A Prototype Methodology for Fire Hazard Analysis

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Abstract

The first version of a method for predicting the hazards to occupants involved in a building fire is described. The method and available computer software, called HAZARD I, can predict the time varying environment within a building resulting from a specified fire; the locations and actions of occupants; and the impact of the exposure of each of the occupants to the fire products in terms of whether the occupants successfully escape, are incapacitated, or are killed.

Introduction

The Center for Fire Research at the U.S. National Institute of Standards and Technology has released a method for quantifying the hazards to occupants of buildings from fires, and the relative contribution of specific products (e.g., furniture, wire insulation) to those hazards. The culmination of six years of development, this method, called HAZARD I, is the first such comprehensive application of fire modeling in the world. HAZARD I combines expert judgment and calculations to estimate the consequences of a specified fire. The procedures involve four steps: (1) defining the context, (2) defining the scenario, (3) calculating the hazard, and (4) evaluating the consequences. Steps 1, 2, and 4 are largely judgemental and depend on the expertise of the user. Step 3, which involves use of the extensive computer software, requires considerable expertise in firesafety practice. The heart of HAZARD I is a sequence of computer software procedures that 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.

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

"Technical Reference Guide for the HAZARD I Fire Hazard Assessment Method," which details the methodology, theory, and limitations of HAZARD I,[1]
"Software User's Guide for the HAZARD I Fire Hazard Assessment Method," which provides detailed documentation of the extensive computer software provided with the package,[2] and
"Example Cases for the HAZARD I Fire Hazard Assessment Method," which presents a set of eight examples of the use of HAZARD I.[3]

A set of computer disks provides the software necessary for the calculation in HAZARD I. All of the software will operate on any IBM* PC (XT, AT, or PS/2) or compatible MS-DOS computer with the following minimum hardware configuration:

640 K memory
graphics card (IBM CGA, EGA, or VGA; or Hercules compatible)

*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 HAZARD I has been tested. Such use does not constitute any endorsement of those products by the National Institute of Standards and Technology or the National Fire Protection Association.

hard disk drive (about 2 Mb required for the files)
math co-processor (8087, 80287, or 80387)
printer (with graphics capability)
MS-DOS 3.0 or higher

Although this initial version is focused on single-family residential occupancies, it is potentially of use for other occupancies. In its initial testing, it is hoped that this prototype method will be widely tested by those with experience in the field of firesafety. Constructive feedback from such experts 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 therein.

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

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

Figure 1 illustrates the elements and interactions that 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 consumption of mass over time. The transport of this energy and mass through the building is influenced by the structural geometry, the construction materials used, and the fire protection systems employed. The response of occupants and the consequences of the fire depend on when the occupants are notified, their physical capabilities, the decisions they make, and their susceptibility to the hazards to which they are exposed.

Tools for fire hazard analysis make it possible to evaluate product fire performance against a firesafety goal. For example, a goal of firesafety has always been to keep the fire contained until the people can get out. The problem is that it is very difficult to keep the smoke contained. Quantitative hazard analysis allows the determination of the impacts of smoke, such as toxicity, *relative* to the impact of other hazards of fire for a prescribed building and set of occupants and determines if the time available for egress is greater than the time required; and if not, why not. Time is the critical factor. Having 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 problems from occurring.

Quantitative hazard analysis techniques have the potential of providing significant cost savings. Alternative protection strategies can be studied within the hazard analysis framework to give the benefit-cost relation for each. In addition, measures are evaluated as a system with their many interactions, including the impact of both structure and contents. Examination of these alternatives promotes design flexibility, reduces redundancies, and lowers cost without sacrificing safety. New technology can be evaluated prior to actual practice, and can therefore reduce 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.

Background

The CFR project to develop a quantitative hazard assessment method was initiated following the NBS Workshop on Combustion Product Toxicology held in 1982.[4] In this workshop, papers were presented in which some of the initial concepts of hazard analysis were discussed. The general approach for the hazard analysis capability was discussed in the *Journal of Fire Science* early in 1983.[5] Later that year, NBS made a commitment to produce a practical hazard assessment method in 3 to 5 years.[6] HAZARD I and the accompanying software and documentation are a prototype of this method.

In February 1984, the National Fire Protection Association (NFPA) sponsored a two-day workshop, "Practical Approaches for Smoke Toxicity Hazard Assessment,"[7] involving groups of leading toxicologists, fire

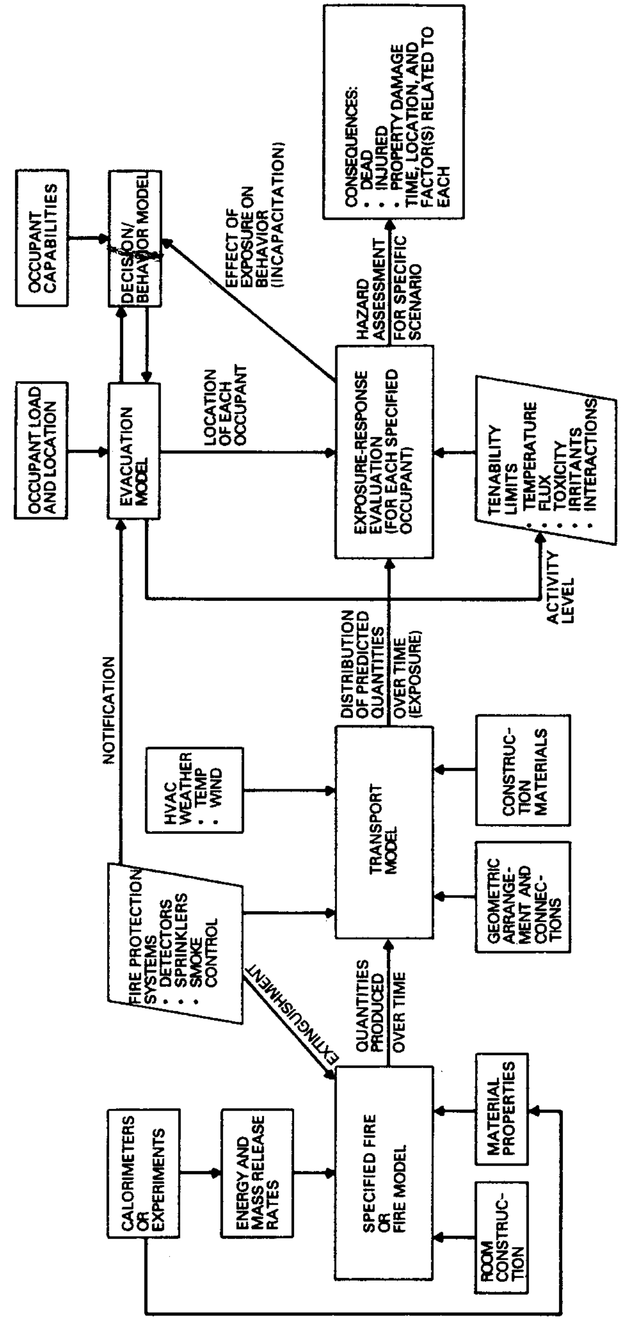

Figure 1. Interrelationships of major components of a fire hazard model.

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 derived from the workshop's efforts.[8] As the project progressed, papers that discussed the evolving philosophy and structure of the hazard assessment methodology were published.[9,10] 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.

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.[11] In this report, Bukowski based the estimating procedure on a series of algebraic equations that 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 in assessing fire hazards on ships.[12] 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.[13] 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 requires a computer to solve the differential equations that describe these transient phenomena. This is computer fire models' role.

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[14] 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[15] calculates post-flashover room temperatures. And, very detailed models like the HARVARD 5 code[16] 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, a smaller number of multi-room models have been developed. These include the BRI (or Tanaka) transport model,[17] which is similar to the FAST model included as part of HAZARD I, and the HARVARD 6 code; a multi-room version of HARVARD 5.[18] 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, smoky 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.

Over the past few years, models began to be used within a hazard analysis framework to address questions of interest. In 1984, Nelson published a "hazard analysis" of a U.S. Park Service facility which used a combination of models (including ASET) and hand calculations.[19] 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.[20] 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 2 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 redesign of a product.

A more recent example of a hazard analysis application is the work of Emmons on the MGM Grand Hotel fire of 1980.[21] Using the HARVARD 5 model, 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. Additionally, a report of the National Academy of Sciences[22] 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.

Overall Approach

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

The buildings and scenarios of interest to the user of a fire hazard assessment will depend on the purpose of the evaluation. For example, product manufacturers generally will not be concerned with a particular building but rather with any scenarios significantly involving their products in all the building types in which they may be found. The interest of fire investigators will be with specific fires in specific buildings, since they are reconstructing incidents that 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 paper allows the user to substitute a different product for ones used in one of the examples 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, questions can be answered simply by estimating or inferring the expected performance of a 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 user of HAZARD I may be concerned about situations beyond the current capabilities of the system, in which case traditional approaches should be implemented. These include some combination of experience, judgement, and small- or full-scale fire tests. The third alternative is that the user chooses to run through a complete set of new calculations for a problem situation. The flow chart shown in Figure 2 illustrates these three alternatives.

The Logic of the Procedure

Initially, the context of use and scenario(s) of concern (steps 1 and 2 of the hazard analysis method) for the product in question are established, and compared against the matrix of example cases provided. If it is

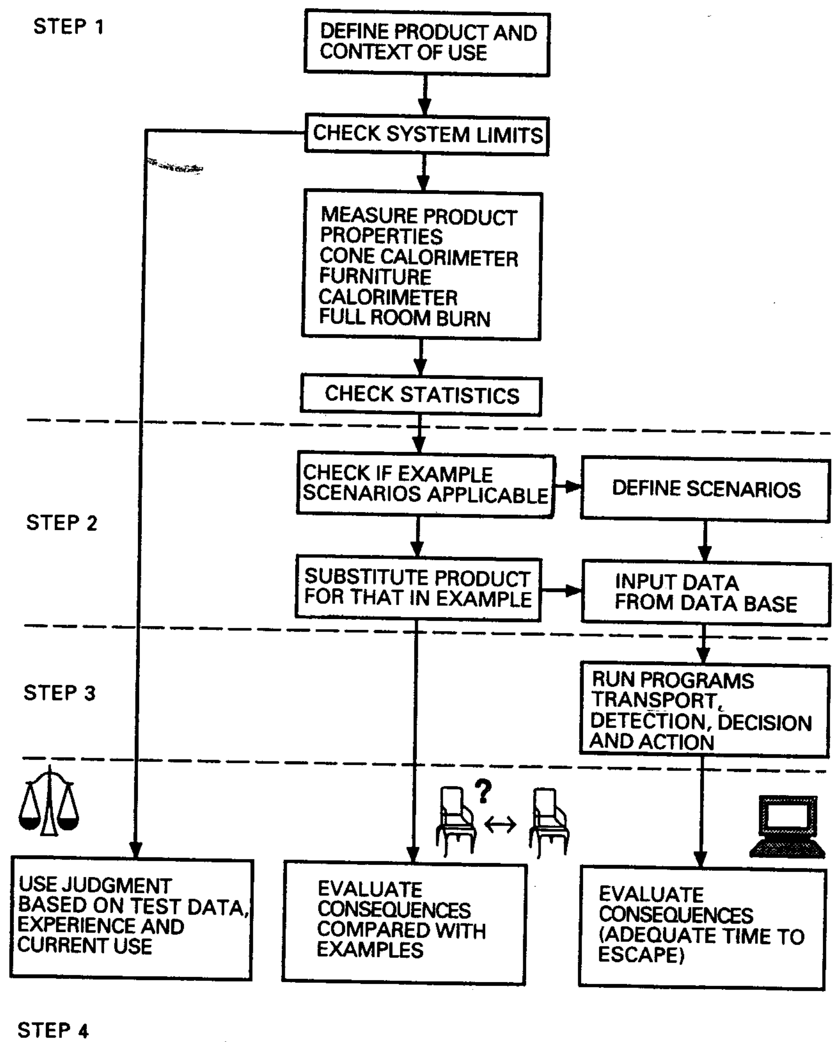

Figure 2. The overall method.

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 3 of the process) is needed.

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 relate their experiences, both good and bad, back to CFR to enable corrections and improvements to be made.

When proceeding with a hazard analysis, the user should try to understand the method and the reasons for each step. Representative examples should be referred to as a guide to the method 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 being questioned and re-examined.

Table 1 details the four steps in the hazard analysis method.

Step 1: Defining the Context

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

The user should clarify, up front, the basis on which the judgement of the product is to be made. It is preferable to state explicitly the required or desired level of safety the product is expected to meet. An appropriate criterion for a new product may be that its firesafety performance be at least as good as existing products in the same use, or that the product exceed a specified level of performance. For example, the product might be judged to be less flammable, result in fewer losses, reduce the likelihood of ignition. The appropriateness of the procedures to be used in step 3 must be evaluated in relation to the chosen criteria. For example, if a reduction in life loss is the criterion, the procedures must predict fatalities. It should also be determined whether calculation/test procedures that deal with key aspects of product performance are available.

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

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

Step 2: Defining the Scenario(s) of Concern

A significant amount of information relevant to scenario definition can be obtained from historical fire incident experience involving the product or related products (for example, see Gross[24] and Karter[25]). Data bases such as the National Fire Incident Reporting System (NFIRS)

Table 1. Hazard analysis procedure.

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

2. Define Fire Scenario(s) of Concern: (A scenario is a specified fire in a prescribed building with well-characterized contents and occupants.)
   - Examine relevant fire incident experience with same/similar products,
   - Identify the likely role/involvement of the product in fire,
   - Which fire scenarios do the decision-makers feel are...
     most common/likely?
     most challenging?

3. Calculate Hazards/Outcomes: For each of the scenarios identified above using the technical reference guide and software provided.
   - The major software subroutines are...
     "FAST_in" — scenario specification (building, contents, occupants, fire)
     "FAST" — fire and smoke transport calculations
     "EXITT" — prediction of occupant decisions and actions
     "TENAB" — calculation of outcomes; i.e., impacts on occupants

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

contain relevant data, normally segregated into specific categories. A more detailed discussion of the kinds of data available in NFIRS is provided in the Technical Reference Guide for HAZARD I.[1] Also of value are census data and demographic information compiled by industry trade associations. For example, the American Hotel and Motel Association maintains detailed information on occupancy rates and characteristics of guests in member properties, and on the size, construction, and furnishings found in hotel rooms in each of four classes from "economy" to "resorts."

For each scenario to be analyzed using the HAZARD I software, a significant amount of information is required. An outline of the items that need to be specified is given in Table 2. Detailed discussion of the inputs required is contained in the Software User's Guide for HAZARD I.[2] 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.

Step 3: Calculate the Hazard

The purpose is to provide the best state-of-the-art technical information/estimate of the product's contribution to the overall hazards of fire in general and in particular its smoke toxicity hazard for each scenario of concern. It is preferable for these outcomes to be expressed in quantifiable terms such as deaths, injuries, or extent of damage, so they may be related to the criteria established in step 1 and applied in step 4. One should try to go beyond individual measures such as time to flashover, escape time, peak temperatures, flammability, or other indices that may mislead the decision maker about the overall performance of the product.

Once the detailed problem has been defined, the user interface program (FAST_in)[1,26] is run. This program creates the input file necessary to run the transport model, FAST. It allows the user to work in either English or metric units, converting to the metric (SI) units required by FAST. The results of FAST are output only in metric units, however. FAST_in does error checking on the consistency of the data input and advises the user if a problem is discovered.

The transport model (FAST Version 18) is run as a "batch" program rather than interactively. Contrary to its name, the model takes a significant time to execute. The more complex the case, the longer it takes; so the user should be patient. The model produces a printed output summary at time intervals selected by the user in FAST_in. These

Table 2. Scenario description for using the HAZARD I software.

Building Description
1. Number of rooms
2. Dimensions of rooms
3. Dimensions of openings between rooms (doors, windows, penetrations)
4. Ceiling, wall, and floor construction (up to three layers)
5. Presence and location of detectors or sprinklers

Fire Description
1. Description of all combustible items in the room of origin
    - materials and weights of each
    - dimensions and construction of each item
    - location of each item within the room (adjust for desired spread)*
2. Ignition source
    - description (material and quantity)
    - location with respect to the first item ignited
3. Extent of fire spread
    - single item
    - part of room
    - full room

Occupant Description
1. Number of occupants
2. Age and sex
3. Physical/mental limitations
4. Location and condition at time of fire

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

tabulated data can be directed to the screen, to a printer, or to a file for later printing. This version of FAST also supports run-time graphics, which are easily activated from FAST_in. The user should remember not to send the printer output to the screen if the run-time graphic is active, since one will write over the other. The default plots are upper layer temperature (°C), interface position (the boundary between the layers), upper layer oxygen concentration (%) and heat release rate (kW). The plots displayed by the run-time graphics can be customized by editing the graphics specification in the input file with a text editor such as the one built into the system.

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

FAST is based on solving a set of differential equations that predict the change in the energy (and thus temperature) and mass (and thus the smoke and gas concentrations) over small increments of time. These equations are the conservation equations for energy, mass, and momentum, and the ideal gas law from chemistry. These conservation equations are always correct, everywhere. Thus any errors that might be made by the model cannot come from these equations, but rather come from simplifying assumptions or from processes left out because we don't know how to include them. It is beyond the scope of this paper to describe the theoretical underpinnings of the calculations; these are described in detail elsewhere.[27]

After obtaining the results of the FAST calculation, the evacuation model EXITT is run. Required input includes the room dimensions and occupant descriptions taken from the building drawings and from the data decided upon in step 1. In addition, the data predicted by FAST for the interface position and smoke density in each room are read directly from the dump file produced by FAST. The evacuation model will predict the activation time of any smoke detectors based solely on the smoke data (smoke density and layer thickness) read from the FAST dump file, or a time can be manually entered. While the DETACT model is provided to estimate heat detector or sprinkler head activation times, the impacts of the detector activation are left to the judgement of the user. 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.

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

This is accomplished 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 outlined below. (For a thorough discussion of C_t and FED, and response to other fire products, see

the Technical Reference Guide[1]). The fire-induced environment in each room is usually stratified into two, distinct layers. The upper layer is generally considerably hotter with a much higher concentration of fire gases. Thus, the layer to which the occupant is exposed has a significant impact on the results. In HAZARD I, any time 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, the occupant is 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.

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

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

Toxicity is appraised in two ways: (1) using a concentration-time product parameter *(C_t)*, and (2) by the FED method which considers the exposure to hydrogen cyanide and carbon monoxide, accounting for the impact of the simultaneous exposure to carbon dioxide and reduced oxygen. These gas concentration data are produced by the FAST model when yields of these species are specified by the user. For C_t, 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)."** Since this is an

*The data on the toxic potency of smokes from nearly all materials tested to date indicates that the mass of material necessary to cause a lethal effect falls with a nominal range of 1 to 1.5 orders of magnitude. Extreme toxic potency is defined by LC_{50} data falling substantially below this nominal range.

**The inhalation of smoke from virtually all materials can cause irritation and damage of the respiratory system along with asphyxiation. Thus an unusual toxicological response is evidenced by (1) respiratory irritation or pathology, or both, which vary significantly from that observed following exposure to ordinary smoke and (2) toxic effects influencing tissues, organs, or systems (other than the respiratory system) in a manner not attributable to asphyxiation. Unusual toxicity may also be evidenced by deaths unexplained by the concentrations of the common combustion gases, e.g., CO, CO_2, HCN, and reduced O_2.

approximation of toxicity, it is desirable to determine the sensitivity of the result to the reference value of C_t used. This does not require any additional runs of models, but only the determination of the cumulative value of C_t for each occupant at the time that they exit the building. The reference value given above divided by the maximum accumulated value represents a "safety factor" for the estimate.

The evaluation of the impact of carbon monoxide, hydrogen cyanide, and carbon dioxide along with reduced oxygen, represents the first version of a toxicity evaluation technique referred to as the "N-Gas Model." When the computed value for FED reaches 1, lethality is assumed to occur; at a value of 0.5, incapacitation is assumed. Another set of tenability criteria, based on the work of Purser with non-human primates, are used by TENAB to evaluate incapacitation only. For both the C_t 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 concentrations 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 C_t value up to that time. When moving from room to room, the accumulated exposure-dose for each room is computed. The total exposure is the sum of the exposure-doses accumulated in each room until the occupant exits the building. The same technique is used for the FED data.

Step 4: Evaluate the Consequences

In this final step, the results obtained for the product are analyzed using the criteria established in step 1. This may involve comparison with accepted practice or baseline data. Sensitivity to key parameters are checked. All scenarios are considered and the final decision(s) are made. It must also be decided if all pertinent scenarios have been considered, whether the results make sense, and if any additional steps (e.g., testing) are required as a result of limitations of the method employed.

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

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

Finally, as was stated, the results of any analysis should be challenged by the user's common sense and experience. Results that violate these should be questioned and resolved. Comparisons should be made to data from similar experiments or actual fires wherever possible. In situations where public safety is at risk and no such data are available, it may be advisable to conduct verifying tests.

Examples of the Use of HAZARD I

An Example Hazard Analysis

To illustrate the use of HAZARD I, we will perform a hazard analysis by working through one of the examples documented in the examples cases for HAZARD I.[3] The incident with which we will be working is a kitchen grease fire in the ranch house shown in Figure 3. We wish to estimate the contribution of the kitchen cabinets to the occupant hazard for their most common involvement in residential fires. The product is sold for residential use for both new construction and for remodeling. Such cabinetry typically includes both base and overhead assemblies, and may include free-standing units. While consisting of a series of individual units, they are normally installed abutting each other such that long, continuous surfaces (for flame spread) are formed. We wish to compare the current product with one made with a new core material that burns at half the rate, but uses a nitrogen-containing filler resulting in a 1% yield of HCN.

A review of fire incident data (NFIRS) reveals that the primary ignition exposure for kitchen cabinets comes from grease fires on the stove surface, and secondarily from fires in countertop appliances (which will not be addressed directly in this example). The ranch house is selected as the target building since it represents approximately 70% of U.S. single-family housing stock. A typical ranch house arrangement is provided in the HAZARD I example cases discussed in the Technical Reference Guide for HAZARD I.[1] If the performance of the cabinets in other houses (two-story, apartment, or mobile home) or other ignition scenarios were of interest, these could be analyzed in a similar manner.

Since occupant characteristics in homes are extremely variable, it is decided that a mixed family composition should be used to represent the

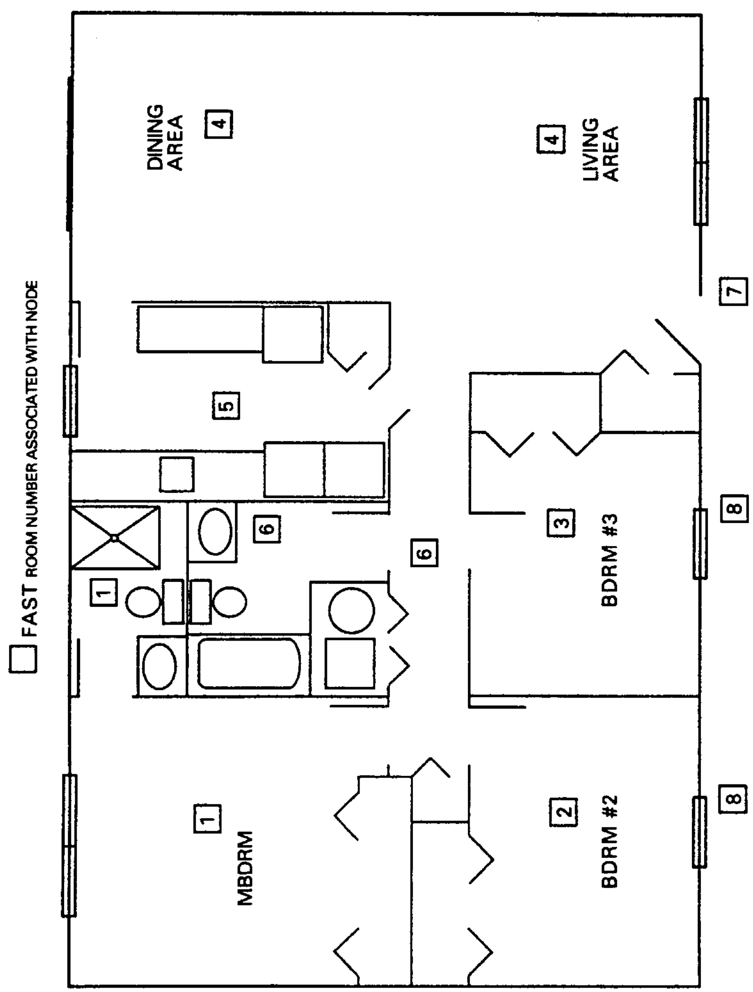

Figure 3. Typical ranch house for kitchen grease fire simulation.

range of characteristics that might be expected.

The family members selected include:

The father, aged 30, located in the master bathroom.
The mother, aged 30, in the hall.
A daughter, aged 7, in the living room watching TV.
A son, aged 5, watching TV with his sister.
A grandmother, aged 71, in bedroom 3.

All occupants are assumed to be awake and fully capable at the time of the fire. Details of assumed occupant reactions to fires are detailed elsewhere.[1,3] The doors to the grandmother's bedroom, the master bedroom, and the master bath are closed (all others are open). A working smoke detector is installed in the hallway of the house. For this example, only a single scenario will be examined. Following the step-by-step procedure for conducting a hazard analysis presented in the Technical Reference Guide for HAZARD I, the HAZARD I software was used to predict the consequences of the scenario described above with the current cabinet construction.

Fire performance data for the current cabinets and the ignition source (a pan of cooking oil on the stove) are taken from the fire properties data base included with HAZARD I. Using the MLTFUEL utility module, the data on multiple items burning simultaneously is converted into a single burning rate curve as required by the transport model FAST. A sample of the output of FAST for this example case is shown in Figure 4.

The EXITT module provides estimates of building evacuation times. For this example, we use one supplied with the HAZARD I software. The results of the calculation show that all occupants escape the building within 180 s.

The TENAB module follows each person's escape route through the building as determined by EXITT, and for each occupant, determines several tenability measures based upon the person's exposure to hazardous conditions. Since the smoke detector provides an early warning of the fire, none of the occupants become incapacitated during escape.

We now repeat the calculation with the new product construction. Therefore, we now go back to the MLTFUEL utility module to reduce the pyrolysis rate of the cabinets by half and add a 1% HCN yield. Repeating each step followed in the original scenario will produce the same final result, that the occupants successfully escape. A better (and more general) way to evaluate the differences in the products is to compare the time to hazards for each room. This is discussed in the Technical Reference Guide for HAZARD I.

Comparing the results from the two cases reveals that the cabinets constructed of the new core material delay the onset of hazardous

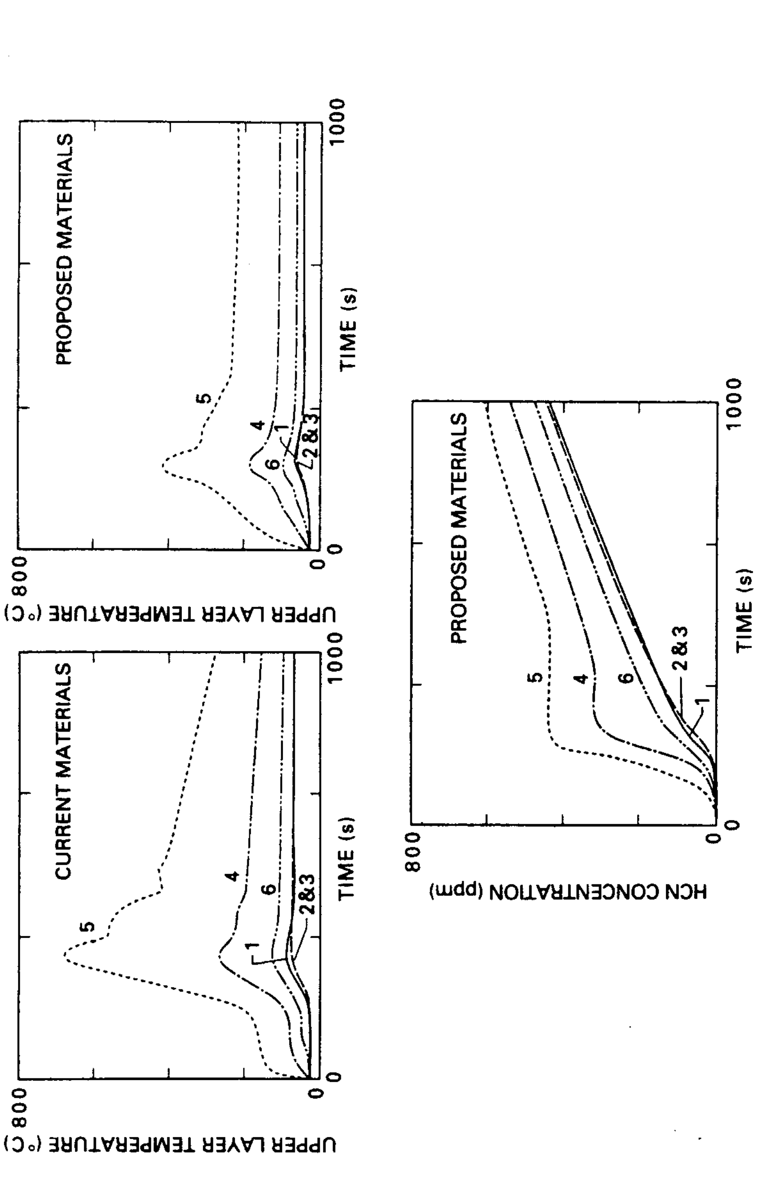

Figure 4. Upper layer temperature (°C) and HCN concentration (ppm) in all six rooms of the example case for fires involving the current and proposed cabinet materials. Note that HCN concentration is assumed zero for the current materials.

conditions (as indicated by time to incipient incapacitation) by about 30 seconds (out of about 3 minutes) for most rooms and criteria, both thermal and toxic. Thus for this example, the trade-off of increased toxic potency (additional HCN release) for reduced burning rate (by half) provides more escape time for the occupants. By examining the cost differential of the two cabinet constructions, a cost-benefit ratio is obtained. Finally, examination of the sensitivity of these results to variations in some parameters or assumptions can be used as a test of validity.

The Potential (and Limitations) of HAZARD I

HAZARD I can be used to examine a variety of options. Table 3, culled from more than 450 pages of results, shows a matrix of fire types and variables. Three different cases of conditions affecting occupant response to eight example fire scenarios were formulated as follows: working smoke detectors were present, no smoke detectors were present, and an immobile occupant was positioned in each room.

The effect of smoke detectors can be seen by comparing the predicted response of occupants in the cases with smoke detectors (column 1) and without smoke detectors (column 2). It can be seen that the major effect of smoke detectors is predicted to be earlier evacuation based on an earlier warning of the occupants to the presence of the fire. An effect on fatalities can also be observed. Without smoke detectors, the occupants become aware of the fire at a much later time and are trapped on the second floor.

As an indicator of the effects of assumptions in the scenario descriptions (for example, fire growth or occupant placement), consider the last case of an occupant trapped in each of the six rooms in the houses (column 3). Deaths occur in all cases, with some deaths occurring in as little as 2 minutes from the start of the fire. In almost all examples, the first person to die is the one located in the room of fire origin. Obviously the assumed rate of fire growth is very important. In some scenarios, occupants remain safe in their room for the duration of the fire. This may be the result of the fire itself never growing large (e.g., the trash fire in the townhouse), or because occupants are protected by closed doors (e.g., scenarios in the two-story house).

While HAZARD I can be used for many such "what if" comparisons, the user must take into account the limitations of the methodology. For example, since fire growth is based upon a user defined input, the effects of structural involvement and ultimate failure are difficult to predict. Thus, occupants who remain behind closed doors may "survive" the fire while those who investigate or attempt to escape may become disabled and die. Thus, observed effects may be real or may be artifacts of the

Table 3. HAZARD I example cases. Column (1): with smoke detectors; Column (2): without smoke detectors; Column (3): immobile occupant in each room.

Fire Scenarios[1]	Flashover (min)	(1) Escape Time[2] (min)	(1) Number of Fatalities[3]	(2) Escape Time[2] (min)	(2) Number of Fatalities	(3) Time to Fatalities[4] (min)	(3) Number of Fatalities[3]
Ranch House							
1. Smoldering sofa in LR	no	20	0/1	21	0/1	44–49	6/6
2. Grease fire in kitchen	3	1	0/5	1–2	0/5	2–8	6/6
3. Bed fire in MBR	no	1	0/5	2–>15[5]	0/5	2–>15	5/6
Townhouse							
4. Trash in closet	no	1	0/3	6	0/3	2–>15	1/6
5. Christmas tree & chair in LR	no	6	2/4	6	4/4	7–>40	5/6
Two-story "colonial"							
6. Couch, paneling in LR, BR doors closed	4	3	0/4	15	0/4	4–>25	5/6
7. Couch with LR and BR doors closed	4	3	0/4	25	0/4	4–>25	5/6
8. Trash, drapes, desk in office/BR	14	6	0/4	7	0/4	7–>33	4/6

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

assumptions made in the analysis. Further, in HAZARD I, occupant response to a given fire is deterministic. In real fire situations, the responses of different people will vary for similar fire exposures.

While the bulk of the calculational procedure embodied in HAZARD I, the FAST model, has been subjected to comparative validation against several series of multi-room size experiments,[27] 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.

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 focused 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.

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

Additional building features that need to be addressed to extend the method to larger buildings include vents in floors and ceilings and HVAC systems. In a fire, a building's HVAC system may distribute fire products to some parts of the building faster than the fire would alone. A model of the HVAC system has been developed[32] and will be linked to or incorporated in the smoke transport model.

The accuracy of the current procedure is limited by the fire being uninfluenced by radiation from its surroundings, and by our inability to quantify accurately the effects of fire on people and their actions. Research is under way to better understand radiation-enhanced burning under postflashover 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.

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Foam Concentration Measurement Techniques

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Abstract

Three types of foam concentration measurement techniques are examined: total fluorine content, optical absorption, and specific conductivity. Specific conductivity was found to be the most useful for field measurements and was therefore compared with the traditional refractive index approach. It was found that electrical conductance provides a more accurate method of estimating the concentration of AFFF solution than does the refractive index technique described in NFPA 11.

Introduction

This paper examines an alternative method to that described in NFPA 11, "Low Expansion Foam and Combined Agent Systems," for determining the concentration of Aqueous Film Forming Foam (AFFF).

AFFF is a fluorocarbon foam which suppresses liquid fuel fires by forming a film over the fuel surface that inhibits the release of flammable vapors. AFFF in Australia has primarily been used in fixed systems, portable units, and hand-held extinguishers for the protection of fuel farms and aircraft hangars, etc. In these systems the foam concentrate is mixed (water and foam concentrate are drawn together from separate supplies and mixed in proportions) or pre-mixed (water and concentrate already mixed to the required proportions) with fresh or sea water in either 1, 3 or 6% V/V concentration.

In Australia the quality of the foam produced by these fire suppression systems is determined in accordance with NFPA 11. This code requires the measurement of:

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Key Words: AFFF; NFPA 11; foam concentration, conductivity, refractive index.