke.
5. Escape. Egress without helping others.
7. Go to occupant (in other room) who needs waking or alerting.
11. Rescuer assigned. This assignment is made to Occupant JJ--an occupant who needs assistance. This assignment is made when Occupant J makes the choice of going to rescue Occupant JJ.
13. Take someone out of building. This choice is permitted only if Occupant J and an occupant needing rescue are in the same room. (Use choice 7 if in different rooms.)
21. Rescuer has started assisting this occupant.
50. Awaiting new choice. This assignment is made when Occupant J has completed the actions required by his most recent choice of action, e.g. occupant completed investigation by arriving at room with visible flame.
100. Actions completed. This assignment is made when Occupant J has left the building. Note that in this version occupants do not reenter the building.

ACT1(J) is a flag to indicate if investigation is a permitted choice for Occupant J. Investigation is not a permitted choice for an occupant who has already completed an investigation or who has been awakened by an occupant who has completed an investigation.

0. Investigation is a priority choice.
1. Investigation is not a priority choice. See Section 4.5.3, Criteria for Setting ACT(J)=1.
2. Investigation is not a permitted choice. See Section 4.5.4, Criteria for Fire to be Considered Serious.

ACT2(J) indicates the status of Occupant J in accomplishing the goal of his most recent action choice.

0. Initial status including sleeping.
90. Successfully completed action or terminated investigation due to seeing flame or moderate smoke--accomplished goal.
93. Cannot reach GOAL using current shortest path--shortest path blocked by smoke.
95. Cannot reach GOAL--cannot find route using subroutine 6200.
98. Trapped--cannot find route to outside of building using subroutine 6200.
99. Waiting at a window for help in evacuating disabled occupant--all routes to exit doors are through bad smoke. Completed final action.

100. Completed final action--outside building.
101. Needs assistance--that is, ACT(J) = 1, 11, or 21.

ADJ is an adjustment to TCR(J) that permits subroutines to be called at different times in relationship to instruction 2158 of Program DEC3.

ADJ1 is an adjustment to TCR(J) that permits subroutines to be called at different times in relationship to instruction 2158 of Program DEC3.

ADV(I) are switches for using or by-passing "advanced" features. Default values are zero.

ADV(1)=0. Bypass all "advanced" features.
ADV(1)=1. Can use "advanced" features.
ADV(2)=0. Will not store input data for future run.
ADV(2)=1. Will store input data in file on disk.
ADV(3)=0. Will not rerun simulation using input data from previous run.
ADV(3)=1. Will rerun simulation using input data stored during a previous run where ADV(2)=1.
ADV(4)=0 or 1. Progress of the simulation can be followed on the monitor screen.
ADV(4)=2. Graphic presentations on monitor are suppressed and pauses that permit reading of the screen also are suppressed.

AGE(J) is the age of Occupant J. Children who have not reached their first birthday are considered to be 0 years old. The maximum age permitted to be entered through the keyboard is 110 (See instruction 5254 of Program DEC1).

ALARM(I) is a flag to indicate if there is sufficient smoke to activate smoke detector I if it is working.

0. Not sufficient smoke to activate a detector.
1. Sufficient smoke (but detector may be broken and not sound.)

ALEFF is the difference between the loudness of the smoke detector alarm and the background noise. It is used in the subroutine for calculating the awareness index which starts with instruction 5000.

ALERT(J) is a flag indicating that someone is coming to alert occupant J.

0. Default value--no one is coming.
1. An occupant is coming.

ALONE(J) indicates if Occupant J is the only one in the room.

0. Occupant is alone.
1. Other occupants are also in the room.

AWARE(J) is the sum of the impacts of all the fire cues. It is described in Section 4.4, Awareness of Fire.

B$ indicates if the smoke detectors are broken.

"N". All smoke detectors are working properly.
"Y". All smoke detectors are broken.

BABY is upper limit of the age of children who will not make rational decisions.

C indicates if the monitor is color.

1. Color.
2. Monochromatic.

CFIRE is the scaling factor for seeing fire when determining how quickly an occupant will respond to the fire cues. See Section 3.5.3, Measures of Fire Cue Impact.

COLF is the scaling factor for smoke odor (olfactory sense) when determining how quickly an occupant will respond to the fire cues. See Section 4.4.3, Measures of Fire Cue Impact.

CLSP(J) is a sleeping penalty for occupants who have difficulty waking, such as occupants who have hearing loss and young children. Occupants who awake more easily than most, such as mothers of infants, can be assigned a negative penalty. The units are additional decibels. When entering the value through the keyboard, permitted values are -15 to 50.

CSMK is the scaling factor for seeing smoke when determining how quickly an occupant will respond to the fire cues. See Section 4.4.3, Measures of Fire Cue Impact.

DET(I) indicates the room location of detector I.

DIST(K,KK) is the distance from node K to node KK in meters. The distance from a node to itself is defined to be 1 cm. so that the shortest path algorithm will operate more efficiently. The distance from K to KK is defined to be equal to the distance from KK to K in this version. A distance of 999 meters or greater indicates there is no link between the two nodes.

DOPEN(I) indicates if the door to room I is open or closed. When entering a building's characteristics through the keyboard and when using the Ranch House, the room with the smoke detector is the corridor and it is considered to have no doors. This variable is not used when modelling two story buildings.

0. open.
1. closed.

DT is the distance, in meters, to be travelled by the occupant in this time period (or in the remaining time of this time period).

E is a flag that warns that an input value is not within the permitted range.

0. Value is within the prescribed range or the string is an acceptable string of alpha characters.
1. Value is not within the prescribed range or the string is not an acceptable string of alpha characters.

E has a second use. When screen is not in the graphics mode, pressing E, after a pause, will terminate the run. (See instructions 3165 of program DEC1 and 3162 of program DEC3.)

F is a count of the number of times the examples of the smoke densities have been printed. After 5 printings, the printing is suppressed. (See instruction 3651 of programs DEC1 and DEC3).

FAST indicates if the user will provide the smoke data through the keyboard.

0. Provide smoke data through the keyboard.
1. Use smoke data in data statements or input file.

FF indicates if this is the first or second series of passes through subroutine 7000 of Program DEC3. (See statements 2144 and 7140.)

FFF indicates if all occupants are either outside the building or are trapped. When this is true, FFF=0 and the simulation will end (see instruction 2948 of Program DEC3).

FIRST$ indicates if the user calls himself a first time user.
"Y". Yes.
"N". No.

FLAME(I) indicates the location of flame visible from room I.
0. No visible flame.
1. Flame in another room is visible from room I.
999. Flame is in room I.

FRONT is the number of the exit node representing the front door (see, for example, instructions 1144-1148 of program DEC1).

G(K,II) is a matrix of information about the location on the screen of node K. (See Section 5.5.4, Labelling Nodes.)

G1 is a variable for the LOCATE instruction in locating an occupant on the screen. (See Section 5.5.4, Labelling Nodes and statement 11410 of programs DEC1 and DEC.)

G2 is a variable for the LOCATE instruction in locating an occupant on the screen. (See Section 5.5.4, Labelling Nodes and statement 11415 of programs DEC1 and DEC3.)

GOAL is the number of the node toward which the movement of an occupant is directed.

GOALJ(J) is the number of the node toward which movement of Occupant J is directed.

H$ indicates if some displays on the screen are to be bypassed because information is redundant and user is in a hurry.
"Y". Yes.
"N". No.

H(J) indicates the next time to print on screen the status of occupant J, if his status does not change earlier. Only has meaning if H$="Y".

HELP$ is a temporary variable indicating if an occupant needs assistance in evacuating. Y=Yes, N=No

HF(I) is the height of the floor at a node compared to the height at the bottom of a stairs. Applies only when there is more than one node in a room and the different node are at different heights, e.g., bottom of stairs & hallway at top of stairs, or room & balcony.

HR(I) is the height of room I in meters.

HUE indicates if the location of the occupants will be displayed on the screen. it is used in setting the color on the screen.
0. Use colors for showing occupant locations.
1. Use colors for showing only node locations.

I is the number of the room under consideration. It also is used as a general index number.

IFLAG is a flag that warns that an input value is not within the permitted range.

0. Value is within the prescribed range or the string is an acceptable string of alpha-numeric characters.
1. Value is not within the prescribed range or the string is not an acceptable string of alpha-numeric characters.

II is the number of a room or node. It is used when determining in which room a node is located.

III indicates the character position in a string.

J is the number of the occupant under consideration.

J9 is used to temporarily store the value of J.

JJ is the number of an occupant--usually an occupant who needs assistance of some sort (e.g. waking, evacuating).

JK is the number of an occupant--usually an occupant who needs assistance of some sort (e.g. waking, evacuating). There is no logical difference between JJ and JK.

K is the number of a node--often the node at the end of a path.

KK is the number of a node other than the one at the end of a path.

KK1 indicates the character position in a string.

KKK is the sequence number of a node on a route. It is used in recording the route to node J in PATH(J,KKK). PATH(J,KKK)=0 when KKK is greater than the number of nodes in the route.

LALARM is a measure of the loudness or signal intensity of all smoke detector alarms. The measure used is decibels as heard by a person in the same room as the detector. (The possibility that the sound might vary within a room is ignored.)

LP is switch for sending output to the printer. This switch is part of each statement that sends output to the printer.

0. Send output to the printer.
1. Do not send output to the printer.

LROOM(I) is the loudness or signal intensity of the smoke detector alarm in room I. The units are decibels.

M$ indicates on which disk drive the program is stored.

MATCH1$ is a temporary string variable used in checking keyboard input.

MATCH2$ is a temporary string variable used in checking keyboard input.

MMM is an alpha-numeric character in ASCII code.

MN$ is string for use in the CHAIN command.

N is the number of a room or node--often a room being considered for entry and which needs to be evaluated for safety.

NE is the number of exits--doors and qualifying windows.

NELSON(I,J) is a array of variables that stores the values of input variables that change during a simulation run so that the run can be "repeated" using the same input data.

NELSON(1,J)=ACT(J)
NELSON(2,J)=RP(J)
NELSON(3,J)=SLEEP(J)
NELSON(4,J)=SPEED(J)

NLEN indicates the length of a string.

NN is the total number of nodes including exits.

N1 is a local variable.

NB is the building number of the building stored in programs BLDG1, BLDG2, BLDG3, and BLDG4.

NB1 indicates the screen resolution used in the graphics for the different buildings.

1. medium resolution--used for one story buildings.
2. high resolution--used for two story buildings.

NOISE(I) is the background noise in room I. The units are decibels. If NOISE(I)<35, it is treated as if it were 35 (see statement 5111 of program DEC3).

NP is the number of occupants.

NPATH(J) is the number of nodes in the route from the location of occupant J to his desired goal.

NR is the number of rooms.

NSD is the number of smoke detectors.

NT is the maximum number of time periods or time cycles to be simulated.

NZ is the number of time periods.

NZZ is the maximum number of time periods for which smoke conditions can be stored, i.e., DIM SDU(12,NZZ) and DIM SDL(12,NZZ).

OWN$ indicates if the computer operator is to define the building or if the computer will use a pre-defined building. After the building characteristics are entered, it is used to bypass the graphical representation.

"N". User will not define own building and graphical representation of the building layout, and occupant locations will be shown on the screen.

"Y". User will define own building and graphical representations will be bypassed.

P$ indicates if the user or the computer will place occupants in the building

"N". User places occupants in the building by answering questions through the keyboard.

"Y". Computer places occupants in the building from stored information.

PATH(K,KKK) contains the sequence of nodes in the path to each node K (i.e. the Kth row of the matrix defines the path to node K). Zeros indicate that the path to node K was fully described by previous (more to the left) cells in row K.

PATHJ(J,KKK) indicates the sequence of nodes (path) in Occupant J's route to his goal. Zeros indicate that the path to node K is fully described by previous (more to the left) cells in row K.

PPATH(J) indicates where on his route Occupant J is located. If PATH(J)=KKK, then occupant J is located at node PATH(J,KKK).

Q$ is a switch that indicates if the computer operator will be given the opportunity to override or change some of the decisions made by the computer for the occupants.

- "N". No, computer operator cannot override decisions.
- "Y". Yes, computer operator will have an opportunity to override some of the decision.

QUICK indicates if there are any occupants who need assistance in waking or evacuating.

- 0. No occupants need help.
- 1. At least one occupant needs help.

R(XP) indicates the number of occupants found so far to be located at node XP. Used to prevent locating two occupants at the same precise location on the screen when they are at the same node (i.e. avoid erasing one occupant when locating another).

RMNOD(K) indicates the room in which node K is located.

RP(J) indicates the room in which Occupant J is located.

RR indicates the number of occupants already located on the screen at node XP. Used to prevent locating two occupants at the precise location on the screen even though they are at the same node. Note in instruction 11400 RR=R(XP)-1.

S(I) is used to define a block of times and rooms where the smoke conditions will be changed. That is, S(I) is used to define a block of rows and columns in matrices SDU(II,NZ) and SDL(II,NZ).

- I=1. First time period
- I=2. Last time period
- I=3. First room in block.
- I=4. Last room in block.

S1(K) is used in the shortest path algorithms (subroutines starting at instructions 6100 and 6200) to indicate the length (distance in meters or demerits, see Section 3.7.2, Handling Obstacles) of the shortest path found so far from node START to node K. S1(K) also is used to indicate changes that will be made in the input data, if the input data is entered into the computer using program AGAIN, i.e. if input data from a previous run is being used. Default values are zero.

- S1(1)=0 or 1. No changes in occupants.
- S1(1)=2. User will have opportunity to change characteristics of occupants through the keyboard..

S1(1)=3. User will be required to provide characteristics of new set of occupants through the keyboard.

S1(2)=0 or 1. No changes in building characteristics.

S1(2)=2. User will have an opportunity to change characteristics of the building.

S1(3)=0 or 1. No changes to fire/smoke conditions.

S1(3)=2. User will have opportunity to change some of the smoke characteristics.

S1(3)=3. User will enter the smoke characteristics as the simulation progresses.

S2(K) is used in the shortest path algorithms (subroutines starting at instructions 6100 and 6200) to indicate if the path to K should be tested as the first n-1 nodes of a path (with n nodes) to each of the other nodes.

0. The path to node K either has already been tested or it is not a promising candidate.
1. The path to node K needs to be tested to determine if it can be extended to form a shorter route to other nodes.

S4 is a flag in the shortest route algorithms (subroutines starting at instructions 6100 and 6200) to indicate if any S2(K) has been set equal to 1 since the last check of the flag.

0. No value of S2(K) has been set equal to 1 since the last time S4 was set equal to 0.
1. At least one S2(K) has been set equal to 1 since the last time S4 was set equal to 0.

S5 is the length of a trial route in the shortest route algorithms (subroutines starting at instructions 6100 and 6200). The units are meters or demerits (see Section 4.6.2, Handling Obstacles).

S6(K) contains the numbers of nodes in the current shortest path from node START to the other nodes. The origin node, START, and the destination node, GOAL, are both counted.

SAV(J) indicates the occupant number of the occupant that Occupant J is assigned to assist. If SAV(J) is 0, then Occupant J is not currently assigned another occupant to awaken or rescue.

SDL(I,NZ) a matrix containing the values of SDLL(I) for all time periods.

SDLL(I) is the height of the top of the lower layer of smoke (i.e. the top of the clear layer at the bottom) of room I for the current time period. The units are meters.

SDU(I,NZ) a matrix containing the values of SDUL(I) for all time periods.

SDUL(I) is the smoke density in the upper layer of room I for the current time period.

SETAL(I) indicates when detector I will sound.

0. Will sound when sufficient smoke reaches the detector.

1 or greater. Detector will sound at (SETAL-1) seconds. (Note the sound of the detector affects the decisions and actions of the occupants only if it sounds at the beginning of the time period.)

SEX(J) indicates the gender of Occupant J.

0. Female.
1. Male.

SHORT(J) indicates if a shortest path for occupant J from node START(J) to node GOAL is stored in the Jth row of PATHJ(J,KKK).

SLEEP(J) indicates if occupant J is asleep.

0. Asleep.
1. Awake.

SLP indicates if an occupant is asleep, i.e., current value of SLEEP(J).

SMOKE is a measure of the impact of the smoke in a room (or at a node). See instructions 3090-3098 of program DEC3.

SPD is the current travel speed for Occupant J in meters per second in program DEC3. Before DEC3 is run, SPD is the normal speed of typical occupants.

SPD1 is a parameter (multiplier) for increasing the travel speed of an occupant who considers the fire to be serious.

SPEED(J) indicates the normal travel speed of Occupant J. The unit of speed is meters per second. If occupant characteristics are not entered through the keyboard, SPEED(J)=SPD.

START is the number of the first node in a route.

0. Shortest path not stored.
1. Shortest path is stored.

SX indicates if screen is in the graphics mode.

0. In graphics mode.
1. Not in graphics mode.

TCR(J) indicates the time remaining for movement of Occupant J in the current time period of time cycle. It is also the unused time at the end of the time period. TCR(J) is often greater than the length of one time period because at first it includes the length of the current time period plus the unused time of the previous period.

TCYCLE is the number of seconds in one time cycle or time period.

TH is the threshold for awareness of fire cues in terms of loudness or volume of sound, i.e. units of decibels. Measures of odor and visibility are scaled to "equivalent" units of decibels.

TLENGTH indicates the approximate maximum length of the run in seconds. It is defined in statement 1066 of program DEC1. The program will also stop whenever each occupant is either out of the building or awaiting rescue at a window. Periodically (every 10 time cycles as currently set in instructions 2911-12 of program DEC3) the computer operator has the option of stopping the simulation.

TNOW indicates the number of the current time cycle or time period. TNOW = 1 for the time period beginning at time 0.

TOL(I) are parameters related to response to smoke. See Section 4.2, Parameters.

TPAUSE is the time, in seconds, between completion of one action and the start of the next--decision time.

TRESP(J) is a delay time (in seconds) before occupant(J) will respond. Its initial value (set in instructions 4215 and 5251 of program DEC1) is 9999 or 999 which corresponds to infinity. Once an occupant decides to perform an action (e.g. investigate, evacuate) the value of TRESP(J) represents a response time that includes time for preparatory actions. Ten seconds is frequently used. Sometimes it includes time to wake up which can be up to 70 seconds.

W(J) indicates if occupant J has started moving toward his current or soon to be assigned GOAL.

0. Has not yet started.
1. Has started.

WINDO(K) indicates if an exit is a window. If an exit is not a window, it is assumed to be a door.

0. Exit is a door.
1. Exit is a window.

X is a local variable. It is often used as the temporary storage location of an input parameter while the computer checks if the input parameter value is within a defined range.

X$ is a local string variable.

X1 is a local variable. It indicates: 1, the location (node number) of an occupant in the graphics subroutine; 2, the first node of a link in the subroutine that moves occupants (starting at instruction 6800 of program DEC3); 3, the contribution of seeing the fire in the subroutine for computing the awareness index starting at instruction 5000 of program DEC3.

X2 is a local variable. It indicates the second node of a link and, also, the contribution of the odor of smoke in the subroutine for computing the awareness index starting at instruction 5000 of program DEC3.

X3 is a local variable. It indicates the contribution of seeing smoke in the subroutine for computing the awareness index starting at instruction 5000 of program DEC3.

X4 is a local variable. It indicates the contribution of being awake in the subroutine for computing the awareness index starting at instruction 5000 of program DEC3.

X5 is a local variable.

XHIGH indicates--for an input variable--at what magnitude a value is so high that the computer operator should review the input value before the computer accepts it.

XLL indicates the lowest value of an input parameter that the computer will accept.

XLOW indicates--for an input variable--at what magnitude the input is so low that the computer operator should review the input value before the computer accepts it.

XP is the node at which Occupant JJ is located. It is used in graphics only.

XT$ is a dummy variable used in examining structure of user's response.

XUL indicates the largest value of an input parameter that the computer will accept.

XX is a local variable.

Y is a local variable.

Y$ is a string variable used in checking to see if an input string is "Y" or "y" for a yes answer. See subroutine 3660-3669 of programs DEC1 and DEC3.

YY is a local variable.

Z is a local variable.

Z$ is a local string variable used in entering input from the keyboard.

ZZ is a local variable.

ZZ$ is local string variable.

ZZZ is a local variable.

ZZZ$ is a local string variable.

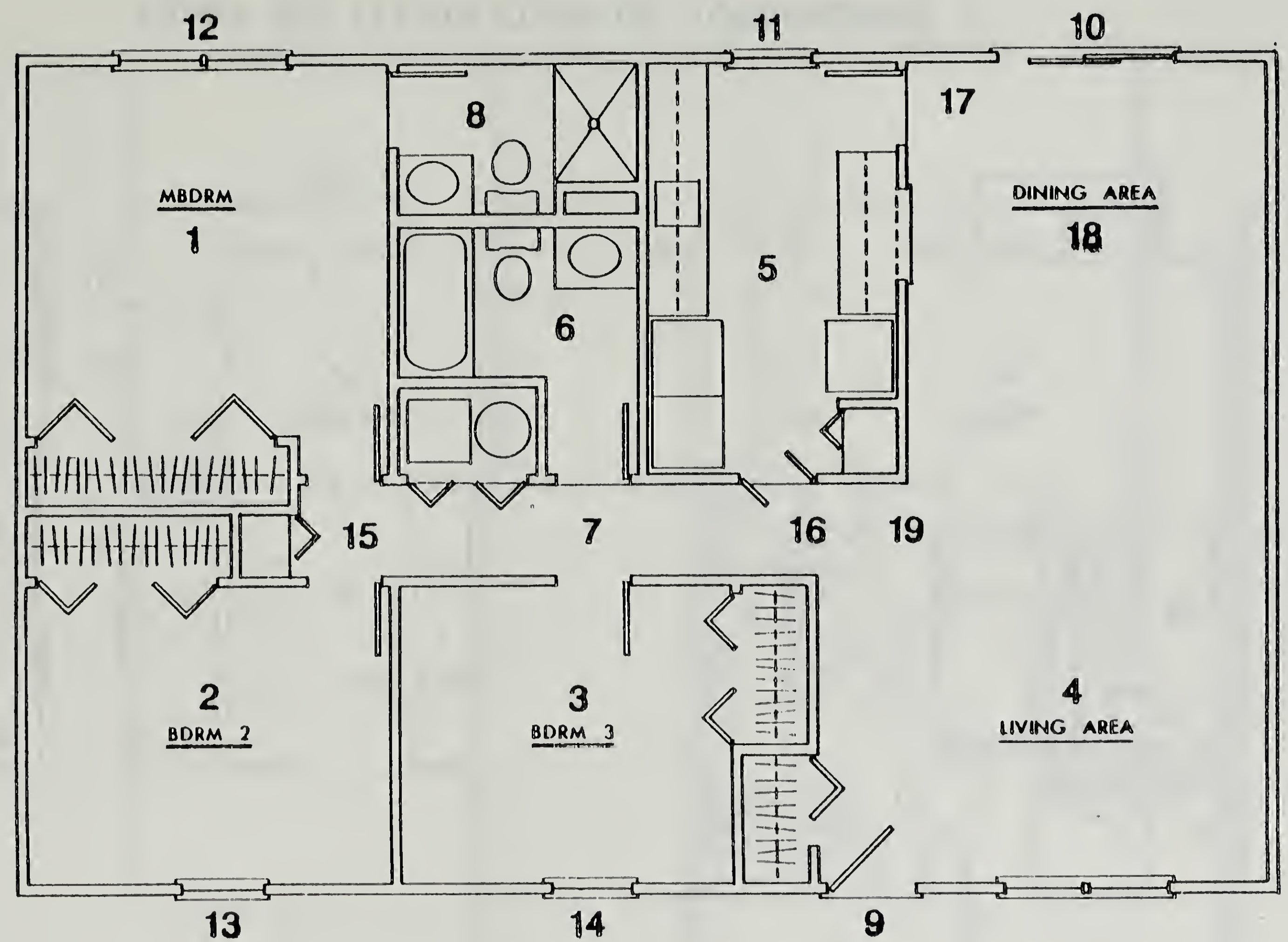

Figure 1a. FLOOR PLAN OF A TYPICAL RANCH HOUSE

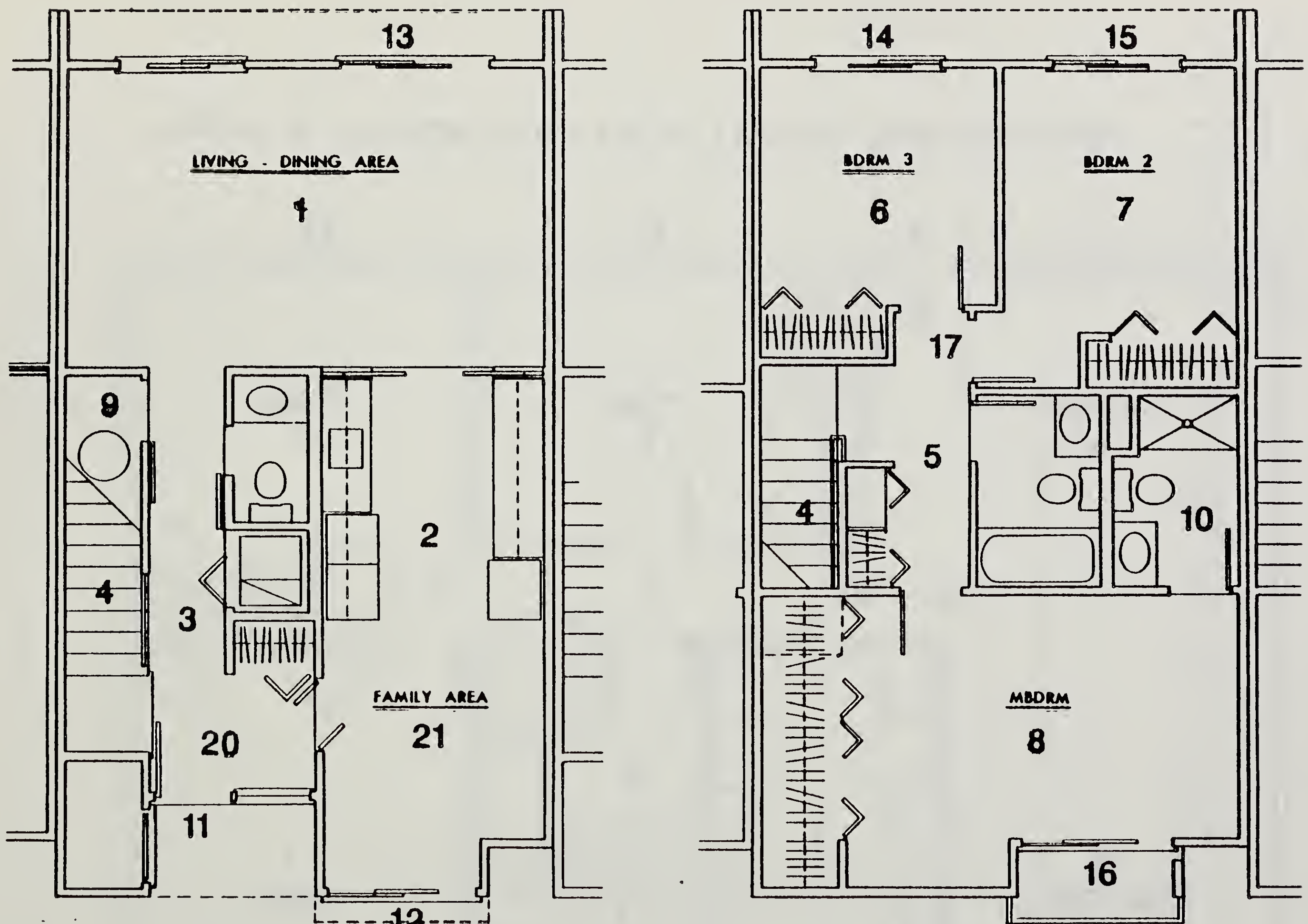

Figure 1b. FLOOR PLAN OF TOWNHOUSE

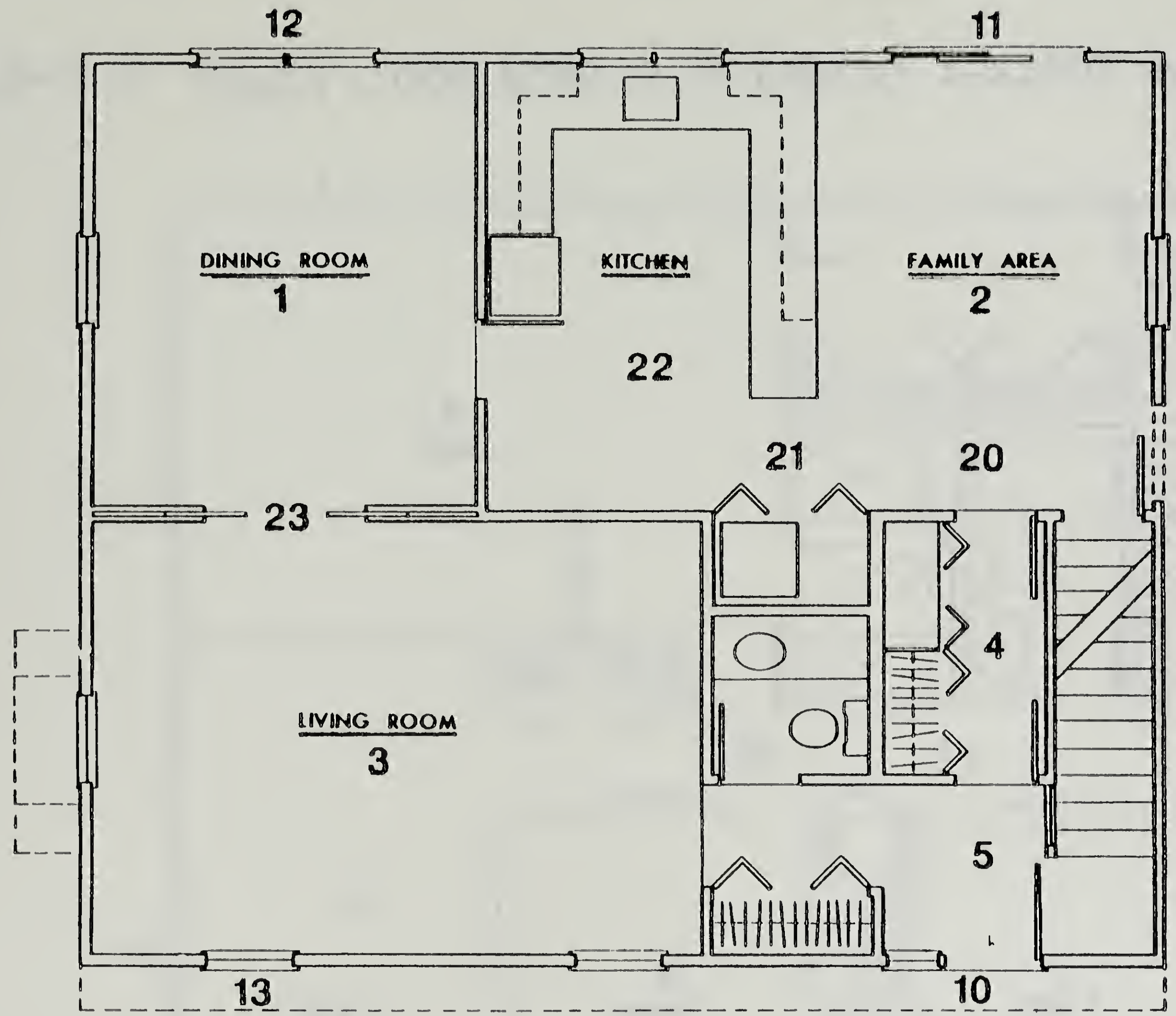

Figure 1c. LOWER FLOOR PLAN OF A TYPICAL 2-STORY HOUSE

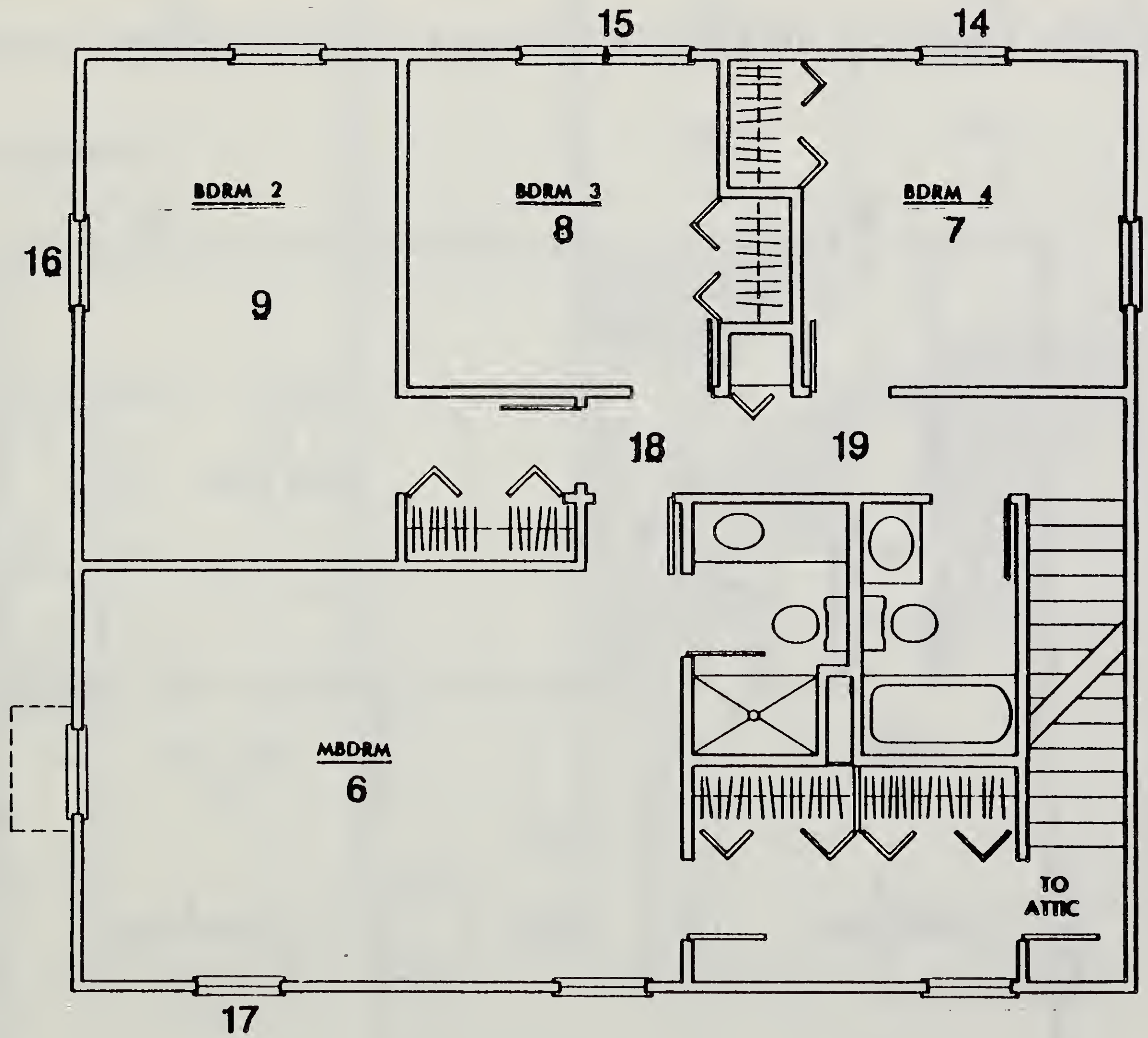

Figure 1d. UPPER FLOOR PLAN OF A TYPICAL 2-STORY HOUSE

APPENDIX C

NBSIR 85-3167

METHODS TO CALCULATE THE RESPONSE TIME OF HEAT AND SMOKE DETECTORS INSTALLED BELOW LARGE UNOBSTRUCTED CEILINGS

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METHODS TO CALCULATE THE RESPONSE TIME OF HEAT AND SMOKE DETECTORS INSTALLED BELOW LARGE UNOBSTRUCTED CEILINGS

Abstract

Recently developed methods to calculate the time required for ceiling mounted heat and smoke detectors to respond to growing fires are reviewed. A computer program that calculates activation times for both fixed temperature and rate of rise heat detectors in response to fires that increase in heat release rate proportionally with the square of time from ignition is given. This program produces nearly equivalent results to the tables published in Appendix C, Guide for Automatic Fire Detector Spacing, (NFPA 72E, 1984). A separate method and corresponding program are provided to calculate response time for fires having arbitrary heat release rate histories. This method is based on quasi-steady ceiling layer gas flow assumptions. Assuming a constant proportionality between smoke and heat released from burning materials, a method is described to calculate smoke detector response time, modeling the smoke detector as a low temperature heat detector in either of the two response time models.

1. INTRODUCTION

Studies of the response of heat detectors to fire driven flows under unconfined ceilings have been conducted since the early 1970's [1, 2, 3, 4]. 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 published in the standard NFPA 72E, 1984 [5].

Although the NFPA heat detector spacing calculation is a well documented method, it is not in a convenient form for use by the Nuclear Regulatory Commission (NRC) in evaluating the response characteristics of existing systems for two reasons. 1) Currently, the only available form of the information is the tabular form published in the NFPA 72E standard. An analytic form or computer subroutine that produced equivalent answers would be more flexible and of greater use to NRC. 2) The published tables are organized to look-up spacing requirements for a given response time. In the evaluation of existing systems, the opposite problem is of interest - for a given spacing and detector determine the response time.

As part of this study, the basis for the calculation method published in Appendix C of the NFPA 72E standard was determined. Alternative correlations of the same experimental data that are the basis for the tables in Appendix C of the NFPA 72E standard were used to construct a FORTRAN program (DETACT-T2 Code) to evaluate the response time of existing heat detector systems. Using the program, calculated values for response time agree to within 5 percent of those published in the tables contained in Appendix C of the NFPA 72E standard. Although this calculation method is the most firmly based of those to be discussed in this report, it is restricted to application in which the fire to be detected increases in energy release rate proportionally with the square of time from the ignition.

A separate program (DETACT-QS Code), written in PC BASIC, is capable of evaluating detector response for a fire with an arbitrary energy release rate history. The only restriction is that the energy release rate must be represented as a series of connected straight lines, the end points of which are entered as user input data. Inaccuracies may be introduced in the analysis of rapidly varying fires because this code uses a 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 one meter per second. Thus a quasi-steady analysis for locations close to the fire will only be in error by a few seconds, while remote locations can be delayed by tens of seconds. Keeping this approximation in mind, this program represents the most flexible of available methods but has not been tested against experimental data.

Both of the codes discussed above analyze detector response at installation sites under large unconfined ceilings. For smaller compartments, in which confining walls will cause a layer of fire products to accumulate under the ceiling, hence submerging the ceiling-jet flow before the heat detector can respond, different calculations are necessary. The problem of analyzing the response of heat detectors or sprinklers in a two-layer environment (warm fire products over cool air) has been studied [6], 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 [7].

2. DETECTOR RESPONSE TO t^2 - FIRES

Appendix C of the NFPA 72E standard [5], "Guide for Automatic Fire Detector Spacing," contains methods to determine the required heat detector spacing that will provide alarms to growing fires before the fire has grown to a user specified energy release rate. Tables provide information to evaluate different fire growth rates, ceiling heights, ambient temperatures, detector alarm conditions (fixed temperature or rate of rise), and detector thermal time constant. The tables reflect the extensive experimental studies and mathematical fire modeling performed by Heskestad and Delichatsios at Factory Mutual Research Corporation [3, 4].

Beyler [8] uses a different correlation of Heskestad and Delichatsios' data than was used to produce the tables in NFPA 72E Appendix C to obtain an analytical expression for the gas flow temperature and velocity produced under ceilings that can be used to evaluate heat detector response. Beyler's solutions are limited to evaluation of fires that increase in energy release rate proportionally with the square of time from ignition. This class of fire is commonly referred to as a "t-squared-fire." Briefly, the problem of the heat detector response is solved using analytic solutions for the time dependent temperature of the detector sensing element up to the point when it is heated to the specified alarm conditions. The model for the detector sensing element temperature is based on a convective heat transfer process. Characterization of the thermal response of heat detector and sprinkler thermal sensing elements is discussed by Heskestad and Smith [9], and Evans [10]. The first order differential equation that describes the rate of temperature increase of the sensing element is [6]:

$$\frac{dT_s}{dt} = \frac{U^{1/2}}{RTI}\left[T - T_s\right] \tag{1}$$

The notation for all equations is given in the notation section. The value of RTI (Response Time Index), a measure of the thermal time constant of the detector, is determined by testing [9]. Values of the time-dependent gas temperature and velocity are obtained from the following correlations [8].

$$\Delta T_2^* = 0 \quad \text{for } t_2^* < (t_2^*)_f$$

$$\Delta T_2^* = \{[t_2^* - 0.954(1 + r/H)]/[0.188 + 0.313\ r/H]\}^{4/3} \quad \text{for } t_2^* > (t_2^*)_f$$

$$(t_2^*)_f = 0.954\ [1 + r/H] \tag{2}$$

$$U_2^* = 0.59\ [r/H]^{-0.63}[\Delta T_2^*]^{1/2}$$

where

$$U_2^* = U/[A\ \alpha\ H]^{1/5}$$

$$\Delta T_2^* = \Delta T/[A^{2/5}(T_\infty/g)\ \alpha^{2/5}\ H^{-3/5}]$$

$$t_2^* = t/[A^{-1/5}\ \alpha^{-1/5} H^{4/5}]$$

$$A = g/(c_p T_\infty \rho_\infty)$$

$$\Delta T = T - T_\infty$$

$$\alpha = t^2/Q$$

The solutions to equation (1) for detector sensing element temperature, T_s, and rate of temperatue rise, dT_s/dt, in response to the t^2 - fire with growth rate specified by the value of α are from Beyler [8] as follows:

$$\Delta T_s = (\Delta T/\Delta T_2^*)\ \Delta T_2^*\ [1 - (1 - e^{-Y})/Y] \qquad (3)$$

$$\frac{dT_s}{dt} = \frac{(4/3)(\Delta T/\Delta T_2^*)(\Delta T_2^*)^{1/4}}{(t/t_2^*)(0.188 + 0.313\ r/H)}\ (1 - e^{-Y}) \qquad (4)$$

where

$$Y = \frac{3}{4}\ \frac{U}{U_2^*}^{1/2}\ \frac{U_2^*}{\overline{\Delta T_2^*}}^{1/2}\ \frac{\Delta T_2^*}{RTI}\ \frac{t}{t_2^*}\ (0.188 + 0.313\ r/H)$$

assuming that $\Delta T_s = 0$ initially. T and U in equation 1 are obtained from the correlations in equation set (2) for ΔT_2^* and U_2^* respectively. Equations 3 and 4 were programmed into a user interactive FORTRAN code called the DETACT-T2

Code. This code solves for the time required to reach a specified positive value of ΔT_s or dT_s/dt representing detector alarm. Details of the DETACT-T2 Code use, a worked example, and program listing are given in Appendix A. Briefly for a fixed temperature detector, the user enters values for:

Ambient air temperature

Detector response temperature or rate of temperature rise

Detector RTI

Fuel to ceiling distance

Radial distance of detector from the fire plume axis

Fire growth rate constant α (for t^2 fires)

Outputs of the code are the time to detector response and fire energy release rate at that time.

In Appendix A, use of the DETACT-T2 Code to calculate the response time of a fixed temperature detector is demonstrated in a worked example using the following program inputs:

Ambient air temperature	21.1°C (70°F)
Detector response temperature	54.44°C (130°F)
Detector RTI	370.34 $m^{1/2}s^{1/2}$ (670.8 ft $^{1/2}s^{1/2}$)
Fuel to ceiling distance	3.66 m (12 ft.)
Radial distance of detector from axis of fire	2.16 m (7.07 ft.)
Fire growth rate constant	11.71 J/s^3 (0.0111 BTU/s^3)

The calculated response time using the DETACT-T2 Code is 298 seconds and corresponding fire energy release rate is 1.04 MW (986 BTU/s). This same fire and detector combination can be seen in the table C-3-2.1.1(e) in Appendix C of NFPA 72E [5], (in the table notation, threshold fire size 1000 BTU/s, fire growth rate, medium; DET TC = 300 Δ s, ΔT = 60^{0}F, ceiling height = 12 Δft, installed spacing in the body of the table 10ft). All values in table C-3-2.1.2(e) [5] are for detector response times of 300 seconds. This is in agreement with the 298 s calculated with the DETACT-T2 Code given in Appendix A of this report.

Eleven other 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 [5]. Of these cases the greatest deviation was 7.5% and least was 0.17%.

Use of the DETACT-T2 Code has two main advantages over the tables in Appendix C of NFPA 72E [5]. One is that the code is specifically designed to evaluate existing facilities. The other is that any t^2 - fire growth rate can be analyzed. The tables in Appendix C of NFPA 72E [5] contain only three different fires. At present, an NBS special publication is being prepared containing tabular results with the same information as those in the NFPA 72E, Appendix C [5], but recast into a form useful for evaluation of existing facilities. This publication "Evaluating Thermal Fire Detection Systems," by Stroup, Evans, and Martin should become available in 1986.

3. DETECTOR RESPONSE TO ARBITRARY FIRES

The DETACT-T2 Code is useful for evaluating the response of specified detectors to t^2 - fire growth rates. In some cases a fire of interest does not follow an energy release rate that is proportional to the square of time from ignition. For these cases use of the DETACT-T2 Code to evaluate the responses of detector systems is inappropriate.

To evaluate detector response to an arbitrary energy release rate history, an assumption of quasi-steady gas flow temperatures and velocities is made. With this assumption, correlation for ceiling-jet temperatures and velocities obtained from experiments using steady fire energy release rate sources can be used to evaluate growing fires. The growing fire is represented in the calculation as a series of steady fires with energy release rates 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 [1]. Recast into metric form they are:

$$\Delta T = 16.9\ Q^{2/3}/H^{5/3} \qquad \text{for} \quad r/H < 0.18$$

$$U = 0.95\ (Q/H)^{1/3} \qquad \text{for} \quad r/H < 0.15 \qquad (5)$$

$$\Delta T = 5.38 (Q/r)^{2/3}/H \qquad \text{for} \quad r/H > 0.18$$

$$U = 0.2\ Q^{1/3}\ H^{1/2}/r^{5/6} \qquad \text{for} \quad r/H > 0.15$$

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

A computer code to perform the integration of equation 1, the differential equation for detector sensor temperature, using the quasi-steady fire driven flow approximation and Alpert's correlations from equations in 5, is listed in Appendix B. This code, called the DETACT-QS Code, is written in PC BASIC. The code requires user input similiar to the DETACT-T2 Code in Appendix A, with the one exception that the fire energy release rate is specified as a series of time, energy release rate data pairs.

The same fire and detector case used as an example of execution for the DETACT-T2 Code was evaluated using the DETACT-QS Code. The example inputs and results are given in Appendix B. The fire was input as time, energy release rate pairs at intervals of 5 seconds to match the t^2 - fire with α = 11.7105 W/s^2. Other parameters were maintained the same. The resulting predicted detection time using the DETACT-QS Code was 313 seconds with the corresponding fire energy release rate at detection of 1147 kW. Remember that with the DETACT-T2 Code the calculated time of detection was 298 seconds with fire energy release rate at detection of 1040 kW. This example was chosen to demonstrate specifically that there will be differences between the two methods even in the evaluation of the same fire. The quasi-steady fire analysis on which the DETACT-QS Code is based has the advantage that arbitrary fire energy release rates can be input as a data set.

4. SMOKE DETECTOR RESPONSE

Both of the heat detector response models discussed are based on predictions of the temperature and velocity of the fire driven gas flow under the ceiling and models of the heat detector response. The same calculations could be used to predict smoke detector response given a relationship between smoke concentration and temperature rise in the fire driven gas flow and the response characteristics of the smoke detector.

The response characteristics of smoke detectors are not as well understood as thermal detectors. Smoke detector alarm conditions depend on more than smoke concentration. Smoke particle sizes and optical or particle scattering properties can affect the value of smoke concentration necessary to reach alarm conditions. For thermal detectors, measured values of RTI characterize the lag time between gas temperature and sensing element temperature. For smoke detectors there is no analogous method to characterize the lag time between gas flow smoke concentration and the smoke concentration within the sensing chamber. In the absence of understanding of the many processes affecting smoke detector response, a smoke detector will be considered to be a low temperature heat detector with no thermal lag, i.e. RTI = 0. The analogy between smoke obscuration in the gas flow and temperature rise will be developed in order to determine the corresponding temperature rise to use as a model for a smoke detector known to alarm at a given smoke obscuration.

Similarity between temperature rise and smoke concentration will be maintained everywhere within a fire-driven flow if the energy and smoke continuity equations are similar. For the case of constant c_p, k, and D these equations are:

$$\rho c_p \frac{d\Delta T}{dt} - k \nabla^2 \Delta T = \dot{Q}''' \qquad (6)$$

$$\rho \frac{dY_s}{dt} - \rho D \nabla^2 Y_s = \dot{m}''' \qquad (7)$$

If the Lewis number $k/\rho c_p D = 1$, then the ratio of temperature rise to smoke concentration can remain constant throughout the fire driven flow, if the ratio $\dot{Q}''' / c_p \dot{m}_s'''$ is maintained constant in all regions where energy is exchanged with the flow. Reactions in the flame over the burning fuel will determine the ratio of temperature rise to smoke concentration throughout the flow. Other energy exchanges in normal fire flows, convection to cool room boundaries, and radiation from smokey gases decrease the ratio of temperature rise to smoke concentration because energy is extracted from the flow without a proportional decrease in smoke concentration. Mixing of hot combustion products with cool smokey gases that may accumulate in an enclosure also decrease the ratio of temperature rise to smoke concentration because smoke mass is added to the flow without a 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 smoke detectors 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, [3]

$$OD = \left(\log_{10} \frac{I_o}{I}\right)/L \tag{8}$$

By testing, Seader and Einhorn [11] 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:

$$OD = 3330 \quad C_s \tag{9}$$

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 a fire driven flow to smoke concentration may be recast in terms of optical density using equation 9 as:

$$\frac{\Delta T}{Y_s} = \frac{\rho \Delta T}{C_s} = \frac{3330 \rho \Delta T}{OD} \tag{10}$$

Under the assumption discussed at the beginning of this section, this ratio will be equal to the ratio $\dot{Q}''' / c_p \dot{m}_s'''$. The last ratio may be approximated by a volume average over the combustion region so that

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

or

$$\frac{OD}{\Delta T} = \frac{3330 \rho c_p \dot{m}_s}{\dot{Q}} \qquad (11)$$

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 [12]

$\dot{m}_s$ = 0.017 kg smoke/kg fuel consumed per unit time [12]

air c_p = 1 kJ/kg°C

air ρ = 1.165 kg/m^3 at 30°C

From equation (11) $\frac{OD}{\Delta T} = 8.68 \times 10^{-3}$ $(m^0C)^{-1}$.

Heskestad and Delichatsios [3] have reported representative optical density per meter for smoke detector alarm and corresponding temperature rise in the gas flow. For wood crib (unknown type) fires, the ratio of these values was OD/ΔT = 1.2×10^{-3} [1/m^{0}C]. 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 Delichatsios [3] report that an ionization detector will alarm in response to a wood fire at OD = 0.016 1/m.

Using the OD/ΔT 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 at 13°C above ambient for a wood fire.

Other measurements of the ratio OD/ΔT are obtained for burning materials in a laboratory scale apparatus developed by Tewarson [7]. Values for a large number of plastics and wood under many environmental conditions are given by Tewarson [12].

5. SUMMARY

Two methods have been presented to calculate the response of heat detectors installed under large unobstructed ceilings in response to growing fires. Smoke detector response is calculated using the same thermal calculations by approximating the smoke detector as a low temperature, zero lag time thermal detector.

6. ACKNOWLEDGMENT

The authors are grateful to Mr. Doug Walton for coding DETACT-QS version 1.1 for exection in PC BASIC.

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8. NOTATION

A	$g/(c_p \; T_\infty \rho_\infty)$
c_p	specific heat capacity of ambient air
C_s	smoke mass concentration
D	effective Binary diffusion coefficient
g	acceleration of gravity
H	vertical distance from fuel to ceiling
I	light intensity
I_o	initial Light intensity
L	light beam length
$\dot{m}_s'''$	smoke gas mass production rate per unit volume
OD	optical density per unit length (see eq. 8)
$\dot{Q}$	fire energy release rate
$\dot{Q}'''$	energy release rate per unit volume.
r	radial distance from fire axis to the detector
RTI	response time index, the product of the detector thermal time constant and the square root of the gas speed used in the test to measure the time constant [9].
t	time
t_2^*	dimensionless time $t/[A^{-1/5} \alpha^{-1/5} H^{4/5}]$
$(t_2^*)_f$	dimensionless time for time delay for gas front travel.
T_∞	ambient temperature
T	gas temperature at detector location
T_s	temperature of detector sensing elements
ΔT	$T - T_\infty$
ΔT_2^*	dimensionless temperature difference $\Delta T/[A^{2/5} (T_f/g) \alpha^{2/5} H^{-3/5}]$
U	gas speed at the detector location
U_2^*	dimensionless gas speed $U/[A \alpha H]^{1/5}$

Y_s	local ratio of smoke mass to total mass in flow
α	proportionality constant for t^2- fire growth = Q/t^2
ρ_∞	ambient air density

APPENDIX A - DETACT-T2 CODE

FORTRAN Program to Calculate

Detector Response to t^2 - Fires

1) Example Calculation

2) Program Listing

APPENDIX A. DETACT-T2 CODE

A FORTRAN Program to Calculate Detector Response to t^2 - Fires

This appendix describes the theory and use of a computer program which determines the response of fixed temperature and rate of rise heat detectors to fires with energy release rates described by the expression $Q = \alpha t^2$. The program is designed for use in evaluating detectors installed at known spacings.

The activation time of a given detector is a function of fire growth rate, ceiling height, detector spacing, detector activation temperature, ambient temperature, and detector response time index (RTI). The program prompts the user to provide this information. These input data are converted to a dimensionless form for use in the calculations. Equations for the activation time of a fixed temperature detector and a rate of rise detector are set up. The two equations are then solved using a Newton-Raphson technique. Once the activation times are known, the fire energy release rates at those times are calculated. Finally, the results for each detector type are printed as well as some appropriate input data.

In the following example, input prompts from the computer program are printed in all capital letters while user responses are printed in lower case (where possible) and proceeded by the character ">".

EXAMPLE

Calculate the activation times for fixed temperature and rate of rise heat detectors installed, using a 3.05 meter spacing, in an area with a ceiling height of 3.66 meters. The detectors have an RTI of 370.3 (m-sec)$^{1/2}$. The detector activation temperature is 54.4°C, and the activation rate of rise is 8.33°C/min. Ambient temperature is 21°C.

```
ENTER 1 FOR ENGLISH UNIT INPUT
      2 FOR METRIC UNIT INPUT
>2
ENTER THE AMBIENT TEMPERATURE IN DEGREES C.
>21
ENTER THE DETECTOR RESPONSE TIME INDEX (RTI) IN (M-SEC)**1/2.
>370.3
ENTER THE DETECTOR ACTIVATION TEMPERATURE IN DEGREES C.
>54.4
ENTER A DETECTOR RATE OF RISE IN DEGREES C/MIN.
>8.33
ENTER THE CEILING HEIGHT IN METERS.
>3.66
ENTER THE DETECTOR SPACING IN METERS.
>3.05
ENTER:  S FOR SLOW FIRE GROWTH RATE
        M FOR MEDIUM FIRE GROWTH RATE
        F FOR FAST FIRE GROWTH RATE OR
        O FOR OTHER
>m
```

RESULTS:

CEILING HEIGHT = 3.66 METERS (12.0 FEET)

DETECTOR SPACING = 3.05 METERS (10.0 FEET)

DETECTOR RTI = 370.3 (M-SEC)**1/2 (670.8 (FT-SEC)**1/2)

FIRE GROWTH CONSTANT = .1171+002 WATTS/SEC**2)

(.1111-001 BTU/SEC**3)

FOR TEMPERATURE ACTUATED DETECTOR:

ACTIVATION TEMPERATURE = 54.4 DEGREES C (129.9 DEGREES F)

TIME OF ACTIVATION = 297.88 SECS

HEAT RELEASE RATE = .1038+007 WATTS (.9840+003 BTU/SEC)

FOR RATE OF RISE ACTUATED DETECTOR:

ACTIVATION RATE OF RISE = 8.33 DEGREES C/MIN

(14.99 DEGREES F/MIN)

TIME OF ACTIVATION = 182.75 SECS

HEAT RELEASE RATE = .3908+006 WATTS (.3704+003 BTU/SEC)

The results show that the heat detector would activate approximately 298 seconds after the fire reaches a flaming state. The heat release rate at this time would be 1038 kilowatts. A rate of rise detector would activate at about 183 seconds with a corresponding heat release rate of 391 kilowatts.

If English units had been selected, the input requests would have called for data in English units instead of metric units.

The program is written in ANSI 77 FORTRAN. A PC BASIC version is being coded. Each is in a form which makes it easy to incorporate into existing computer fire models as a subroutine.

```
****** PROGRAM DETACT-T2 ******

      PROGRAM DETACT
C
C*************************************************************************
C
C            DETACT-T2 CODE
C
C A FORTRAN PROGRAM FOR CALCULATING DETECTOR RESPONSE
C TO TIME SQUARED FIRES.
C
C*************************************************************************
C
C*************************************************************************
C
C THIS IS A PROGRAM FOR CALCULATING ACTIVATION TIME AND HEAT
C RELEASE RATE FOR A GIVEN DETECTOR. THE PROGRAM CALCULATES RESULTS
C FOR BOTH TEMPERATURE AND RATE OF RISE ACTUATED DETECTORS. THE
C PROGRAM REQUIRES DATA DESCRIBING THE DETECTOR, ROOM, AND FIRE
C CHARACTERISTICS.
C
C PROGRAM WRITTEN BY D. W. STROUP      1/4/85
C FINAL REVISION 1/9/85
C
C*************************************************************************
C
C====>  VERSION 1.0  <=====================================
C
C INPUT:
C  J      - UNITS CODE  (1 OR 2)
C           1 - INPUT DATA IN ENGLISH UNITS
C           2 - INPUT DATA IN METRIC UNITS
C  TAMB   - AMBIENT TEMPERATURE
C  RTI    - DETECTOR RESPONSE TIME INDEX
C  TACT   - DETECTOR ACTIVATION TEMPERATURE
C  RQR    - DETECTOR ACTIVATION RATE OF RISE
C  HF     - CEILING HEIGHT
C  ZF     - DETECTOR SPACING
C  M      - GROWTH FACTOR CODE, CHARACTER VARIABLE  (S, M, F, OR O)
C  ALPHA - FIRE GROWTH RATE FACTOR
C           IF M = O, ALPHA SHOULD CONTAIN THE GROWTH FACTORR TO BE USED.
C           IF M <> O, ALPHA MAY BE SET TO ZERO.
C
C OUTPUT:
C  T      - TIME OF ACTIVATION FOR A TEMPERATURE DETECTOR
C  QD     - HEAT RELEASE RATE AT TIME OF ACTIVATION, T
C  TR     - TIME OF ACTIVATION FOR RATE OF RISE DETECTOR
C  QDR    - HEAT RELEASE RATE AT TIME OF ACTIVATION, TR
C  IERR   - ERROR CODE  (0 OR 1)
C           0 - SUCCESSFUL
C           1 - UNSUCCESSFUL
C
C*************************************************************************
C
      CHARACTER M
      DATA IRTTY,IWTTY/5,6/
      DATA GE,CPE,RHOE/32.2,0.24,0.0735/
      DATA GM,CPM,RHOM/9.8,1.0035,1.1768/
      IERR=0
```

****** PROGRAM DETACT-T2 ******

```
      WRITE (IWTTY,10)
10    FORMAT (' ENTER: 1 FOR ENGLISH UNIT INPUT'/T9,'2 FOR METRIC UNIT I
     &NPUT')
      READ (IRTTY,*) J
      IF (J.EQ.1) THEN
      WRITE (IWTTY,20)
20    FORMAT (' ENTER THE AMBIENT TEMPERATURE IN DEGREES F.')
      READ (IRTTY,*) TAMB
      WRITE (IWTTY,30)
30    FORMAT (' ENTER THE DETECTOR RESPONSE TIME INDEX (RTI) IN (FT-SEC)
     &**1/2.')
      READ (IRTTY,*) RTI
      IF (RTI.LT.0.000001) RTI=0.000001
      RTIR=RTI
      WRITE (IWTTY,40)
40    FORMAT (' ENTER THE DETECTOR ACTIVATION TEMPERATURE IN DEGREES F.'
     &)
      READ (IRTTY,*) TACT
      WRITE (IWTTY,50)
50    FORMAT (' ENTER A DETECTOR RATE OF RISE IN DEGREES F/MIN.')
      READ (IRTTY,*) ROR
      WRITE (IWTTY,60)
60    FORMAT (' ENTER THE CEILING HEIGHT IN FEET.')
      READ (IRTTY,*) HF
      WRITE (IWTTY,70)
70    FORMAT (' ENTER THE DETECTOR SPACING IN FEET.')
      READ (IRTTY,*) ZF
      WRITE (IWTTY,80)
80    FORMAT (' ENTER: S FOR SLOW FIRE GROWTH RATE'/
     &       '        M FOR MEDIUM FIRE GROWTH RATE'/
     &       '        F FOR FAST FIRE GROWTH RATE OR'/
     &       '        O FOR OTHER ')
      READ (IRTTY,410) M
      IF ((M.EQ.'s').OR.(M.EQ.'S')) ALPHA=0.00277778
      IF ((M.EQ.'m').OR.(M.EQ.'M')) ALPHA=0.0111111
      IF ((M.EQ.'f').OR.(M.EQ.'F')) ALPHA=0.0444445
      IF (M.NE.'O') GO TO 100
      WRITE (IWTTY,90)
90    FORMAT (' ENTER THE FIRE GROWTH RATE CONSTANT (ALPHA) IN BTU/SEC/S
     &EC/SEC.')
      READ (IRTTY,*) ALPHA
100   CONTINUE
      ELSE
      WRITE (IWTTY,110)
110   FORMAT (' ENTER THE AMBIENT TEMPERATURE IN DEGREES C.')
      READ (IRTTY,*) TAMB
      WRITE (IWTTY,120)
120   FORMAT (' ENTER THE DETECTOR RESPONSE TIME INDEX (RTI) IN (M-SEC)*
     &*1/2.')
      READ (IRTTY,*) RTI
      IF (RTI.LT.0.000001) RTI=0.000001
      RTIR=RTI
      WRITE (IWTTY,130)
130   FORMAT (' ENTER THE DETECTOR ACTIVATION TEMPERATURE IN DEGREES C.'
     &)
      READ (IRTTY,*) TACT
      WRITE (IWTTY,140)
140   FORMAT (' ENTER A DETECTOR RATE OF RISE IN DEGREES C/MIN.')
```

```
      READ (IRTTY,*) ROR
      WRITE (IWTTY,150)
150   FORMAT (' ENTER THE CEILING HEIGHT IN METERS.')
      READ (IRTTY,*) HF
      WRITE (IWTTY,160)
160   FORMAT (' ENTER THE DETECTOR SPACING IN METERS.')
      READ (IRTTY,*) ZF
      WRITE (IWTTY,80)
      READ (IRTTY,410) M
      IF ((M.EQ.'s').OR.(M.EQ.'S')) ALPHA=2.930555556
      IF ((M.EQ.'m').OR.(M.EQ.'M')) ALPHA=11.72222222
      IF ((M.EQ.'f').OR.(M.EQ.'F')) ALPHA=46.8888889
      IF (M.NE.'O') GO TO 180
      WRITE (IWTTY,170)
170   FORMAT (' ENTER THE FIRE GROWTH RATE CONSTANT (ALPHA) IN WATT/SEC/
     &SEC.')
      READ (IRTTY,*) ALPHA
180   CONTINUE
      END IF
C
C ************************ CALCULATIONS *****************************
C
      R=0.5*SQRT(2.)*ZF
      ROH=R/HF
      ROR=ROR/60.
      IF (J.EQ.1) THEN
      TAMB=TAMB+460.
      TACT=TACT+460.
      A=GE/(CPE*TAMB*RHOE)
      G=GE
      ELSE
      TAMB=TAMB+273.
      TACT=TACT+273.
      A=GM/(CPM*TAMB*RHOM*1000.)
      G=GM
      END IF
      TOTS2=A**(-1./5.)*ALPHA**(-1./5.)*HF**(4./5.)
      DLTODL=A**(2./5.)*(TAMB/G)*ALPHA**(2./5.)*HF**(-3./5.)
      UOUS2=A**(1./5.)*ALPHA**(1./5.)*HF**(1./5.)
      DELTD=TACT-TAMB
      IF (ROH.GT.0.3) THEN
      UODLTH=0.59*ROH**(-0.63)
      ELSE
      UODLTH=3.87/(9.115**0.5)
      ENDIF
      TS2F=0.954*(1.+ROH)
      A2=(4./3.)*DLTODL*UOUS2**(-0.5)*UODLTH**(-0.5)*RTI/
     &          (TOTS2*(0.188+0.313*ROH))
      C=1.0+DELTD/A2
      CALL NWTN (C,Y,IERR,IWTTY)
      IF (IERR.EQ.1) GO TO 380
      DELTS2=(4./3.)*UOUS2**(-0.5)*UODLTH**(-0.5)*RTI*Y/
     &                 (TOTS2*(0.188+0.313*ROH))
      TS2=0.954*(1.+ROH)+(0.188+0.313*ROH)*DELTS2**(3./4.)
      TS2=TS2+TS2F
      T=TS2*A**(-1./5.)*ALPHA**(-1./5.)*HF**(4./5.)
      QD=ALPHA*T**2
      IF (RTIR.LE.2.0) RTIR=2.0
```

****** PROGRAM DETACT-T2 ******

```
      D1=(4./3.)*ELTODL/(TOTS2*(0.188+0.313*ROH))
      D2=(3./4.)*UOUS2**0.5*UODLTH**0.5*(1./RTIR)*TOTS2
     &                   *(0.188+0.313*ROH)
      CALL BISECT (D1,D2,ROR,DELTS2,IERR,IWTTY)
      IF (IERR.EQ.1) GO TO 380
      TS2R=0.954*(1.+ROH)+(0.188+0.313*ROH)*DELTS2**(3./4.)
      TS2R=TS2R+TS2F
      TR=TS2R*A**(-1./5.)*ALPHA**(-1./5.)*HF**(4./5.)
      QDR=ALPHA*TR**2
C
C ****** PRINT OUT RESULTS ******************************************
C
      ROR=ROR*60.
      WRITE (IWTTY,190)
190   FORMAT ('1  RESULTS:')
      IF (J.EQ.1) THEN
      HF2=HF*0.3048
      ZF2=ZF*0.3048
      WRITE (IWTTY,200) HF,HF2,ZF,ZF2
200   FORMAT ('0    CEILING HEIGHT    = ',F6.2,' FEET (',F6.2,' METERS)'/
     &          T6,'DETECTOR SPACING = ',F6.2,' FEET (',F6.2,' METERS)')
      RTI2=RTI*(0.3048**0.5)
      WRITE (IWTTY,210) RTI,RTI2
210   FORMAT ('0    DETECTOR RTI = ',F6.1,' (FT-SEC)**1/2 (',F6.1,' (M-S
     &EC)**1/2)')
      ALPHA2=ALPHA*1055.
      WRITE (IWTTY,220) ALPHA,ALPHA2
220   FORMAT ('0    FIRE GROWTH CONSTANT = ',E12.4,' BTU/(SEC**3)'/
     &   '                                  (',E12.4,' WATTS/SEC**2)')
      WRITE (IWTTY,400)
      READ (IRTTY,410) M
      WRITE (IWTTY,230)
230   FORMAT (/'0  FOR TEMPERATURE ACTUATED DETECTOR:')
      TACT=TACT-460.
      TACT2=(5./9.)*(TACT-32.)
      WRITE (IWTTY,240) TACT,TACT2
240   FORMAT ('0    ACTIVATION TEMPERATURE = ',F6.1,' DEGREES F (',F6.1,
     & ' DEGREES C)')
      WRITE (IWTTY,250) T
250   FORMAT ('0    TIME TO ACTIVATION = ',F8.2,' SECONDS')
      QD2=QD*1055.
      WRITE (IWTTY,260) QD,QD2
260   FORMAT ('0    HEAT RELEASE RATE = ',E12.4,' BTU/SEC'/
     &   '                              (',E12.4,' WATTS)')
      WRITE (IWTTY,400)
      READ (IRTTY,410) M
      WRITE (IWTTY,270)
270   FORMAT (//'0  FOR RATE OF RISE ACTUATED DETECTOR:')
      ROR2=ROR*(5./9.)
      WRITE (IWTTY,290) ROR,ROR2
290   FORMAT ('0    ACTIVATION RATE OF RISE = ',F6.2,' DEGREES F/MIN (',
     &                  F6.2,' DEGREES C/MIN)')
      WRITE (IWTTY,250) TR
      QDR2=QDR*1055.
      WRITE (IWTTY,260) QDR,QDR2
      WRITE (IWTTY,400)
      READ (IRTTY,410) M
      ELSE
```

```
      HF2=HF*(1./0.3048)
      ZF2=ZF*(1./0.3048)
      WRITE (IWTTY,300) HF,HF2,ZF,ZF2
300   FORMAT ('0    CEILING HEIGHT    = ',F6.2,' METERS (',F6.2,' FEET)'/
     &             T6,'DETECTOR SPACING = ',F6.2,' METERS (',F6.2,' FEET)')
      RTI2=RTI*((1./0.3048)**0.5)
      WRITE (IWTTY,320) RTI,RTI2
320   FORMAT ('0    DETECTOR RTI = ',F6.1,' (M-SEC)**1/2 (',F6.1,' (FT-S
     &EC)**1/2)')
      ALPHA2=ALPHA*(1./1055.)
      WRITE (IWTTY,330) ALPHA,ALPHA2
330   FORMAT ('0    FIRE GROWTH CONSTANT = ',E12.4,' WATTS/(SEC**2)'/
     &      '                                  (',E12.4,' BTU/SEC**3)')
      WRITE (IWTTY,400)
      READ (IRTTY,410) M
      WRITE (IWTTY,230)
      TACT=TACT-273.
      TACT2=(9./5.)*TACT+32.
      WRITE (IWTTY,340) TACT,TACT2
340   FORMAT ('0    ACTIVATION TEMPERATURE = ',F6.1,' DEGREES C (',F6.1,
     & ' DEGREES F)')
      WRITE (IWTTY,350) T
350   FORMAT ('0    TIME TO ACTIVATION = ',F8.2,' SECONDS')
      QD2=QD*(1./1055.)
      WRITE (IWTTY,360) QD,QD2
360   FORMAT ('0    HEAT RELEASE RATE = ',E12.4,' WATTS'/
     &      '                              (',E12.4,' BTU/SEC)')
      WRITE (IWTTY,400)
      READ (IRTTY,410) M
      WRITE (IWTTY,270)
      ROR2=ROR*(9./5.)
      WRITE (IWTTY,370) ROR,ROR2
370   FORMAT ('0    ACTIVATION RATE OF RISE = ',F6.2,' DEGREES C/MIN (',
     &                 F6.2,' DEGREES F/MIN)')
      WRITE (IWTTY,350) TR
      QDR2=QDR*(1./1055.)
      WRITE (IWTTY,360) QDR,QDR2
      WRITE (IWTTY,400)
      READ (IRTTY,410) M
      END IF
      STOP 'PROGRAM COMPLETED'
380   CONTINUE
      WRITE (IWTTY,390)
390   FORMAT (' *******> ERROR IN DETACT ROUTINE <*******')
400   FORMAT (//' <RETURN> TO CONTINUE')
410   FORMAT (A1)
      STOP 'PROGRAM ABORTED'
      END
```

```
****** SUBROUTINE NWTN   ******

      SUBROUTINE NWTN (C,P,IERR,IWTTY)
C
C*******************************************************************************
C
C NEWTON-RAPHSON SUBROUTINE
C
C THIS SUBROUTINE IS USED TO EVALUATE THE TIME EXPRESSION FOR THE
C FIXED TEMPERATURE DETECTOR.
C
C*******************************************************************************
C
      P0=0.1
      TOL=0.00001
      NO=1000
      I=1
      IERR=0
10    CONTINUE
      IF (I.LE.NO) THEN
      IF (P0.GT.50.) THEN
      X=0.0
      ELSE
      X=EXP(-P0)
      END IF
      FX=P0+X-C
      FPMX=1.0-X
      IF (FPMX.LT.0.00000001) GO TO 30
      P=P0-(FX/FPMX)
      IF (ABS(P-P0).LT.TOL) THEN
      IERR=0
      RETURN
      ELSE
      I=I+1
      P0=P
      END IF
      GO TO 10
      END IF
      IERR=1
      WRITE (IWTTY,20) I
20    FORMAT (' NEWTON-RAPHSON FAILED AFTER NO ITERATIONS, NO = ',I4)
      RETURN
30    WRITE (IWTTY,40)
40    FORMAT (' SLOPE OF EQUATION TOO CLOSE TO ZERO FOR '/
     &  '   NEWTON-RAPHSON METHOD.'/
     &  '   ERROR RETURN')
      IERR=1
      RETURN
      END
```

****** SUBROUTINE BISECT ******

```
      SUBROUTINE BISECT (D1,D2,ROR,P,IERR,IWTTY)
C
C***********************************************************************
C
C BISECTION SUBROUTINE
C
C THIS SUBROUTINE EVALUATES THE TIME EXPRESSION FOR THE RATE OF
C RISE DETECTOR USING A BISECTION METHOD.
C
C***********************************************************************
C
      IERR=0
      TOL=0.00001
      NO=1000
      A=0.0
      B=1000.0
      RLMT=TOL/20.0
10    CONTINUE
      IF ((D2*B).GT.50.) THEN
      X=0.0
      ELSE
      X=EXP(-D2*B)
      ENDIF
      FXB=D1*B**0.25-D1*B**0.25*X-ROR
      IF (FXB.LT.0.0) THEN
      A=B
      B=B+500.
      GO TO 10
      ENDIF
      I=1
20    CONTINUE
      IF (I.LE.NO) THEN
      P=A+(B-A)/2.0
      IF ((D2*P).GT.50.) THEN
      X=0.0
      ELSE
      X=EXP(-D2*P)
      ENDIF
      FX=D1*P**0.25-D1*P**0.25*X-ROR
      IF (((FX.GT.-RLMT).AND.(FX.LT.RLMT)).OR.(((B-A)/2.).LT.TOL)) THEN
      IERR=0
      RETURN
      ELSE
      I=I+1
      IF ((D2*A).GT.50.) THEN
      X=0.0
      ELSE
      X=EXP(-D2*A)
      ENDIF
      FXA=D1*A**0.25-D1*A**0.25*X-ROR
      IF ((FXA*FX).GT.0.0) THEN
      A=P
      ELSE
      B=P
      ENDIF
      ENDIF
      GO TO 20
```

****** SUBROUTINE BISECT ******

```
      ENDIF
      IERR=1
      WRITE (IWTTY,30) I
30    FORMAT (' BISECT ROUTINE FAILED AFTER NC ITERATIONS, NO = ',I4)
      RETURN
      END
```

APPENDIX B - DETACT-QS CODE

PC BASIC Program to Calculate

Detector Response to Fire with Arbitrary

Energy Release Rate Histories

1) Example Calculation

2) Program Listing

DETACT-QS Code   Sample Calculation

```
DETACT-QS  VERSION 1.1   WRITTEN BY D.D. EVANS  1985
CONTRIBUTION OF THE NATIONAL BUREAU OF STANDARDS (U.S.).
NOT SUBJECT TO COPYRIGHT.

QUASI-STEADY FIRE CALCULATION OF DETECTOR ACTUATION TIME
BELOW AN UNCONFINED CEILING BASED ON ALPERT'S EQUATIONS
AS PUBLISHED IN FIRE TECHNOLOGY AUGUST 1972.

                    USER SUPPLIED INPUT

HEIGHT OF CEILING ABOVE FUEL (METERS)                 ? 3.6576

DISTANCE OF DETECTOR FROM AXIS OF FIRE (METERS)       ? 2.155

INITIAL ROOM TEMPERATURE (CELSIUS)                    ? 21.111

DETECTOR ACTUATION TEMPERATURE (CELSIUS)
(140 F = 60 C   160 F = 71 C   165 F = 74 C)          ? 54.444

DETECTOR RESPONSE TIME INDEX (RTI)  (m*s)^(1/2)       ? 370.34

NEXT A DESCRIPTION OF THE FIRE HEAT RELEASE RATE AS A
AS A FUNCTION OF TIME MUST BE CONSTRUCTED. THIS WILL BE
DONE BY THE USER ENTERING KEY HEAT RELEASE RATES ALONG
THE DESIRED FIRE CURVE. FOR THE USERS INFORMATION THE
MINIMUM HEAT RELEASE RATE NECESSARY TO ACTUATE THE
DETECTOR AT THE LOCATION GIVEN IS 232  kW.


ENTER KEY HEAT RELEASE RATES THAT DETERMINE THE SHAPE OF THE
DESIRED FIRE DEVELOPMENT CURVE.  USUALLY THE FIRST DATA
PAIR WILL BE  ( TIME  0   HEAT RELEASE  0 ). UP TO 100
PAIRS CAN BE ENTERED.  TO STOP ENTERING DATA  ENTER ANY
NEGATIVE TIME VALUE.  THE PROGRAM WILL GENERATE HEAT
RELEASE RATE VALUES BETWEEN THE VALUES ENTERED AS NEEDED
BASED ON A STRAIGHT LINE INTERPOLATION BETWEEN POINTS AT
ONE SECOND INTERVALS


 1 ..   TIME (SEC)        ? 0

        HEAT RELEASE (kW)? 0


 2 ..   TIME (SEC)        ? 5

        HEAT RELEASE (kW)? 0.2928
```

```
3 ..   TIME (SEC)        ? 10
       HEAT RELEASE (kW)? 1.1711

4 ..   TIME (SEC)        ? 15
       HEAT RELEASE (kW)? 2.635

5 ..   TIME (SEC)        ? 20
       HEAT RELEASE (kW)? 4.684

6 ..   TIME (SEC)        ? 25
       HEAT RELEASE (kW)? 7.319

7 ..   TIME (SEC)        ? 30
       HEAT RELEASE (kW)? 10.539

8 ..   TIME (SEC)        ? 35
       HEAT RELEASE (kW)? 14.345

9 ..   TIME (SEC)        ? 40
       HEAT RELEASE (kW)? 18.737

10 ..   TIME (SEC)        ? 45
       HEAT RELEASE (kW)? 23.71

11 ..   TIME (SEC)        ? 50
       HEAT RELEASE (kW)? 29.28

12 ..   TIME (SEC)        ? 55
       HEAT RELEASE (kW)? 35.42

13 ..   TIME (SEC)        ? 60
       HEAT RELEASE (kW)? 42.16
```

```
14 ..  TIME (SEC)        ? 65
      HEAT RELEASE (kW)? 49.48

15 ..  TIME (SEC)        ? 70
      HEAT RELEASE (kW)? 57.38

16 ..  TIME (SEC)        ? 75
      HEAT RELEASE (kW)? 65.87

17 ..  TIME (SEC)        ? 80
      HEAT RELEASE (kW)? 74.95

18 ..  TIME (SEC)        ? 85
      HEAT RELEASE (kW)? 84.61

19 ..  TIME (SEC)        ? 90
      HEAT RELEASE (kW)? 94.86

20 ..  TIME (SEC)        ? 95
      HEAT RELEASE (kW)? 105.69

21 ..  TIME (SEC)        ? 100
      HEAT RELEASE (kW)? 117.11

22 ..  TIME (SEC)        ? 105
      HEAT RELEASE (kW)? 129.11

23 ..  TIME (SEC)        ? 110
      HEAT RELEASE (kW)? 141.70

24 ..  TIME (SEC)        ? 115
      HEAT RELEASE (kW)? 154.87
```

```
25 ..   TIME (SEC)        ? 120

       HEAT RELEASE (kW)? 168.63

26 ..   TIME (SEC)        ? 125

       HEAT RELEASE (kW)? 182.98

27 ..   TIME (SEC)        ? 130

       HEAT RELEASE (kW)? 197.91

28 ..   TIME (SEC)        ? 135

       HEAT RELEASE (kW)? 213.4

29 ..   TIME (SEC)        ? 140

       HEAT RELEASE (kW)? 229.5

30 ..   TIME (SEC)        ? 145

       HEAT RELEASE (kW)? 246.2

31 ..   TIME (SEC)        ? 150

       HEAT RELEASE (kW)? 263.5

32 ..   TIME (SEC)        ? 155

       HEAT RELEASE (kW)? 281.3

33 ..   TIME (SEC)        ? 160

       HEAT RELEASE (kW)? 299.8

34 ..   TIME (SEC)        ? 165

       HEAT RELEASE (kW)? 318.8

35 ..   TIME (SEC)        ? 170

       HEAT RELEASE (kW)? 338.4
```

```
36 ..   TIME (SEC)        ? 175
       HEAT RELEASE (kW)? 358.6

37 ..   TIME (SEC)        ? 180
       HEAT RELEASE (kW)? 379.4

38 ..   TIME (SEC)        ? 185
       HEAT RELEASE (kW)? 400.8

39 ..   TIME (SEC)        ? 190
       HEAT RELEASE (kW)? 422.7

40 ..   TIME (SEC)        ? 195
       HEAT RELEASE (kW)? 445.3

41 ..   TIME (SEC)        ? 200
       HEAT RELEASE (kW)? 468.4

42 ..   TIME (SEC)        ? 205
       HEAT RELEASE (kW)? 492.1

43 ..   TIME (SEC)        ? 210
       HEAT RELEASE (kW)? 516.4

44 ..   TIME (SEC)        ? 215
       HEAT RELEASE (kW)? 541.3

45 ..   TIME (SEC)        ? 220
       HEAT RELEASE (kW)? 556.8

46 ..   TIME (SEC)        ? 225
       HEAT RELEASE (kW)? 592.8
```

```
47 ..   TIME (SEC)        ? 230
        HEAT RELEASE (kW)? 619.5

48 ..   TIME (SEC)        ? 235
        HEAT RELEASE (kW)? 646.7

49 ..   TIME (SEC)        ? 240
        HEAT RELEASE (kW)? 674.5

50 ..   TIME (SEC)        ? 245
        HEAT RELEASE (kW)? 702.9

51 ..   TIME (SEC)        ? 250
        HEAT RELEASE (kW)? 731.9

52 ..   TIME (SEC)        ? 255
        HEAT RELEASE (kW)? 761.5

53 ..   TIME (SEC)        ? 260
        HEAT RELEASE (kW)? 791.6

54 ..   TIME (SEC)        ? 265
        HEAT RELEASE (kW)? 822.4

55 ..   TIME (SEC)        ? 270
        HEAT RELEASE (kW)? 835.7

56 ..   TIME (SEC)        ? 275
        HEAT RELEASE (kW)? 885.6

57 ..   TIME (SEC)        ? 280
        HEAT RELEASE (kW)? 918.1
```

```
58 ..   TIME (SEC)        ? 285

      HEAT RELEASE (kW)? 951.2

59 ..   TIME (SEC)        ? 290

      HEAT RELEASE (kW)? 984.9

60 ..   TIME (SEC)        ? 295

      HEAT RELEASE (kW)? 1019.1

61 ..   TIME (SEC)        ? 300

      HEAT RELEASE (kW)? 1053.9

62 ..   TIME (SEC)        ? 305

      HEAT RELEASE (kW)? 1089.4

63 ..   TIME (SEC)        ? 310

      HEAT RELEASE (kW)? 1125.4

64 ..   TIME (SEC)        ? 315

      HEAT RELEASE (kW)? 1162.0

65 ..   TIME (SEC)        ? 320

      HEAT RELEASE (kW)? 1199.2

66 ..   TIME (SEC)        ? 325

      HEAT RELEASE (kW)? 1236.9

67 ..   TIME (SEC)        ? 330

      HEAT RELEASE (kW)? 1275.3

68 ..   TIME (SEC)        ? 335

      HEAT RELEASE (kW)? 1314.2
```

```
69 ..   TIME (SEC)         ? 340

        HEAT RELEASE (kW)? 1353.7

70 ..   TIME (SEC)         ? 345

        HEAT RELEASE (kW)? 1393.8

71 ..   TIME (SEC)         ? 350

        HEAT RELEASE (kW)? 1434.5

72 ..   TIME (SEC)         ? 355

        HEAT RELEASE (kW)? 1475.8

73 ..   TIME (SEC)         ? 360

        HEAT RELEASE (kW)? 1517.7

74 ..   TIME (SEC)         ? -1

SEND OUTPUT TO PRINTER (Y OR N) ? N

CEILING HEIGHT= 3.6576  RADIUS= 2.155  DET ACT TEMP= 54.444  RTI= 370.34
```

TIME sec	FIRE kW	GAS TEMP C	DET TEMP C
0.0	0.0	21.1	21.1
10.0	1.2	22.0	21.1
20.0	4.7	23.4	21.1
30.0	10.5	25.2	21.2
40.0	18.7	27.1	21.3
50.0	29.3	29.3	21.4
60.0	42.2	31.6	21.6
70.0	57.4	34.0	21.9
80.0	75.0	36.5	22.2
90.0	94.9	39.2	22.6
100.0	117.1	41.9	23.1
110.0	141.7	44.8	23.6
120.0	168.6	47.7	24.2
130.0	197.9	50.8	24.9
140.0	229.5	53.8	25.7
150.0	263.5	57.0	26.6
160.0	299.8	60.3	27.6
170.0	338.4	63.6	28.7
180.0	379.4	67.0	29.8
190.0	422.7	70.4	31.1
200.0	468.4	73.9	32.4

210.0	516.4	77.5	33.9
220.0	556.8	80.6	35.4
230.0	619.5	84.8	37.1
240.0	674.5	88.5	38.8
250.0	731.9	92.3	40.6
260.0	791.6	96.2	42.6
270.0	835.7	99.2	44.6
280.0	918.1	104.0	46.7
290.0	984.9	108.0	48.9
300.0	1053.9	112.0	51.2
310.0	1125.4	116.1	53.6

**** DETECTOR ACTUATION AT 313.4 SECONDS ****

TYPE A CARRIAGE RETURN TO CONTINUE?

ANALYZE SAME FIRE WITH DIFFERENT DETECTOR (Y OR N) ? N

```
10 DIM S(101),Q(101)
20 K=10
30 PRINT "DETACT-QS  VERSION 1.1   WRITTEN BY D.D. EVANS  1985"
40 PRINT "CONTRIBUTION OF THE NATIONAL BUREAU OF STANDARDS (U.S.)."
50 PRINT "NOT SUBJECT TO COPYRIGHT."
60 PRINT " "
70 PRINT "QUASI-STEADY FIRE CALCULATION OF DETECTOR ACTUATION TIME"
80 PRINT "BELOW AN UNCONFINED CEILING BASED ON ALPERT'S EQUATIONS"
90 PRINT "AS PUBLISHED IN FIRE TECHNOLOGY AUGUST 1972."
100 PRINT " "
110 PRINT " "
120 PRINT "                    USER SUPPLIED INPUT"
130 PRINT " "
140 PRINT "HEIGHT OF CEILING ABOVE FUEL (METERS)                  ";
150 INPUT H
160 PRINT " "
170 PRINT "DISTANCE OF DETECTOR FROM AXIS OF FIRE (METERS)    ";
180 INPUT R
190 PRINT " "
200 PRINT "INITIAL ROOM TEMPERATURE (CELSIUS)                   ";
210 INPUT T1
220 PRINT " "
230 PRINT "DETECTOR ACTUATION TEMPERATURE (CELSIUS)"
240 PRINT "(140 F = 60 C   160 F = 71 C   165 F = 74 C)        ";
250 INPUT T9
260 PRINT " "
270 PRINT "DETECTOR RESPONSE TIME INDEX (RTI)  (m*s)^(1/2)    ";
280 INPUT L
290 PRINT " "
300 PRINT "NEXT A DESCRIPTION OF THE FIRE HEAT RELEASE RATE AS A"
310 PRINT "AS A FUNCTION OF TIME MUST BE CONSTRUCTED. THIS WILL BE"
320 PRINT "DONE BY THE USER ENTERING KEY HEAT RELEASE RATES ALONG"
330 PRINT "THE DESIRED FIRE CURVE. FOR THE USERS INFORMATION THE"
340 PRINT "MINIMUM HEAT RELEASE RATE NECESSARY TO ACTUATE THE"
350 PRINT "DETECTOR AT THE LOCATION GIVEN IS";
360 X=((T9-T1)*H/5.38*R^(2/3))^(3/2)
370 IF R/H>.18 THEN 390
380 X=((T9-T1)*H^(5/3)/16.9)^(3/2)
390 X=X+.5
400 X=INT(X)
410 PRINT X;
420 PRINT " kW."
430 PRINT " "
440 PRINT " "
450 PRINT "ENTER KEY HEAT RELEASE RATES THAT DETERMINE THE SHAPE OF THE"
460 PRINT "DESIRED FIRE DEVELOPMENT CURVE.  USUALLY THE FIRST DATA"
470 PRINT "PAIR WILL BE  ( TIME  0   HEAT RELEASE  0 ). UP TO 100"
480 PRINT "PAIRS CAN BE ENTERED.  TO STOP ENTERING DATA  ENTER ANY"
490 PRINT "NEGATIVE TIME VALUE.  THE PROGRAM WILL GENERATE HEAT"
500 PRINT "RELEASE RATE VALUES BETWEEN THE VALUES ENTERED AS NEEDED"
510 PRINT "BASED ON A STRAIGHT LINE INTERPOLATION BETWEEN POINTS AT"
520 PRINT "ONE SECOND INTERVALS"
530 PRINT " "
540 PRINT " "
550 N=1
```

```
560 FOR I=1 TO 101
570 S(I)=1.701412E+38
580 Q(I)=0
590 NEXT I
600 PRINT N;
610 PRINT "..   TIME (SEC)        ";
620 INPUT S(N)
630 IF S(N)<0 THEN 710
640 PRINT " "
650 PRINT "          HEAT RELEASE (kW)";
660 INPUT Q(N)
670 PRINT " "
680 N=N+1
690 PRINT " "
700 GOTO 600
710 S(N)=S(N-1)+1
720 PR=0
730 PRINT " "
740 PRINT "SEND OUTPUT TO PRINTER (Y OR N) ";
750 INPUT A$
760 IF A$="Y" OR A$="y" THEN PR=1
770 PRINT " "
780 PRINT "CEILING HEIGHT=";H;" RADIUS=";R;" DET ACT TEMP=";T9;" RTI=";L
790 PRINT " "
800 PRINT "       TIME       FIRE  GAS TEMP  DET TEMP"
810 PRINT "        sec         kW         C          C"
820 IF PR=0 THEN 920
830 LPRINT "DETACT-QS  VERSION 1.1"
840 LPRINT " "
850 LPRINT "CEILING HEIGHT=";H;" m"
860 LPRINT "DETECTOR DISTANCE FROM AXIS OF FIRE=";R;" m"
870 LPRINT "DETECTOR ACTUTATION TEMP=";T9;" C"
880 LPRINT "RTI=";L;" (m*s)^(1/2)"
890 LPRINT " "
900 LPRINT "       TIME       FIRE  GAS TEMP  DET TEMP"
910 LPRINT "        sec         kW         C          C"
920 I=N-1
930 P=K
940 N=0
950 T4=T1
960 T5=T1
970 T6=T1
980 J=1
990 IF N<S(J+1) THEN 1020
1000 J=J+1
1010 GOTO 990
1020 O=(N-S(J))/(S(J+1)-S(J))*(Q(J+1)-Q(J))+Q(J)
1030 T4=T5
1040 S6=T6
1050 T6=16.9*O^(2/3)/H^(5/3)+T1
1060 IF R/H<=.18 THEN 1080
1070 T6=5.38*(O/R)^(2/3)/H+T1
1080 V6=.95*(O/H)^(1/3)
1090 IF R/H<=.15 THEN 1110
1100 V6=.2*O^(1/3)*H^(1/2)/R^(5/6)
```

```
1110 IF V6>.1 THEN 1130
1120 V6=.1
1130 L1=L/V6^.5
1140 B=T6-S6
1150 T5=T4+(S6-T4)*(1-EXP(-1/L1))+B*L1*(EXP(-1/L1)+1/L1-1)
1160 IF P<K THEN 1200
1170 PRINT USING "########.#";N,O,S6,T4
1180 IF PR=1 THEN LPRINT USING "########.#";N,O,S6,T4
1190 P=0
1200 N=N+1
1210 P=P+1
1220 IF T5<T9 THEN 990
1230 GOSUB 1680
1240 PRINT " "
1250 PRINT "        **** DETECTOR ACTUATION AT";
1260 PRINT USING "######.#";E;
1270 PRINT " SECONDS ****"
1280 PRINT " "
1290 IF PR=0 THEN 1350
1300 LPRINT " "
1310 LPRINT "        **** DETECTOR ACTUATION AT";
1320 LPRINT USING "######.#";E;
1330 LPRINT " SECONDS ****"
1340 LPRINT " "
1350 PRINT "TYPE A CARRIAGE RETURN TO CONTINUE";
1360 INPUT A$
1370 PRINT " "
1380 PRINT "ANALYZE SAME FIRE WITH DIFFERENT DETECTOR (Y OR N) ";
1390 INPUT A$
1400 IF A$="Y" OR A$="y" THEN 1420
1410 END
1420 PRINT "CHANGE RTI VALUE (Y OR N) ";
1430 INPUT A$
1440 IF A$<>"Y" AND A$<>"y" THEN 1470
1450 PRINT "NEW VALUE = ";
1460 INPUT L
1470 PRINT "CHANGE ACTUATION TEMPERATURE (Y OR N) ";
1480 INPUT A$
1490 IF A$<>"Y" AND A$<>"y" THEN 1520
1500 PRINT "NEW VALUE = ";
1510 INPUT T9
1520 PRINT "CHANGE FUEL TO CEILING HEIGHT (Y OR N) ";
1530 INPUT A$
1540 IF A$<>"Y" AND A$<>"y" THEN 1570
1550 PRINT "NEW VALUE= ";
1560 INPUT H
1570 PRINT "CHANGE RADIUS OF DETECTOR FROM FIRE AXIS (Y OR N) ";
1580 INPUT A$
1590 IF A$<>"Y" AND A$<>"y" THEN 1620
1600 PRINT "NEW VALUE= ";
1610 INPUT R
1620 PRINT "CHANGE PRINTOUT INTERVAL (Y OR N) ";
1630 INPUT A$
1640 IF A$<>"Y" AND A$<>"y" THEN 1670
1650 PRINT "NEW VALUE = ";
```

```
1660 INPUT K
1670 GOTO 770
1680 E=N-1+(T9-T4)/(T5-T4)
1690 E=E*100+.5
1700 E=INT(E)
1710 E=E/100
1720 RETURN
```

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U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET (See instructions)	1. PUBLICATION OR REPORT NO. NBSIR-85/3167	2. Performing Organ. Report No.	3. Publication Date July 1985

4. TITLE AND SUBTITLE

Methods to Calculate the Response Time of Heat and Smoke Detectors Installed Below Large Unobstructed Ceilings

5. AUTHOR(S)

David D. Evans, David W. Stroup

6. PERFORMING ORGANIZATION *(If joint or other than NBS, see instructions)*

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, D.C. 20234

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U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

Recently developed methods to calculate the time required for ceiling mounted heat and smoke detectors to respond to growing fires are reviewed. A computer program, that calculates activation times for both fixed temperatures and rate of rise heat detectors in response to fires that increase in heat release rate proportionally with the square of time from ignition is given. This program produces equivalent results to the tables published in Appendix C, Guide for Automatic Fire Detector Spacing, (NFPA 72E, 1984). A separate method and corresponding program are provided to calculate response time for fires having arbitrary heat release rate histories. This method is based on quasi-steady ceiling layer gas flow assumptions. Assuming a constant proportionality between smoke and heat release from burning materials, a method is described to calculate smoke detector response time modeling the smoke detector as a low temperature heat detector in either of the two response time models.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

ceilings; computer program; egress; escape; fire alarms; fire detection; fire suppression; heat detectors; smoke detectors; sprinkler systems

13. AVAILABILITY

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APPENDIX D

Three Proposed Typical House Designs

for Energy Conservation Research

August 10

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National Bureau of Standards

Prepared for:

Department of Housing and Urban Development

and

Energy Research and Development Administration

FOREWORD

This is one of a series of working reports documenting NBS research efforts to develop energy and cost data. The work described in this report was jointly funded through ERDA/NBS Mod. No. 2 of Contract E (49-1) 3800 and Task Order No. EA-77-A-01-6010 and through HUD/NBS Contract No. RT193-12.

The background work for this report was completed in support of two other reports "Geographic Variation in the Heating and Cooling Requirements of a Typical Single-Family House", and "Determination of Optimal Energy Conservation Designs in Single-Family Housing: Preliminary Results".

The house designs presented in this report are not intended as "model" houses which should be copied for any particular design qualities. Their purpose is merely to typify a large percentage of new house construction being built in the U.S. today. They are presented to provide a basis for comment with suggested revisions to improve their representativeness welcome.

ABSTRACT

The ability of various energy conservation design features to reduce residential energy consumption can only be judged by comparing houses with and without such features. Comparisons can be made based on measuring energy consumption of actual houses, or by computer modeling energy consumption. With either approach, if the houses being evaluated are the basis for estimating regional or national energy savings possible with a given change from current construction practice, it is important that the houses be typical of the given population of houses. For that purpose this report contains three house designs typical of new house construction for much of the nation.

TABLE OF CONTENTS

SI Conversion

In view of present accepted practice by the building industry in the United States, common U.S. units of measurement have been used throughout this paper. In recognition of the position of the U.S.A. as a signatory to the General Conference on Weights and Measures, which gave official status to the Metric SI System of units in 1960, the following conversion factors are provided to assist readers who use the SI units.

Length

1 inch (") = 0.0254 meter
1 foot (') = 0.3048

Area

1 square foot (ft^2) = 0.0929 $meter^2$

Volume

1 cubic foot (ft^3) = 0.0283 $meter^3$

Thermal Resistance

1 °F h ft^2/Btu = 0.1761m^2 °C/W

1. INTRODUCTION

House designs typical of today's construction practices are needed as a basis for comparing the effectiveness of various energy conservation strategies. This report proposes three typical houses as follows:

1) a compact "ranch style" house

2) a townhouse

3) a larger two story detached house

These are not intended to be "model" houses which should be copied because of any particular design qualities. Instead, they are intended to be typical of housing now being built in the U.S.A.

The design of the three houses was based upon the judgment of the author (an architect experienced in residential design) and upon a 1974 report by the National Association of Home Builders (NAHB) titled, "A National Survey of Characteristics and Construction Practices for All Types of One Family Houses." The survey data represented 84,000 homes built by 1600 builders selected randomly from the 27,000 builder members of NAHB.

The decision to present three house designs was based on the NAHB statistics on the frequency of various house configurations. Out of the total number of houses constructed by builders in the survey, 73 percent were detached, 19 percent were townhouses, and 8 percent were duplexes, quadruplexes, or "other." Given these percentages it was decided to present designs for the detached and townhouse categories but not for the duplex, quadruplex, and other category since the latter represented a small percentage comprised of diverse configurations. The decision to present two detached designs was based on the fact that of all detached houses in the survey, 52 percent were one-story and 17 percent were two-story. Since detached houses constituted such a large percentage of the houses, separate designs for one and two-story houses were deemed necessary. Separate designs were not presented for "split level" houses (bedroom area half a flight up from living area) nor for "bi-level" or "raised ranch" houses (ranch plan above a half out of the ground basement) because these configurations are merely a variation of the ranch design and can easily be derived, given the information for the ranch design.

Each of the three house designs presented varies slightly from the national average for all houses. The basementless ranch house, with 1176 sq.ft. of floor area, is smaller than the national average detached house of 1684 sq.ft. The smaller size was based on two judgment factors: First, the three-bedroom, one-story houses would tend to be smaller than the overall average floor area of all single-family detached houses which include two-story houses and houses with basements. Second, since 1974, the trend has been for new houses to be more compact and it is expected that this trend will continue. A final note regarding the ranch design, windows have been excluded from the side elevations. This is a common practice due to closeness of neighboring houses. Window areas for the front and rear elevations were selected as the minimum desirable for the room areas, given that orientation is unknown.

The ranch house design, as well as the other two house designs, is meant to be typical of today's home building practices and is not a house specifically designed for energy conservation.

The townhouse, with a floor area of 1315 sq.ft., is also smaller than the national average of 1393 sq.ft., again reflecting the trend towards more compact houses. Also, three bedrooms were included, rather than the national average of 2.2 bedrooms, because it was felt that this configuration has become prevelent as townhouses have become increasingly common.

The two-story house, with 1994 sq.ft. of finished floor area plus a basement, is slightly larger than the national average of 1684 sq.ft. This house design is included to represent a high-priced category of large houses.

2. Drawings

Schedule of Drawings

Ranch	plan
	elevations
	section
	schedule of component surface areas
Townhouse	plans
	elevations
	section
	schedule of component surface areas
Two-Story	1st floor plan
	2nd floor plan
	front elevation
	rear elevation
	section
	schedule of component surface areas

Key to Symbols Used in Drawings

2850 = 2'-8" W x 5'-0" H

TW = twin windows

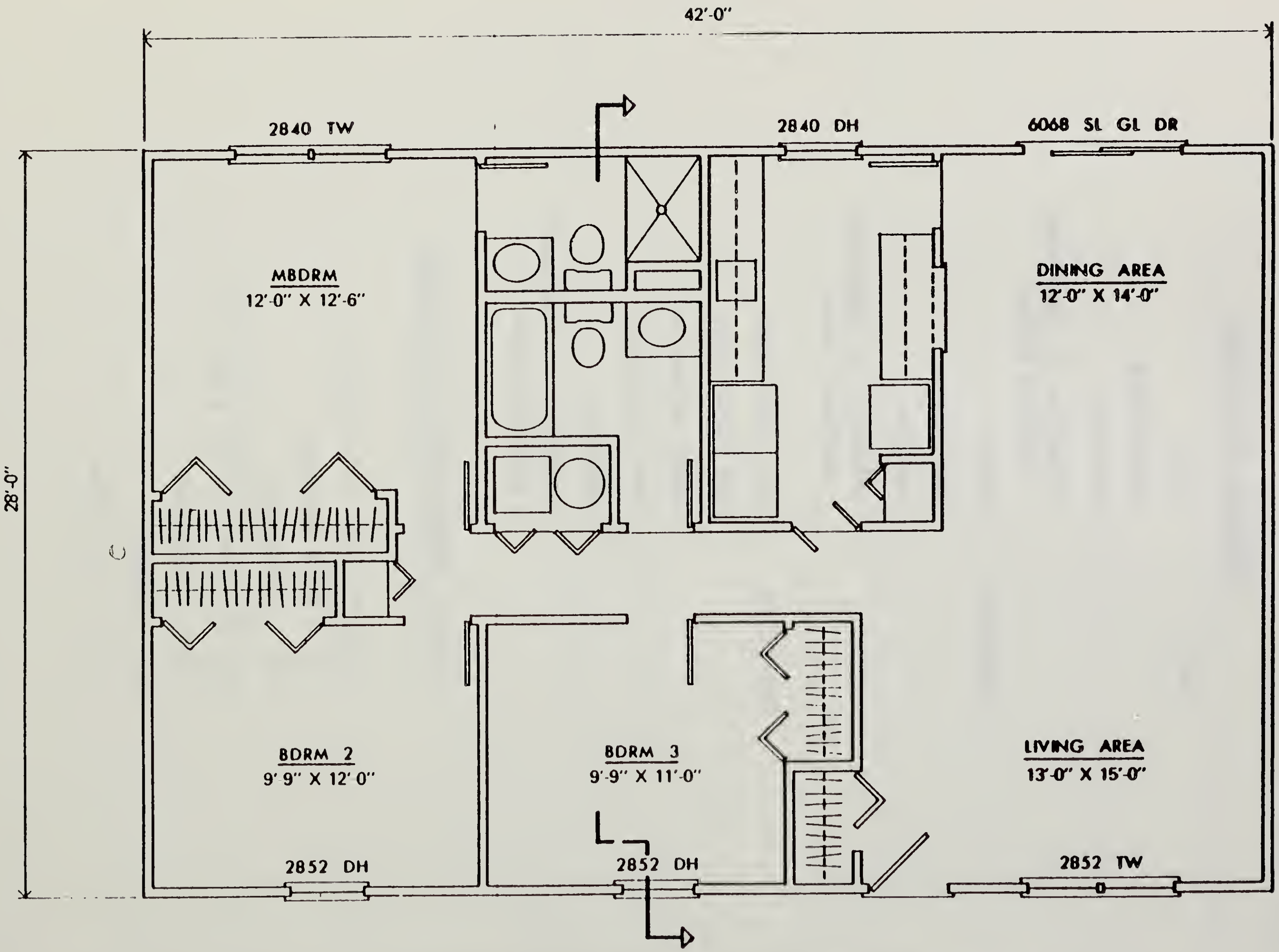
DH = doublehung

SL GL DR = sliding glass door

FG = fixed glass

HT = height

O.C. = on center



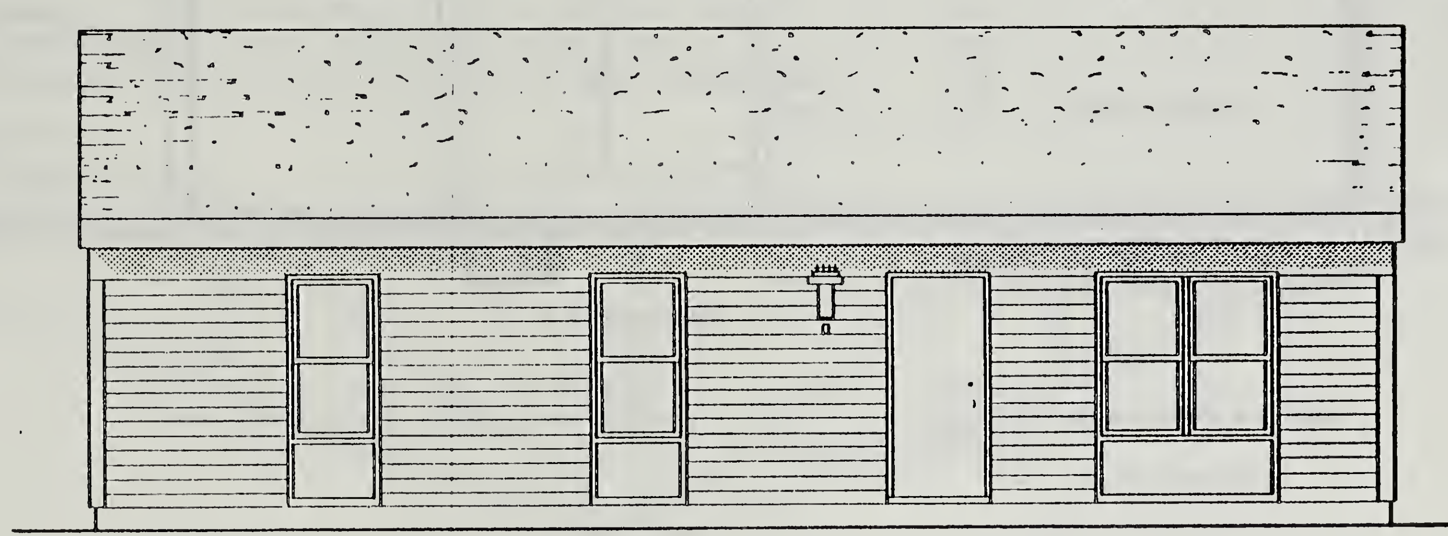
FLOOR PLAN OF A TYPICAL RANCH HOUSE

AUG.10,1977 0 2 4 8 NBS

REAR ELEVATION OF A TYPICAL RANCH HOUSE

0 2 4 8

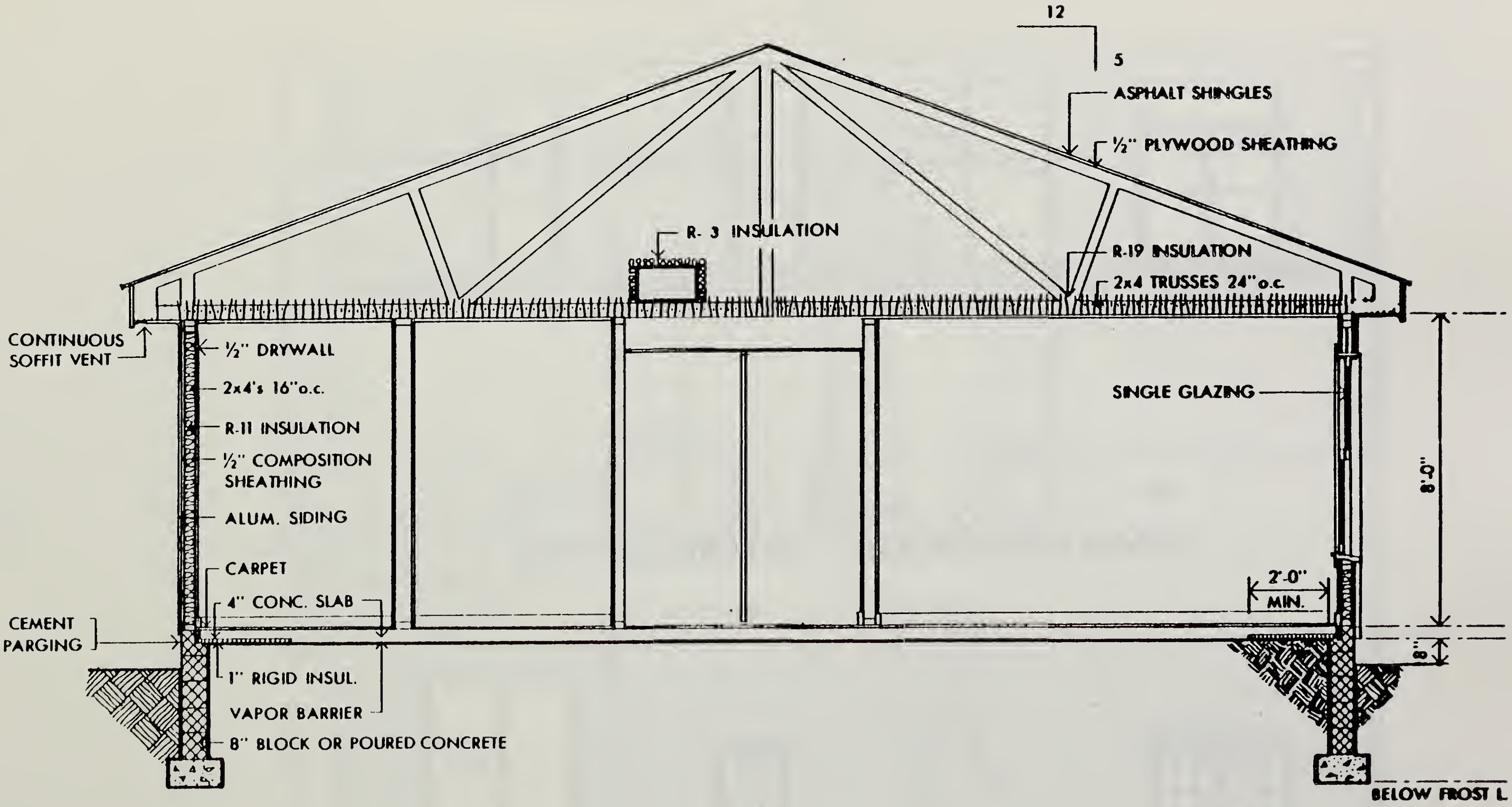
AUG.10,1977 NBS



FRONT ELEVATION OF A TYPICAL RANCH HOUSE

0 2 4 8

AUG.10,1977 NBS



SECTION THRU TYPICAL RANCH

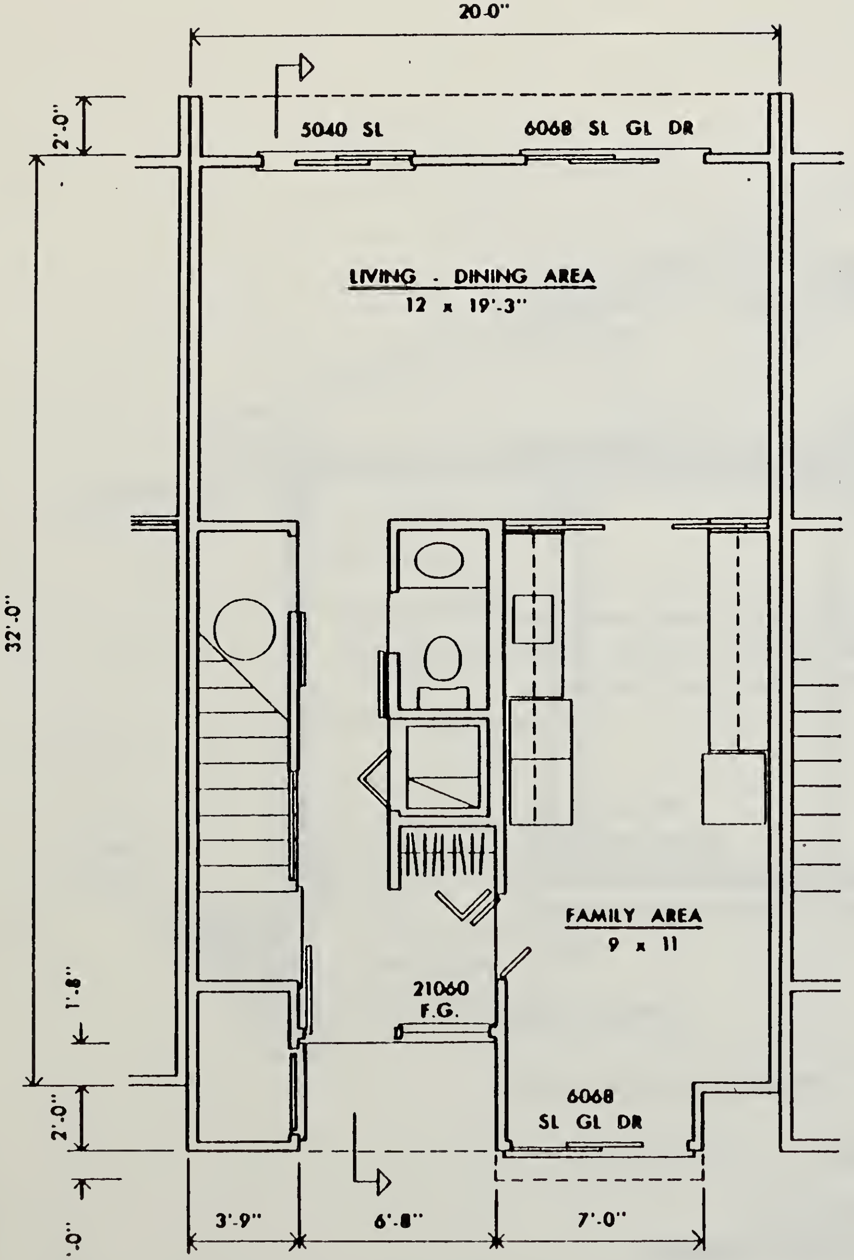
0 2 4 8

AUG. 10,1977 NBS

SCHEDULE OF COMPONENT SURFACE AREAS

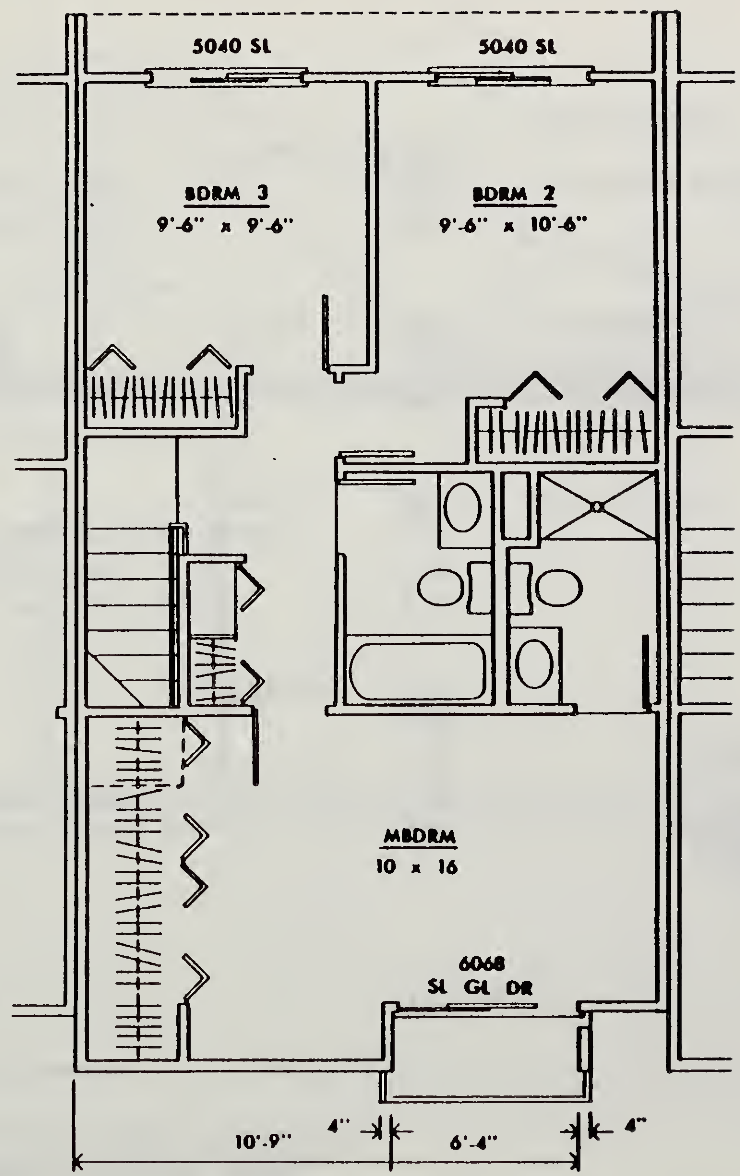
(Ranch House)

Slab (ground contact area)		1176 sq.ft.
Wall Areas		
Front		
Insulation Area (75% of net wall area)		196
Stud Area (25% of net wall area)		65
Window Area		55
Door Area		20
	Total	336
Rear		
Insulation Area (75% of net wall area)		198
Stud Area (25% of net wall area)		66
Window Area (including single-glass door)		72
	Total	336
Sides		
Insulation Area (85% wall area)		190
Stud Area (15% wall area)		34
	Total	224
Ceiling		
Insulation Area (90% floor area)		1058
Truss Cord Area (10% floor area)		118
	Total	1176



LOWER FLOOR PLAN OF A TYPICAL TOWNHOUSE

AUG. 10, 1977 — 0 2 4 8 — NBS



UPPER FLOOR PLAN OF A TYPICAL TOWNHOUSE

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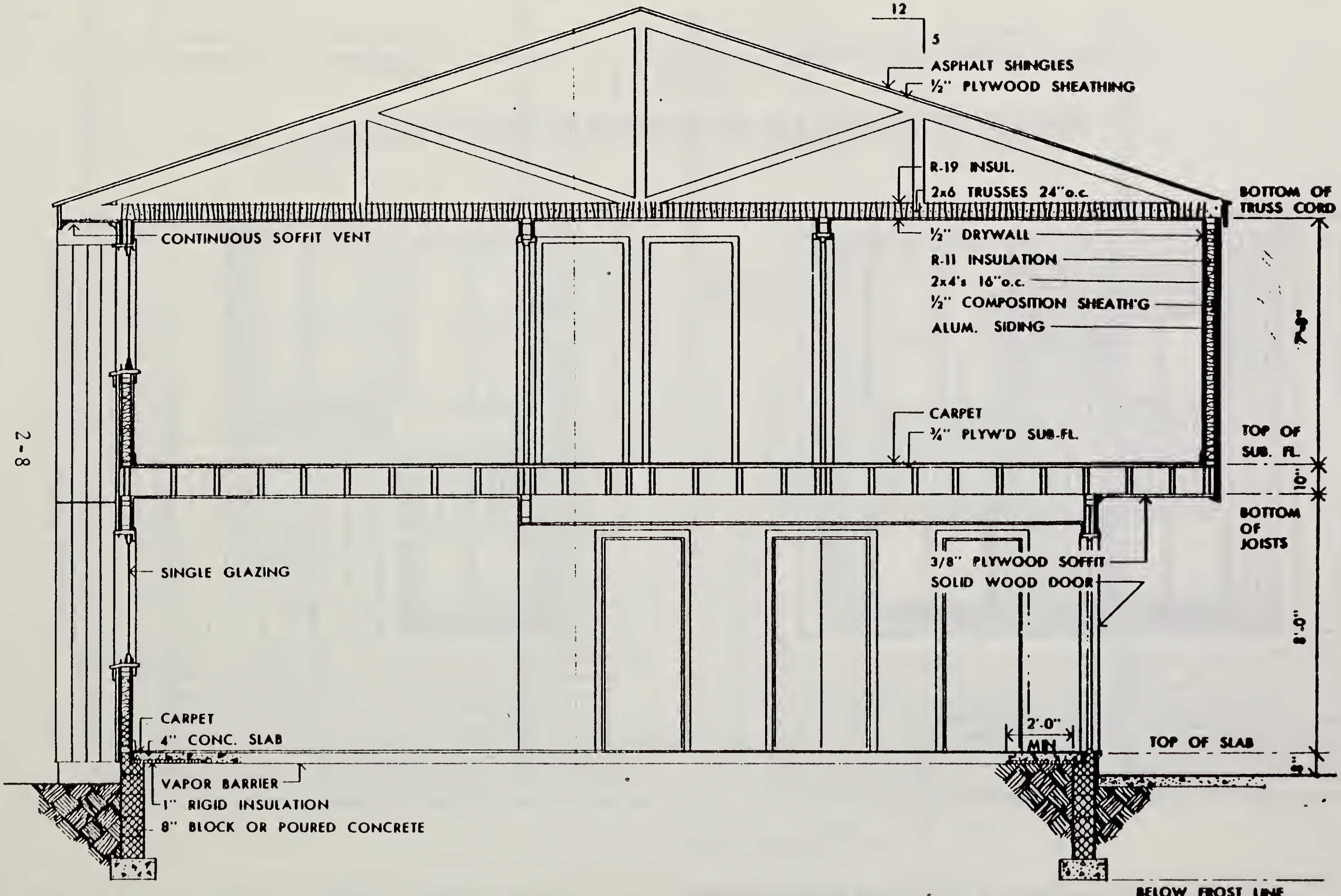
FRONT & REAR ELEVATIONS OF A TYPICAL TOWNHOUSE

AUG.10,1977

0 2 4 8

NBS



SECTION THRU TYPICAL TOWNHOUSE

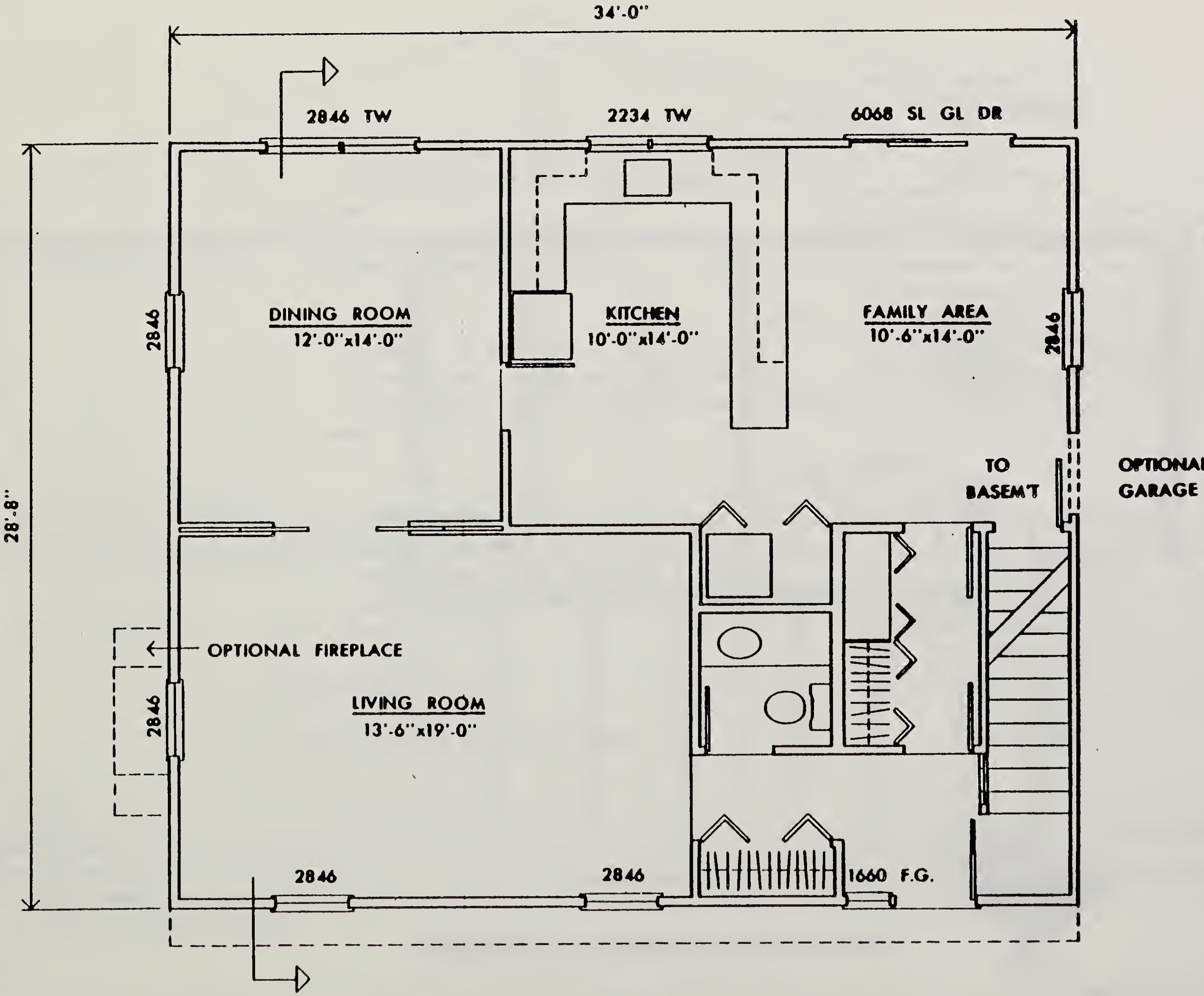
0 2 4 8

AUG. 10, 1977 NBS

SCHEDULE OF COMPONENT SURFACE AREAS

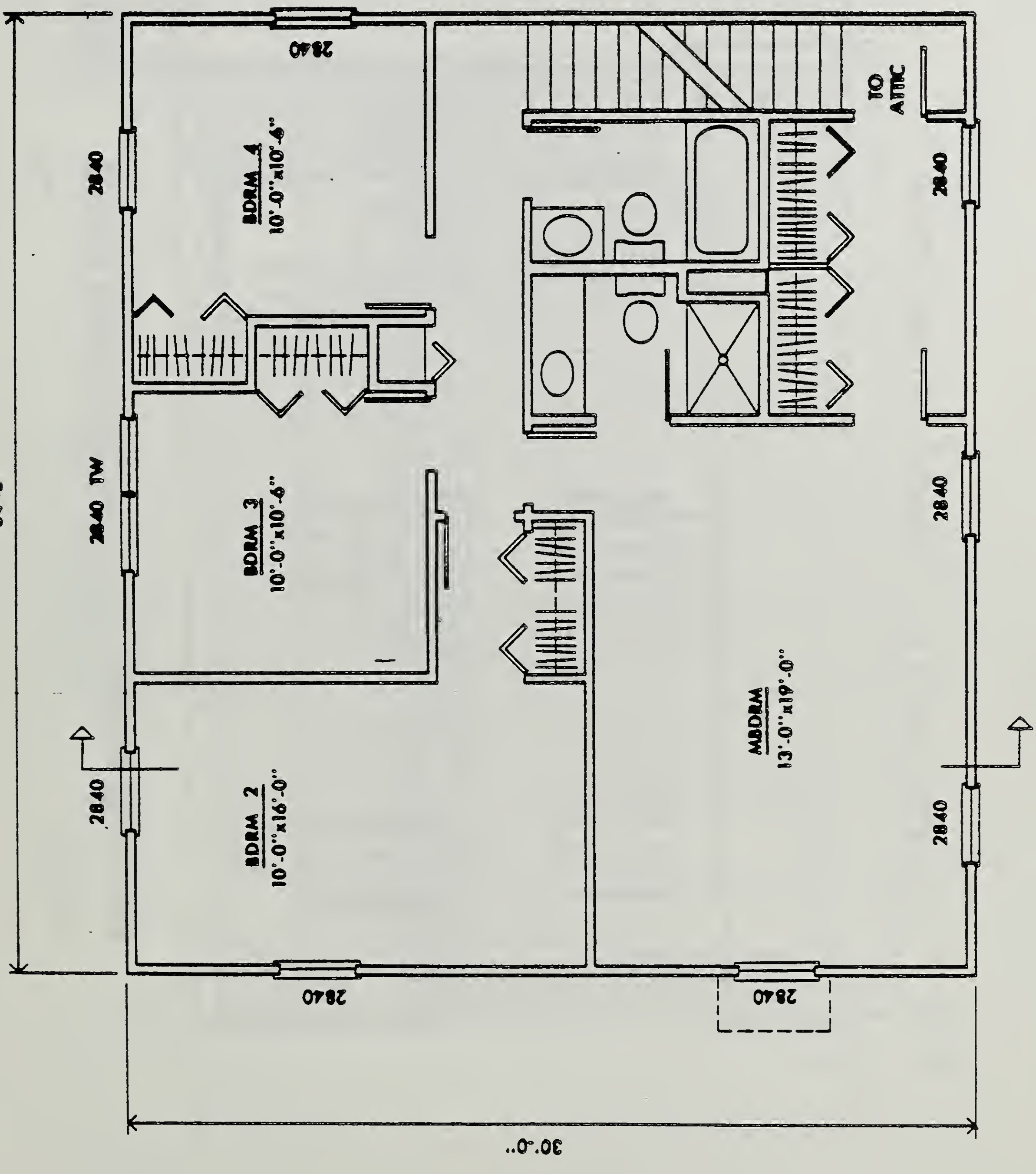
(Townhouse)

Slab (ground contact area)		654 sq.ft.
Wall Areas		
Front		
Insulation Area (75% net wall area)		160
Stud Area (25% net wall area)		53
Window Area		97
Door Area		20
	Total	330
Rear		
Insulation Area (75% net wall area)		172
Stud Area (25% net wall area)		58
Window Area (incl. sl. gl. dr.)		100
	Total	330
Sides - (Party walls)		
Ceiling		
Insulation Area (90% floor area)		595
Truss Cord Area (10% floor area)		66
	Total	661 sq.ft.



LOWER FLOOR PLAN OF A TYPICAL 2-STORY HOUSE

AUG. 10,1977 0 2 4 8 NBS



UPPER FLOOR PLAN OF A TYPICAL 2-STORY HOUSE

0 2 4 8

AUG.10,1977

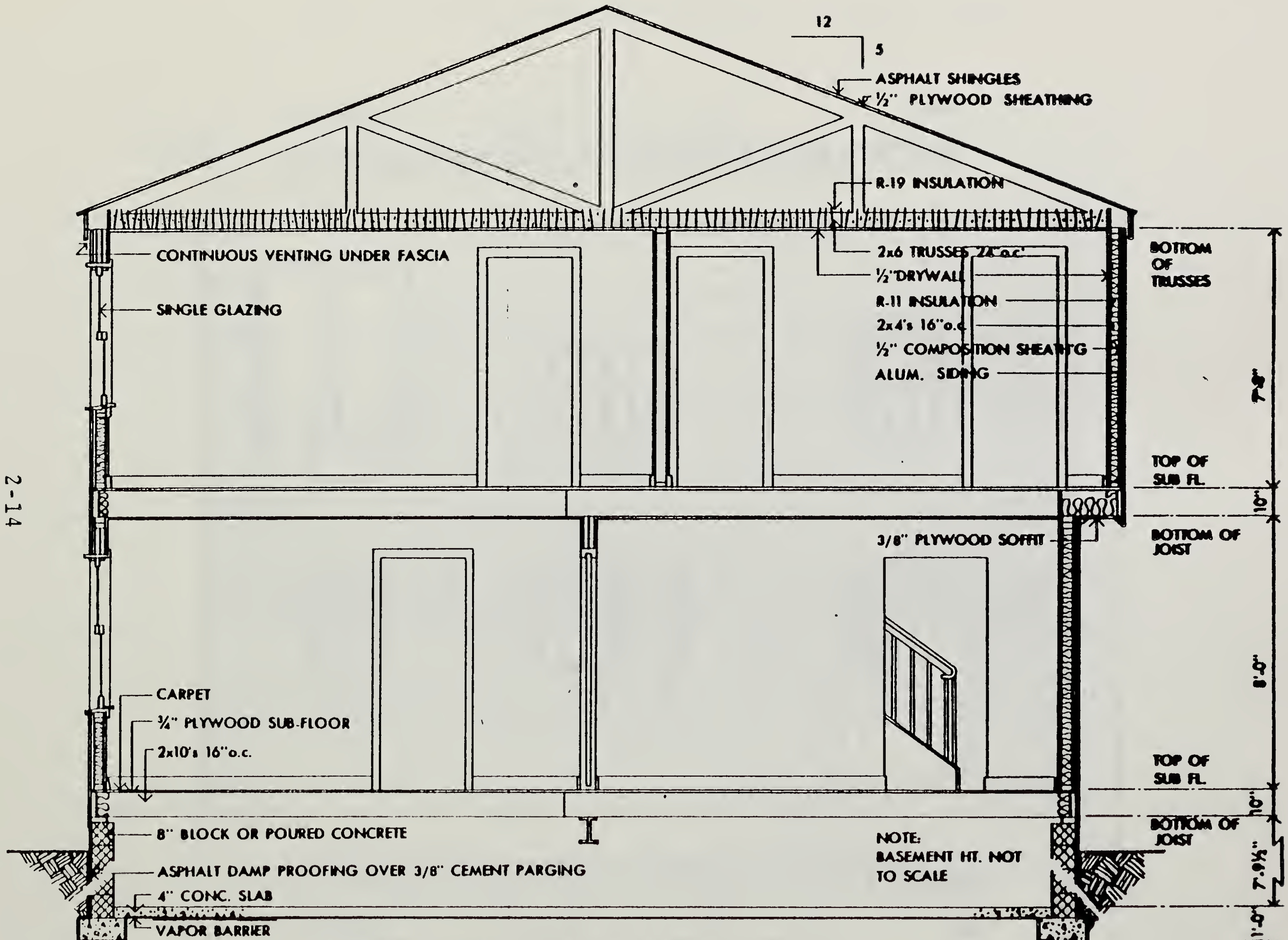
NBS

FRONT ELEVATION OF A TYPICAL 2-STORY HOUSE

AUG.10,1977 NBS

REAR ELEVATION OF A TYPICAL 2-STORY HOUSE

AUG.10,1977 0 4 8 NBS



SECTION THRU TYPICAL 2-STORY HOUSE

0 2 4 8

AUG.10,1977 NBS

SCHEDULE OF COMPONENT SURFACE AREAS

(Two-Story House)

Basement		
Slab		975 sq. ft.
Foundation Walls		977
Wall Areas		
Front		
Insulation Area (75% net wall area)		378
Stud Area (25% net wall area)		126
Window Area		65
Door Area		20
	Total	589
Rear		
Insulation Area		368
Stud Area		123
Window Area (incl. sl. gl. dr.)		98
	Total	589
Sides (right & left sides similar if optional fireplace built)		
Insulation Area (85% net wall area)		412
Stud Area (15% net wall area)		73
Window Area		23
	Total	508
Ceiling		
Insulation Area (90% floor area)		918
Truss Cord Area (10% floor area)		102
	Total	1020

3. MATERIAL SPECIFICATIONS

The following is a list of the materials noted on the drawings for the ranch and two-story houses (detached) and for the townhouse, along with the percentage of houses in the NAHB survey which were built using these materials. Also, included are design features incorporated in the three house designs with associated NAHB reported percentages from the same survey. In a few instances the material specified or the design feature included in the typical house designs do not represent the highest percentage reported in the NAHB survey. The basis for such deviation is the author's judgment of changes in building practice since the 1974 NAHB survey. In these cases, both the selected material or design feature and its associated percentage as well as the material or design feature with the highest survey percentage (shown in parentheses) are reported. In some instances the majority of responding builders did not answer a question regarding use of a material. This is indicated by "no answer" in the percentage column.

MATERIALS SPECIFIED	NAHB Reported Percent of Total	
First Floor (on grade):	Detached	Townhouses
1 inch perimeter insulation	no answer	
Carpet	85	89
First floor (above basement):		
no insulation	no answer	
5/8" plywood underlayment	17	40
Carpet	85	89
Exterior Walls:		
Aluminum siding	15	24
(Brick)	(34)	(24)
1/2" intermed. density insul. bd.	27	35
2 x 4 framing 16" o.c.	78	95
3 1/2" R-11 Batt insul.	71	81
Kraft paper vapor barrier	35	30
1/2" gypsum wallboard	82	78
Windows:		
Aluminum	64	78
Double-hung	33	--
Horizontal sliders	--	35
Single glazing	70	66
No storm sash	75	72
Doors:		
Solid wood (front entry)	67	43
No storm door	75	72
Sliding glass door (dining area)	not reported	

	NAHB Reported	
	Percent of Total	
	Detached	Townhouses
Roof/Ceiling:		
Asphalt Shingle	85	77
1/2 inch plywood sheathing	55	51
2 x 4 (or 6) trusses 24 inches o.c.	63	72
R-19 loose fill (±6") insulation	41	29
R-19 batt (6") insulation	--	(39)
1/2 inch drywall	80	89
Plumbing/Mechanical:		
Warm air, ducted heating	79	80
Electric furnace	not reported	
Natural gas furnace	(49)	(40)
Central air conditioning	67	86
Electric domestic water heater	51	55

	NAHB Reported Percent of Total	
	Detached	Townhouses
DESIGN FEATURES		
Foundation:		
Slab-on-grade	34	70
(Full basement)	(34)	(25)
Number of floors:		
One-story	52	--
Two-story	17	73
Finished Floor Area:		
1200-1599	31	57
1600-2399	43	--
Garages:		
none	not reported	
one-car	--	29
two-car	(70)	--
Number of bedrooms:		
three	68	66
four	25	
Number of bathrooms:		
(one and one half)	--	(38)
two	50.1	--
two and one half	22	36.7
Roof form - gable	75	76
(Fireplace)	(57)	(50)

4. THERMAL RESISTANCE OF MATERIALS USED IN THE THREE HOUSES

COMPONENT	R (for thickness listed)
First Floor (on grade):	
Expanded polystyrene extruded (1")	5.00
Poured concrete slab (4")	0.32
Carpet and fibrous pad	2.08
Horizontal air film (still, heat flow down)	0.92
Total	8.32

First Floor (above basement):

The basement is assumed to be unheated. However, transient heat from the heating plant (located in the basement) warms the air near the basement ceiling sufficiently to make it unnecessary to calculate downward heat loss through the first floor according to the ASHRAE Handbook of Fundamentals, page 378, (see note 5).

COMPONENT	R (for thickness listed)
Walls (insulation area):	
Vertical air film (15 mph wind)	0.17
Aluminum siding	0.60
Intermediate density insulating sheathing (1/2")	1.22
Cavity insulation	11.00
Gypsum wallboard (1/2")	0.45
Vertical air film (still)	0.68
Total	14.12
Walls (stud area):	
Vertical air film (15 mph wind)	0.17
Aluminum siding	0.60
Intermediate density insulating sheathing	1.22
2 x 4 wooden studs	4.35
Gypsum wallboard (1/2")	0.45
Vertical air film	0.68
Total	7.47

Windows:		
Vertical air film (15 mph wind)		0.17
Architectural glass		0.03
Vertical air film (still)		0.68
	Total	0.88
Doors - (front entry)		
Vertical air film (15 mph wind)		0.17
Solid Hardwood (1 3/4")		1.59
Vertical air film (still)		0.68
	Total	2.44
Ceiling (insulation area)		
Horizontal air film (still, heat flow up)		0.61
Gypsum drywall (1/2")		0.45
Insulation		19.00
Horizontal air film (still, heat flow up)		0.61
	Total	20.67
Ceiling (truss cord area)		
Horizontal air film (still, heat flow up)		0.61
Gypsum drywall (1/2")		0.45
2 x 4 wooden truss cords		4.35
Horizontal air film (still, heat flow up)		0.61
	Total	6.02

Notes:

1. The resistances in the above table are calculated from tables given in Chapter 20 of the 1972 edition of the ASHRAE Handbook of Fundamentals published by the American Society of Heating, Refrigeration, and Air-Conditioning Engineers, Inc., New York.

2. It could be inferred that since R-values were given for the ceiling and insulation only, the attic temperature is assumed to be

at the outside air temperature. This may or may not be true depending on the amount of attic ventilation. An ongoing National Bureau of Standards project recording attic temperatures for various attic ventilation conditions will provide more data to help quantify the extent the attic serves as a buffer in winter and a heat trap in summer.

3. Since the windows are specified to be aluminum, the R-value can be applied to the entire window area. It is unreasonable, however, to assert that the windows are typically left uncovered at night given the privacy concern in urban or suburban environments. A tight-weave drapery hanging to the floor and in loose contact with the walls at the sides of the windows could be expected to increase the resistance to heatflow of the window by 10 to 15 percent. This is substantial as the reduction occurs at night when winter outside-inside temperature differences are greatest.

4. In calculating the downward heatflow through the slab a resistance must be assigned to the earth immediately below the slab. The perimeter insulation isolates the earth below the slab from the earth beyond to the extent of the insulation's R-value. To calculate how much heat is lost laterally out of the sides of the slab see Table 2, page 378 of the 1972 ASHRAE Handbook of Fundamentals.

5. In calculating summer heat gain the resistance of the air film is considered to be 0.25 rather than 0.17 as a 7 1/2 mph wind is conventionally assumed rather than the 15 mph wind for winter. Similarly, the value for the air film at the attic surfaces would be slightly better (0.92) in the summer as the direction of heat flow is downward as apposed to upward in winter (0.61).

5. SUGGESTED APPLICATIONS FOR THE THREE TYPICAL DESIGNS

This report provides a basis for research in the areas of energy conservation, fire safety, security, and environmental behavior.

An example research project in the area of energy conservation would be to model the energy consumption of the houses in each of 10 different locations (selected to represent a sampling of the various climates in the U.S.) and quantify the effects of various climate variables on the energy consumption of typical new houses. Such a study has been completed for the ranch house (publication is expected in the near future), but needs to be done for the townhouse and the two-story house. Once these data have been calculated and tabulated they will provide a comparative basis for many energy conservation modifications. For example, the houses could be reanalyzed with the glass areas greatly increased on the elevation facing south and decreased to HUD minimum property standards on the elevation facing north. At the same time, double glazing could be substituted for single glazing. Included in the reports of these data could be illustrations of how energy efficient fenestration and orientation can be achieved while actually enhancing privacy through landscape planning. Examples include the use of trees and shrubs, definition of court spaces, and open space planning. Similar studies could be made to document the energy and cost effectiveness of builders providing external sun protection for the glazed areas of houses, be it sun screens, deciduous trees, awnings, or roof overhangs. Such a study, especially in conjunction with a study of the effectiveness of whole-house-fan ventilation, would document surprising energy savings as a result of the dramatic reduction in the dependence on mechanical air conditioning.

In the area of fire safety, the three house designs and material specification provide a standard basis to study rates of flame and smoke propagation, rates of release of toxic substances, containment of heat, air movement patterns, and egress behavior in conjunction with models of human decision making in fire situations.

Security issues need to be investigated concurrent with research of various energy conservation measures such as adding storm windows and storm doors, increasing glass area on the south-facing side (e.g., replacing a window with a sliding glass door), orientating houses away from the street when necessary to maximize south exposure, and landscaping to shade windows (which may reduce street surveillance of windows and doors).

Finally, in the area of environmental behavior, these three designs provide the starting point to study how trends in new house construction (such as reducing house size) necessitate rethinking the way interior and exterior spaces are divided and defined relative to life styles. As land costs, material costs, and labor costs increase first costs, and as energy costs increase operating costs, future new house design will change. A study is needed, starting, with the three house designes to forecast various design and construction changes as a result of these pressures and suggest the best alternatives. Such a study would help assure that houses of the future are affordable, energy conserving, and accomodate behavioral needs.

Each of these examples of further research benefits from using the same three house designs as a baseline. The designs provide the common denominator for evaluating how design modifications for one objective such as energy conservation may help or hinder the achievement of other objectives such as improved fire safety, security, or habitability.

6. CONCLUSION

The three typical house designs and material specifications described in this report provide a statistically documented basis from which energy savings for various improvements can be calculated.

Of the three houses, the ranch is the most easily typified. There are a limited number of permutations such as the "raised ranch" and the "split level." In the case of the townhouse, there are slightly more variations in design, including the substitution of the upstairs bath with a walk-in-closet, the placement of the kitchen to the front of the townhouse with the previous location of the kitchen becoming a dining area, and the front facade being flush with no overhangs and no sliding glass door off the breakfast area or upstairs master bedroom.

Two-story houses, larger in size and higher in price than the former two examples, are least easily typified. Typical variations from the design shown include: the location of the stair in the center of the house and either parallel or perpendicular to the run as shown, and the location of the upstairs baths in the location of the bedroom number 3 as shown. The interior partitioning in this design, as in the other two designs, is not presently a concern in modeling energy consumption, however. For both the two-story and the ranch it is common to see an attached one or two-car garage, sometimes with a family room to the rear of the garage.

It is apparent, in each of the three designs, that common cosmetic facade elements such as applied vinyl window shutters have not been shown. It should not be concluded that this reflects the commonness or rarity of such features. Rather, they have been omitted merely because they typically have no significant effect on energy performance.

Finally, any conclusions based on these designs must be qualified to reflect the fact that the designs are representative of new house construction at the time of this publication. These designs are not representative of the whole housing stock (pre World War II houses differ substantially), nor do the designs anticipate changes in future house construction. The author invites suggested modifications to the designs from the readers based on their experience of what is typical.

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

This report describes the first version of a method for predicting the hazards to the occupants of a building involved in a fire. To implement this method, a software package called HAZARD I is provided. It includes a scenario development utility (PRODUCT.ONE); an interactive program for inputting data to the fire model (FINPUT); a data base program (FIREDATA) with files of thermophysical, thermochemical, and reference toxicity data; the FAST model 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 behavior (EXITT); and a tenability model (TENAB) which evaluates the impact of the predicted exposure of the occupants in terms of incapacitation or lethality from temperature or toxicity, or incapacitation by burns. All of the software operates on a personal computer. Volume 2 contains complete documentation of a set of worked example cases and Volume 3 contains a complete copy of the data in the data base.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

computer models; evacuation; fire models; hazard assessment; human behavior; toxicity

13. AVAILABILITY

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