A SUMMARY OF THE ASSUMPTIONS AND LIMITATIONS IN HAZARD I

Richard W. Bukowski P.E., Head
Hazard Analysis
Center for Fire Research
National Bureau of Standards
Gaithersburg, MD. 20899

INTRODUCTION: This document is not intended to provide a discussion of hazard assessment in general nor details of HAZARD I in particular; but rather to supplement the presentation made at the meeting and provide a summary of the important assumptions and limitations of the HAZARD I system. It is impossible to provide an exhaustive discussion of these points in a summary document such as this - a full understanding will require study of the complete HAZARD I reports and the references included therein. It is hoped that this summary will provide a sufficient overview to allow an understanding of what HAZARD I can and cannot do, and the background to future enhancements.

GENERAL: HAZARD I is a first, prototype version of a methodology for making quantitative predictions of the hazard to the occupants of a building from a fire within that building. It 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 (although this first version does not account for all of the phenomena listed). The major functions provided include:

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 throughout a series of user specified rooms and connections (doors, windows, cracks, etc.),

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

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 method involves a mix of the "hard" sciences (physics, chemistry, fluid mechanics and heat transfer) and the "soft" sciences (biology, toxicology, and human behavior). Less obvious are the areas where fundamental laws (conservation of mass, energy, and momentum) can be used, versus where empirical correlations or even "educated guesses" must be employed to bridge gaps in existing knowledge. The latter, along with compromises required by considerations of operational practicality result in the introduction of uncertainties in the results which must be quantified by experimental verification and validation. Until such is completed, the user should understand the inherent assumptions and limitations of the procedures and programs in order to make estimates of these uncertainties.

SCOPE LIMITATION: The scope of HAZARD I has been limited to one- and two-family residential structures, as a result of limitations in both technical knowledge and resources. The technical limitations involve insufficient understanding or capability to model such large-building phenomena as the distribution of heat, smoke, and gases through the HVAC system, and the complex flows in stairways. While these should have a negligeable influence on hazard development in small buildings, the effects in large buildings can be great. Also, the behavioral rules first implemented in the EXITT model for small building evacuation have not yet been incorporated into the large building evacuation models.

In addition to these technical considerations, available resources required that the first data base be limited in the number of data entries supplied. The obvious solution was to concentrate on materials and products typical in residential occupancies. If one considers that the majority of US fire losses are in these areas, this does not represent a bad starting point for the first system; and the scope will be broadened in HAZARD II by improvements in the technology and expansion of the data base.

PROGRAMS AND PROCEDURES: Figure 2 presents the HAZARD I software package developed to implement the assessment of hazard as shown in figure 1. Of the nine programs shown, only five perform calculations and so have assumptions associated with them. The others (PRODUCT.ONE, FIREDATA, FINPUT, and FASTPLOT) perform utility and user interface functions only.

Of this latter group, the only point which should be made in the context of assumptions deals with the database files searched by the programs in FIREDATA. The 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. Replicate tests were sometimes done, and some of the sources provide confidence intervals for these data. The material identifications are those provided in the sources and cannot be verified.

SPECIFIED FIRE: The greatest weakness of HAZARD I is in the specification of the rates of energy and mass release by the burning item(s). The procedures available to the user and their associated limitations are:

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 instruments and the degree to which "free-burning" conditions are not achieved (radiation from the gases under the hood or the hood itself, and restrictions in the air entrained by the object causing locally reduced oxygen concentrations affecting the combustion chemistry) in the apparatus. 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, where it is the only item burning and it is ignited in a similar fashion. The differences obtained from the use of different ignition sources or locations of application have not been explored.

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 to 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 chairs with non-combustible frames, but only 63% (range 46% to 83%) for other chairs with combustible frames. Also, the triangle does not include the "tail" of the curve produced primarily by the burning of the frame after the fabric and filler are consumed.

3. The data and procedures provided relate directly only to contents items under "free burning" conditions, initiated by relatively large flaming sources. Almost no data exist for release rates under smoldering combustion, nor for the high external flux and low oxygen conditions post-flashover which strongly influence the combustion chemistry. 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 can only give estimates which are often non-conservative (the actual release rates would be greater than estimated). The only 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. Alternatively, a detailed combustion model such as HARVARD V can be used as the source of the specified fire data, although it too has its own assumptions and limitations.

TRANSPORT: The distribution of energy and mass throughout the rooms included in the simulation is done in the model FAST. This is a zone (control volume) model with all of the attendant assumptions and limitations of such models. The basic assumption 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 (see figure 3 for a representative diagram). The boundary between the two layers in a room is called the interface.

Other than in very large rooms, the zone assumption does not generally represent a large source of error since, at least in the spaces close to the fire, experiments show that buoyantly-stratified layers clearly 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 implementation of any model requires 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 the latter is the fact that none of the models account for 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 less than for others which should be addressed first.

With a highly complex model such as FAST, the only reasonable method of assessing the assumptions and limitations is through the verification and validation process, which is ongoing at CFR. Until the results of this process are available, the following list should provide some insight.

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, regardless of the fact that the available oxygen will limit the portion of that mass which will burn in the room. This will result in extremely high predicted temperatures; exceeding the adiabatic flame temperature. **NOTE: AN ATTEMPT TO ADDRESS THIS IS CURRENTLY BEING MADE. IF SUCCESSFUL, THIS LIMITATION WILL NO LONGER APPLY.**

2. With no extant chemistry, the species yields specified will be used regardless of the oxygen concentration. It is known that the chemistry changes in low oxygen, with an attendant increase in the yields of products of incomplete combustion such as CO. Room fire test data shows that under post-flashover conditions, the production rate (yield) of CO increases (and CO_2 decreases) in the room, but much of the excess CO burns (to CO_2) in the door flame. The resulting concentrations may not differ substantially from the pre-flashover condition.

3. The entrainment coefficients are empirically-determined values. Small errors in this value will have a small effect on the fire plume or the flow in a single door plume. 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.

4. The introduction of gases into the lower layer of each room occurs primarily due to mixing at connections and from the downward flows along walls (where contact with the wall cools the gas and reduces its buoyancy). Since for the former an appropriately-documented mixing coefficient is not known, and for the latter the associated theory is only now being developed, neither is included in FAST. Thus, the lower layer cannot receive smoke or 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.

5. Plumes are the only mechanism to move energy and mass into the upper layer of a room, and are formed only by the burning item(s) in the fire room and by a door jet of upper layer gases flowing through an opening. When warm, lower layer gases move through a low opening (e.g. the undercut of a door) by expansion, they are "trapped" in the lower layer of the room into which they flowed 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 the upper (a physically-impossible condition). Since the temperatures are low and no gases flow until the upper layer drops to the undercut, this should not present a problem for hazard analyses.

6. FAST is the only zone model which <u>does not</u> assume that room pressures remain constant. This allows FAST to track pressure fluctuations caused by transient phenonema and to work on room(s) which are not vented to the outside. Under some conditions, the door flows can become imbalanced (inflow exceeds outflow) for a significant time, causing the room pressures to rise and errors in species concentrations.

<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 mostly associated 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). This represents probabilistic branching, which will be implemented in the future.

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.

ACTIVATION OF THERMAL DEVICES: The activation of heat detectors or sprinklers is handled in the program DETACT. The report (included in an appendix to the HAZARD I 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 done by Factory Mutual Research Corp. for the Fire Detection Institute and on which the NFPA 72E, Appendix C methods were developed.

TENABILITY CRITERIA: The evaluation of the impact of exposure on the occupants is done in the program TENAB. Individual determinations are done for both incapacitation and lethality from temperature and toxicity (both with a concentration-time product and a Fractional Effective Dose) along with potential incapacitation from burns due to flux exposure. No interactions are currently included (e.g. temperature exposure does not affect rate of uptake of toxic species). The basis for the threshold values used and the derivation of the equations in the FED calculation are provided in a 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 [illegible] the sensitivity of the result to the value selected.

The limiting values for temperature are based on the general literature, which includes some human data. The flux criterion comes from work done with pig skin, which is generally held to be very similar to human skin (it is used for temporary grafts for burn patients). The toxicity data however, are from the body of combustion toxicology literature which is based entirely on animal exposures (primarily rodents). Thus, it must be assumed that humans will exhibit a similar physiological response to the exposure. Due to the difficulties of assessing the onset of incapacitation in an animal, the data used are primarily those where death was the end point. The values used for incapacitation are assumed to be half of the lethal level.

The Ct parameter is an attempt to include the toxic impact of the material without differentiating the constituent gases. This represents a broad assumption, and will not include the effect of diminished oxygen. The FED parameter is the first version of the N-Gas model, including 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 N-Gas model is under continuing development, and additional gases will be added as the data are obtained. It is expected that oxygen and the first irritant gas (HCℓ) will be included in the next version.

FIGURE 1

INTERRELATIONSHIPS OF MAJOR COMPONENTS OF A FIRE HAZARD MODEL

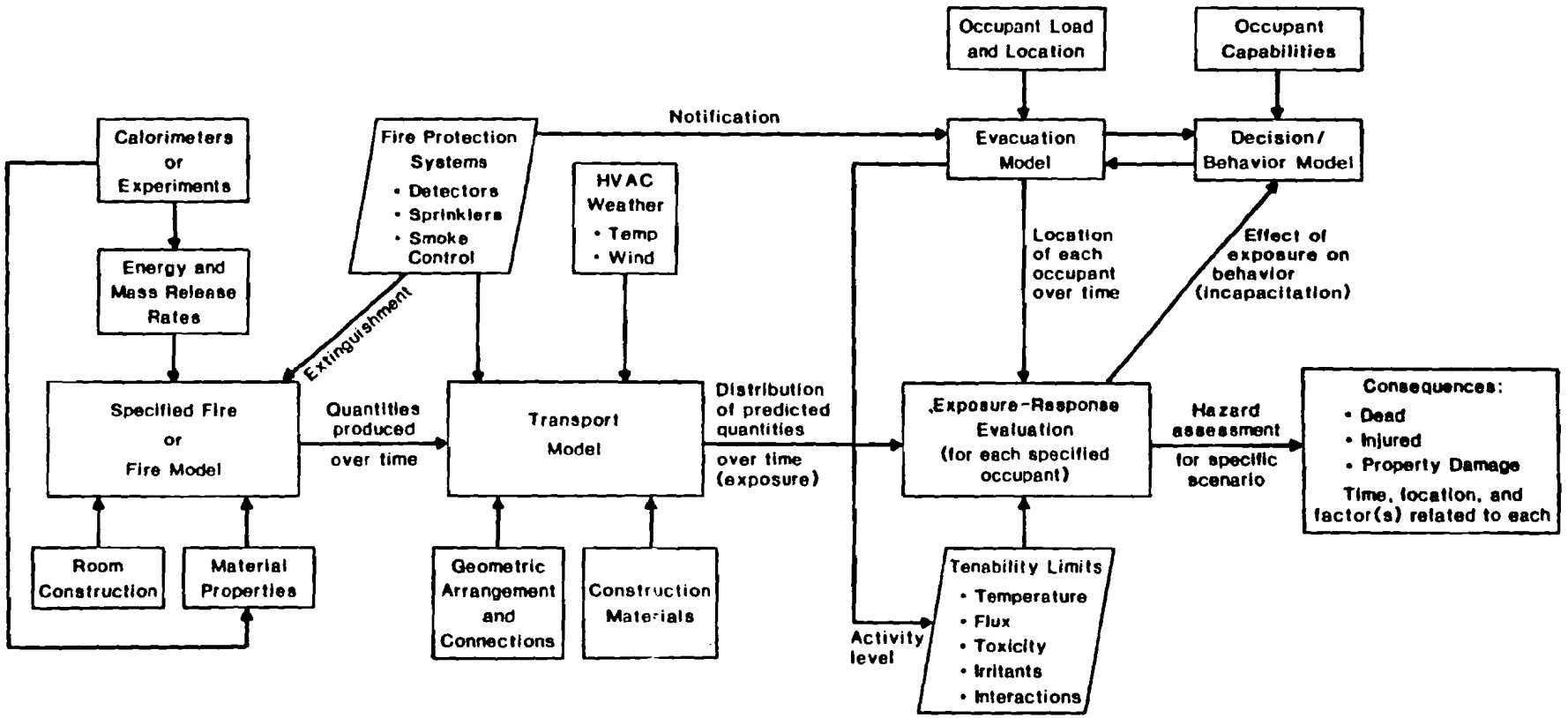
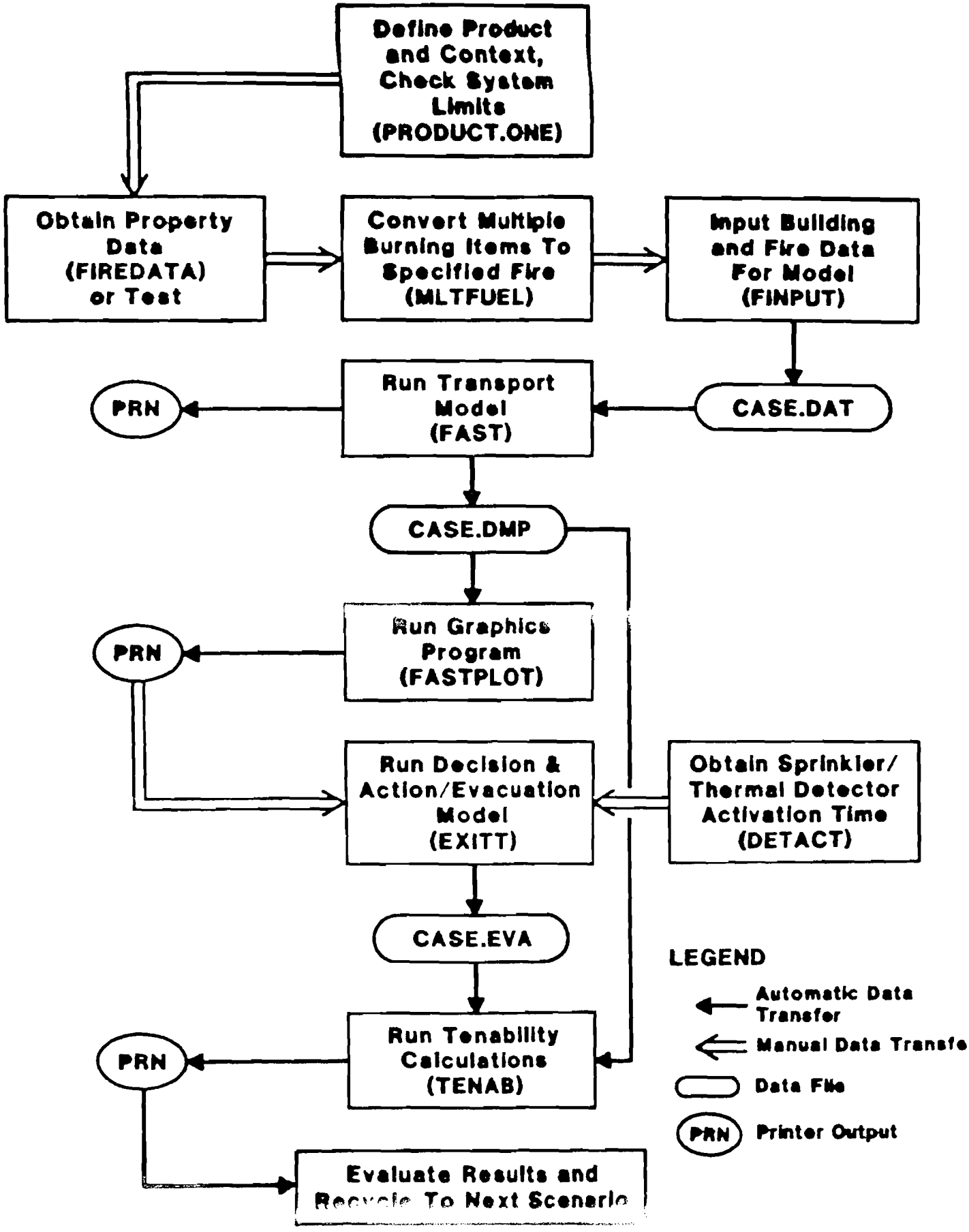


FIGURE 2

HAZARD I SOFTWARE



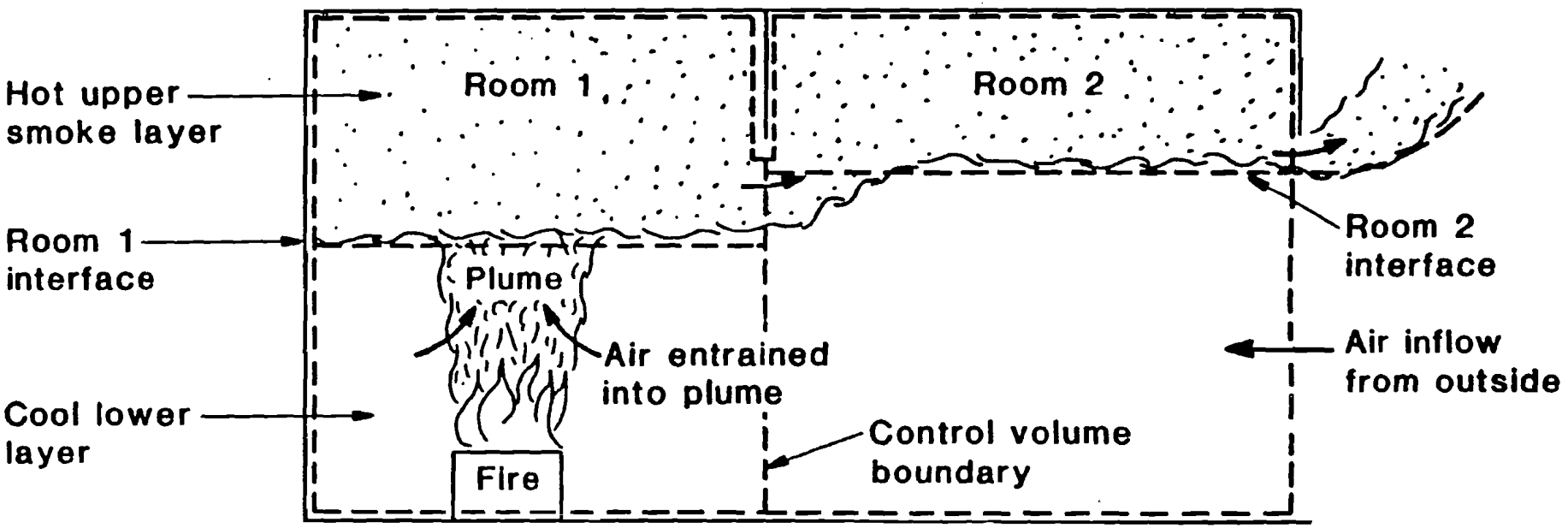


Figure 3. Schematic of upper and lower layer control volumes

The Distinction Between Fire Hazard and Fire Risk: The Importance of Such Assessments to Public Safety

John R. Hall, Jr.
National Fire Protection Association

Summary

New models and methods are rapidly becoming available to calculate not just the physical growth of fire but also the hazard and risk posed by fire. An understanding of the concepts underlying terms like "hazard" and "risk" will be essential for anyone who wishes to solve problems, or assess proposed solutions, using these new computer-based decision aids. A brief review is provided of concepts and a major research initiative now under way.

This decade has seen an explosive growth in the number and diversity of models and analysis methods, either available or under development, for the examination of fire growth, smoke spread, and fire effects on people and property. With this growth in capability has come a number of new terms like "hazard" and "risk", terms that seem deceptively familiar and simple but that are now used in a technically precise manner to distinguish one class of new models from another. In the new world of scientific fire safety decision-making, it will be important to know not only how these new models work but also what questions each is intended to address and what aspects of the fire problem each is designed to capture. This paper will review the meanings of the new terms, provide a brief conceptual overview of the new models, and describe current research now under way to develop them. Throughout this paper, it is assumed that most users wish to model the effects of changes in a product to be used in a certain class of buildings.

Many of the computer-based models in wide use today may be loosely referred to as fire growth models. Examples of these models would include (1) the various editions of the Harvard code, originally developed by Howard Emmons, (2) the highly simplified ASET, or Available Safe Egress Time Model, developed by Leonard Cooper, and (3) the FAST model, or Fire And Smoke Transport model, developed at the National Bureau of Standards. In these models, a fire is defined primarily as a rate of heat release time-curve and a particular location in a larger space. Although the models are often called fire growth models, they are really smoke and heat spread models. The specific curve defining the fire typically must be provided by the model user, who in turn may derive it based on the reference curves that have been developed for a wide range of burning items. The principal function of the model is then to use the laws of physics to simulate the build-up of heat, smoke, and toxic gases in sections of the larger space as a result of the externally defined fire.

Fire growth models vary considerably in complexity, speed, cost, and sophistication. Some are field models, providing physical characteristics as a function of specific locations in the fire-affected space. Some are zone models, providing physical characteristics only for large segments of the fire-affected space and modeling the movement of the borders or interfaces between these spaces. Some can model only one room, while others can model several rooms, including such non-room areas as concealed spaces. But none of

these models address two major aspects of fire safety - the likelihood that the fire they model will occur and the practical consequences to people or property of the physical characteristics they show developing.

A model that includes both a model of fire growth and a model of the practical consequences of that growth is called a hazard model. A hazard model therefore must include a model that translates the physical phenomena of fire into damage to people or property. The leading hazard model in the U.S. is HAZARD I, developed at the National Bureau of Standards, and it models damage to people through a modeling component called TENAB, which stands for TENABility. TENAB is a comparison program. Its point of reference may be a particular room or a moving location representing an occupant. At each point in time, TENAB calculates the instantaneous and cumulative effects fire has had on the location or occupant of interest, then compares those effects to known criteria regarding lethal or incapacitating levels or combinations of fire effects. The best current knowledge on toxic potency of gases and on heat stress enter the hazard model in this way.

To put it another way, HAZARD I uses FAST, a fire growth model, to generate a description of the hazardous conditions at each location in the building as a function of time. TENAB then calculates, based on a fixed location or a moving location representing a moving occupant, the point in time when the cumulative exposure at that location would have been lethal or incapacitating. If escape has not occurred by that time, the occupants at that location will be considered to have died.

In this way, HAZARD I directly addresses many of the concerns that have been raised about the direct use of toxic potency tests for regulation. HAZARD I uses toxic potency information, like LCt50 values, to translate the accumulating fire effects into practical consequences of incapacitation or death. But HAZARD I does not treat a single toxic potency value as safe or unsafe in itself. If a product has high toxic potency but is very difficult to ignite, then this should be captured in the initial specification of the fire curve, which will show the product entering the fire later. If a product has high toxic potency but releases mass slowly, then the time calculations of HAZARD I can reflect that fact.

What HAZARD I cannot do is compensate for limitations in the state of the art of its components, whether they be test methods for calculating input variables or physical, chemical, or biological relationships that are used to make the calculations. Like an experimental automobile, HAZARD I is an integrated system which includes some components that perform in a nearly ideal fashion and other components that are subject to considerable uncertainty and need to be carefully monitored by knowledgeable users.

HAZARD I includes another major component that it treats as part of hazard and which others have treated as part of the population-exposure element of risk. That component is EXITT, a model of human behavior in fire, which is the medium by which HAZARD I provides a dynamic picture of the exposure of occupants to a developing fire. In simple terms, HAZARD I uses FAST to determine what fire effects are in a room, uses TENAB to determine how lethal those effects are, and uses EXITT to determine whether anyone is present to be affected.

As complex and comprehensive as HAZARD I may already sound, there are many elements of hazard it does not include. One is the process of suppression, whether by automatic systems or by manual means. Others are non-lethal effects of fire on people and damage effects on property. Each of these may be thought of as a challenge for the future. HAZARD I also does not include the key defining element of a risk model, which is the relative likelihood of the conditions it models.

The simplest extension of a hazard model to a risk model would consist of adding on a single probability number. This simple extension is not satisfactory, no matter how it is considered. Suppose the probability is defined narrowly as the likelihood of the very specific situation used in HAZARD I - a specific fire in a specific location of the specific building with specific occupants in indicated locations. Then the probability will inevitably be near zero, and the significance of knowing anything about that situation will appear to be nil. At the other extreme, suppose the probability is defined broadly as the likelihood of any fire in any location of any of that class of buildings with all their variations in occupancy. Then it is unlikely that a user will know enough to be comfortable - let alone accurate - in selecting one detailed description to be representative of all that variety in a HAZARD I run.

The solution to this dilemma is the use of what is called a scenario structure. One begins with an occupancy class of interest and a product class of interest, and one wishes to model the risk of fire involving that kind of product in that kind of occupancy. The universe of fires that can occur in that occupancy class are then subdivided into what are called scenario classes. Each scenario class is defined by several characteristics, such as a room of origin, a description of the initial fire, and a description of the locations and characteristics of the building occupants when the fire began. These characteristics are referred back to the data on historical fires and other data sources to obtain a probability for that scenario class. At the same time, a representative case is identified within the scenario class. It is designed to be representative of all the variety in the scenario class, but this will be a much more manageable and defensible task than selecting one representative of the universe of fires because each scenario class will be more homogeneous than the whole universe of fires. This representative case is called the reference scenario for that scenario class.

The identification of scenario classes and reference scenarios involves considerable judgment and a balancing of two different concerns. If the number of scenario classes is too large, then (a) the time and cost of running the model will be unacceptably large, and (b) the existing data bases may be inadequate to provide reasonably accurate probability estimates for each scenario class. But if the number of scenario classes is too small, then there will be grave, unresolveable doubts about the representativeness of many of the reference scenarios, given the tremendous variation that will exist in the scenario classes they represent.

Finding ways to deal with this dilemma, and many others, is the mission of the National Fire Protection Research Foundation's fire risk assessment research project. Begun in 1986 and due to be completed in 1990, this project

is designed to construct a fire risk model around a fire hazard model and to demonstrate its general applicability to estimation of the projected impact of product design changes on the national fire death toll. Of the three developmental cases used to bring the project to its current position, one addressed wire and cable insulation in hotel and motel installations. The other two were carpets in office buildings and upholstered furniture in homes. Future work will include a developmental case on interior wall coverings in restaurants and more focused work to refine the accuracy and measure the sensitivity of the risk method's individual modeling components.

The following is a very brief listing of some major modeling challenges that have been and are being addressed in the fire risk assessment project:

o What characteristics, recorded or estimateable for most real fires, can be used to estimate when, at what size, and for what reason the fire stopped growing? Most fires are interrupted, and this affects the estimation of the hazard consequences of changing a product involved in the fire.

o What characteristics, recorded or estimateable for most real fires, can be used to estimate whether and when a product will become involved in a fire that did not begin with its ignition? The secondary ignition of a product may depend on the burning properties and location of any other item in the building.

o What data exists, recorded for either real fires or the population in general, that can be used to describe the layouts of rooms and the number, locations and conditions of occupants in enough detail to support hazard-model calculations?

o What characteristics, recorded or estimateable for most real fires, can be used to determine whether, when, and with consequences for fire spread, fires cross into or out of concealed spaces? This may be called the barrier breach model, although there is a possibility of barrier compromise prior to the fire which should be captured as well.

o How can a hazard model, designed to handle up to ten rooms, be used to estimate risk or hazard in buildings having hundreds of rooms and dozens of floors?

o How can a risk or hazard model, which calculates risk as a cumulative effect of toxic gases and heat stress, capture the many rapid fatal injuries to persons located very close to the point of ignition? This includes people smoking in bed, the torch operators who ignite the materials they are working on, and clumsy arsonists who trap themselves in fast-moving fires.

As these questions are answered, fire risk and fire hazard assessment methods will become sufficiently well developed to be used in all the major fire safety decision-making areas we now work in using less sophisticated tools. Fire hazard models may be the key to our long-stated goal of movement from specification codes to performance codes. Because they can address the net effects of many simultaneous changes in a product or a building, fire hazard models will permit greater flexibility in assessing new technology.

Fire risk assessment methods should have a similar impact but will be of particular use if ease of ignition is among the product design changes being contemplated. Fire risk assessment methods also will be the models of choice for economic decisions, such as whether to regulate, because they are the only models capable of estimating benefits in terms like expected lives saved that can be validly compared to estimates of the cost of regulation. Agencies like the U.S. Consumer Product Safety Commission therefore are likely to be prime users of the new fire risk assessment tools, while building code officials are more likely to find that fire hazard models will suit most of their needs.

It is important to view all of these tools as systems in a constant state of development. As with other computerized decision aids, there will always be gaps - the gap between the version in widespread use and the version the lab boys and girls consider their best current model, the gap between the model applications that can be safely and confidently performed by the typical user in the field and the wider range of model applications that can be executed by the model developers and their peers, and lastly, the gap between the scientific state of the art embedded in the model and the state of knowledge required to answer all questions and concerns to everyone's satisfaction. Notwithstanding all these gaps ~~between the~~ ideal and the real, by the next decade, we can look forward to a new level of scientific power in our public and private decisions about fire safety. If I may hazard a guess, we have nothing to risk and everything to gain.

VIII. REVIEW OF NFPRF PROGRAM

- NFPRF AND RELATIONSHIP TO NATIONAL FIRE PROTECTION ASSOCIATION

- NFPRF FIRE RISK ASSESSMENT PROJECT

  STUDIES, RESULTS, PROJECT SCHEDULE