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FIRE RISK ASSESSMENT METHOD: DESCRIPTION OF METHODOLOGY

R. W. Bukowski
S. W. Stiefel
J. R. Hall, Jr.,*
F. B. Clarke**

U.S. DEPARTMENT OF COMMERCE
National Institute of Standards and Technology
National Engineering Laboratory
Center for Fire Research
Gaithersburg, MD 20899

*National Fire Protection Assn.
Quincy, MA 02269

**Benjamin/Clarke Assoc.
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Table of Contents

Figures

Tables

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FIRE RISK ASSESSMENT METHOD: DESCRIPTION OF METHODOLOGY

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Executive Summary

The methodology described in this paper is the result of a project funded by a broadly based consortium of manufacturers and trade associations through the National Fire Protection Research Foundation (NFPRF). It builds on recent advances in deterministic fire modeling to provide a physics-based method of estimating the severity of specified fires while retaining the probabilistic framework of traditional risk analysis for estimation of the relative probabilities of various types of fires. This fire risk assessment method is designed to permit the quantitative prediction of the change in expected fire fatalities[1] per year attributable to changes in fire performance properties of combustible products (e.g., building contents and furnishings) in the context of their end use in specific occupancies.

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

The use of scenarios is the technique by which these two modeling components are joined together. The universe of possible fires and situations is divided into scenarios, with each scenario being represented by a single, well-defined case, selected as the most average or typical case of the set of cases represented by the class.

The execution of this technique produces results somewhere between the extreme of (a) running the hazard assessment method once on the allegedly most typical case - a gross oversimplification that could not be reasonably expected to estimate overall risk and (b) the use of classes so precisely and narrowly defined that every class is completely homogeneous with respect to the properties of interest and the issue of typical or average becomes moot - an impractical approach

[1]The limit to fatalities is not inherent in the Risk Assessment Methodology described herein, but rather is a limitation of the current state-of-the-art embodied in the hazard assessment method upon which it is based. As the hazard assessment method is improved to consider injuries and property damage properly, the risks associated with these end points will be calculable.

which would require nearly infinite time and cost to compute and would have to use probabilities that were nearly all pure guesswork.

The selection of a best compromise between these two extremes requires many difficult and uncomfortable choices. Class definitions will inevitably be wide enough that they will encompass some fires or situations with significant differences, thereby placing importance on the process of designating an average case to represent them. At the same time, class definitions will inevitably be narrow enough that the best sources of information on relative likelihoods will not be sufficient and one will need to use less satisfactory sources, including expert judgments.

Much of the parameter estimation for the method requires use of multiple data sources, because of limitations of even the best data sources. For example, national fire incident data is best on representativeness but tends to be quite limited on detail, while laboratory experiments are excellent on detail but tend to have uncertain representativeness.

Throughout this report on the method and in the cases used to test and develop it, one will note many judgments on best current data sources on particular points. In most instances, there is potential for improvement in the quality of these data sources. In a few instances, there may be no acceptable current data source, i.e., even an expert panel cannot give acceptable answers. This means that there are data gathering and data system upgrade projects implied by the method. At the same time, it is recognized that one cannot wait for complete data on all issues collected by best method only.

The method is somewhat modular in that it can readily accept better quality data than that which is now available (and conversely can, if necessary, operate on low quality data). Changes in the *type* of information directly available, however, would require restructuring of the method to fit the new data structures.

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1. INTRODUCTION

1.1 Background

The methodology described in this paper is the result of a project funded by a broadly based consortium of manufacturers and trade associations through the National Fire Protection Research Foundation (NFPRF). It builds on recent advances in deterministic fire modeling to provide a physics-based method of estimating the severity of specified fires while retaining the probabilistic framework of traditional risk analysis for estimation of the relative probabilities of various types of fires. The method, which predicts the risk-impact of changes in the fire performance of products, was developed by a project team consisting of Dr. F.B. Clarke of Benjamin/Clarke Associates as team leader, Dr. J.R. Hall, Jr. of the National Fire Protection Association, who was responsible for work with the fire incident data, and Messrs. S.W. Stiefel and R.W. Bukowski of the Center for Fire Research, National Institute of Standards and Technology (formerly National Bureau of Standards) who with Dr. A. Sekizawa of the Fire Research Institute of Japan (while a guest worker at NIST) developed the deterministic modeling approaches and the system software, and executed the case studies.

To describe fire risk and the fire risk assessment process, it is necessary to define some terms [1].

• *Fire hazard* is the fire's potential for inflicting harm to some person(s) or thing(s); the magnitude of the fire hazard is the amount of harm that might result, including the seriousness and the number of people exposed.

• *Fire risk* combines the fire hazard with the probability that potential harm or undesirable consequences will be realized. The result includes the predicted outcome of all fires under consideration.

• *Fire risk assessment* is the process of characterizing the potential impact on risk of changes in any factor which affects the expected outcome. It includes estimates of the risk and uncertainties in measurements, analytical techniques and interpretive models which affect those estimates.

• *Occupancy* is a use category of a building established by a code organization. In this project, occupancy refers to the property classifications used in the 1976 edition of the National Fire Protection Association NFPA 901 Standard, *Uniform Coding for Fire Protection*. Examples include public assembly, educational, institutional, residential, store/office, and manufacturing. The classifications may be further narrowed to buildings with specific activities because NFPA 901 includes subclassifications within each major occupancy.

- *Fire Scenario* is the detailed description of a specific fire incident. This description includes the building (room sizes, connections, and materials of construction), fire (items, their fire properties, and sequence of burning), and occupants (number, initial location, and characteristics).

- *Occupant Set* is a group of occupants of specific characteristics present in a fire scenario.

Briefly, fire risk is measured in terms of both the probability of an event (fire) and the consequence of that event (e.g., deaths resulting from a fire). The challenge is to predict how a change in the fire properties of a product (ignitability, heat release rate, toxic potency, etc.) will change the life safety risk in a given occupancy. This new method for calculating risk combines the likelihood of a fire, based upon fire incident databases, with the expected consequences or severity of a fire, predicted by a computer based simulation (HAZARD I) [2]. The method provides an organized structure for a large series of fire scenarios constructed to represent all the possible ways that a fire might involve the product. The fire risk assessment methodology is currently constrained to predicting death and <u>not</u> injury to exposed occupants and does not consider property damage as a consequence of the current state-of-the-art of the hazard method employed.

A contrast can be drawn between this approach and most fire risk assessment methods in use today. Those employ probabilistic trees as the analysis structure. Methods using probabilistic trees quantify outcomes (e.g., some either/or fire safety event) using the probability of success (success trees) or failure (fault trees). The use of physics, chemistry, and biological effects of the fire and the behavior of the people are used outside these methods, either to estimate probabilities of transition between fire conditions or to estimate magnitudes of loss for a specified fire outcome.

This new method uses simulation models based on known laws of physics of fire, in combination with information on the behavior of people confronted with fire and the effects of heat and smoke on people, to estimate the severity of a specified fire. HAZARD I, a computer based hazard calculation method developed at the Center for Fire Research, was used for this purpose. Traditional probabilistic tree structures are used to estimate only the probability of each specified fire.

The advantages of this approach are several. Standardized tests for the fire performance of products or buildings can be used more directly because the descriptions of specified fires are made in terms of the properties these tests measure. The fine structure of the physical models provides greater confidence that the estimates of fire severity are scientifically sound and provides a greater understanding of the factors that create the hazard in each case. New products, for which no real fire experience yet exists, can be analyzed on an equal footing with existing products, because each enters the model as a string of product fire performance characteristics, which are measurable in the laboratory.

1.1.1 Uses and Limitations

The methodology discussed herein is a first attempt to apply deterministic models to the assessment of product risk. To do so requires that we predict, at least in aggregate form, the outcome of every fire incident which can possibly involve the target product in the target occupancy. To make this herculean task even somewhat tractable, numerous compromises must be made. Further, we find that many required details of actual incidents are not collected and many important phenonema are not sufficiently understood, such that approximations and estimates must be employed to fill in the gaps.

What has emerged is an analytical method which has extremely powerful potential which may or may not be realizable at the present time, depending on the specific case (product/occupancy pair) of interest. As is so clearly demonstrated in the four case studies conducted, we were able to do a fairly complete and competent job with Upholstered Furniture in Residences (Case 1) and were unable to perform a risk assessment at all (although the method was able to provide some valuable insight into product performance and hazard) for Interior Finish in Restaurants (Case 4). The state-of-the-art of both the fire science and data requires the method to rely extensively on the expert judgement of the analyst, to accept substantial bounds of uncertainty on the results of many cases, and to rely on the skills of the user to adapt the method for best results in any given case.

Regardless of where a case of interest might fall in the continuum of capability, the method can be of substantial benefit. Its detailed structure provides a procedure by which the important fire involvements (including for the first time, secondary ignitions) of a specified product can be determined with an estimable degree of confidence - a "scenario generator". In most (but not all) cases, the method's results can be calibrated against actual incident data, giving an estimate of accuracy. But this is not a standardized, self-contained method that will be executed the same by all users and produce comparative statistics of high precision. However it should improve the decision making process of any user group, not the least by identifying unstated assumptions in the less formal and explicit procedures now used to combine and synthesize information relevant to product risk.

In the remainder of this and the case study reports, details of the compromises, assumptions and limitations, uncertainty estimates, and confidence in the results will be presented. It is crucial that these be kept in mind whenever these risk analyses are examined for conclusions. And, as the technology continues to develop, the method will eventually realize its full potential.

1.2 Approach

The approach for this risk assessment method is shown below. It begins with the construction of a model , steps 1-5, that reflects real world fire experience as a basis for both the probability estimates and the inputs for the calculation of scenario probabilities. Since we can alter this model at will, it becomes a way to predict risk changes in the real world in response to a change in any independent variable (e.g., a measure of the fire performance of the product) in the model. The model can effect changes instantly, and can be used to examine the impact of changes in the fire performance of products without incurring any **true** losses. It is also easier to observe the model world, and thus to interpolate to data not directly available from the real world.

NFPRF Risk Assessment Methodology
Summary of the Approach

1. Select product and occupancy pair.
2. Specify "representative" building characteristics.
3. Develop scenario structure.
4. Adapt fire model to meet needs of product and occupancy pair.
5. Specify occupant sets.
6. Perform risk calculation for "base" case and compare results with available fatality statistics, by scenario.
7. Perform risk calculation for the "new" product and compare results with "base" case.
8. Interpret the outcome.

Next, the consequences of each scenario are calculated for the "Base" and "New Product" cases. steps 6 and 7. Typically, a number of iterations between the initial steps and the "base" case calculation, step 6, may be needed to adjust model inputs to obtain suitable agreement between the "base" case calculated probabilities and the available fire death statistics. The emerging technology of deterministic fire modeling has provided the fundamental predictive capability which has enabled this advance. The risk assessment method encompasses detailed procedures for formulating such a model, calibrating it so that it behaves like the real world, and then using it to obtain the desired information.

Finally, the results of both calculations are compared to obtain a "relative risk" for the "new" product relative to the "base" case, steps 7 and 8. The risk method assumes that the full range of fire scenarios that might involve the product in the real world can be represented by a limited number of scenarios in the model world. In this approach, a full range of scenarios that might involve the product is created and probabilities and other input parameters are specified. Calibration and validation include checking that recent fire losses are accurately predicted (e.g., recent fire death rates) when recent patterns of usage of the product are provided as input (e.g., input parameters representative of the fire-related properties of upholstered furniture now in use). This is called the base case or baseline case. The change in the risk measure produced by changing the assumed properties of the product can then be used as the measure of the fire risk impact of changing the product to have those properties. This second calculation is called the new-product case. In this way, a multifaceted product change (e.g., universal use of a new style of upholstered furniture that is harder to ignite and has a lower peak heat release rate but produces faster fire growth and more toxic smoke when it burns) can have its net effect on fire risk determined.

The subject for analysis is a particular class of mutually substitutable products (e.g., upholstered furniture or carpeting) in a particular type of occupancy (e.g., detached dwelling or office building). The method calls for a scenario structure that will represent both the most typical and the most hazardous fires that may involve that product in that occupancy. Each scenario is defined primarily by characteristics that can be derived from what is known about the product, the occupancy, and the pattern of use of the product in the occupancy.

For example, specification of an occupancy typically will imply a certain range of building sizes. Typical internal layouts and construction methods also will be implied. Databases often exist to indicate the relative likelihood of building characteristics among the members of this occupancy class (e.g., how many dwellings are two stories). Fire data analysis may be able to determine whether the relative likelihood of these building characteristics differs among buildings that experience fires.

By following the defined process, one constructs a range of scenarios, each defined with enough physical detail to permit the estimation of fire severity for that scenario, using one of the new deterministic hazard calculation methods, such as HAZARD I. At the same time, traditional methods are used to estimate probabilities for each scenario. These methods rely particularly on representative national databases, including the national estimates method for estimating patterns in U.S. fire experience from the U.S. Fire Administration's (USFA's) National Fire Incident Reporting System (NFIRS) [3] and the National Fire Protection Association's annual stratified random-sample survey of U.S. fire departments [4].

We can only find some of the information needed to develop scenario descriptions in the fire incident data. Thus, we must turn to data collected on the US population as a whole. Table 1 lists sources of such information which were used in this study. The sources are listed in order of priority with respect to their inherent ability to provide representative information. In general, we try to find the best/most appropriate data available. The method is not highly prescriptive in that it allows for different sources of similar data or results so that the most appropriate to the particular characteristics of the case can be employed. We generally want to choose from standardized methods if available, if for no other reason than they usually have uncertainty or accuracy estimates available.

It may be useful to think of this modeling process as a particular form of abstracting from the real world to a model world that can be manipulated by analysis. In the real world, every fire can appear to be unique. However, from the point of view of estimating fire losses, certain factors are more important than others, and they can be used as a basis for modeling the real world. Similarly, in the real world, the possible variation (e.g., number of losses) on just one characteristic may be enormous. Again, from the point of view of estimating fire losses, it often is possible to select only a few of the variety of possibilities to be representative of the others and to show that such a simplified model world produces estimates of fire loss that are not significantly different from those experienced in the real world. Demonstrating that the model world accurately reproduces results from the real world is the step of model validation.

Table 1 - Overview of Information Sources
(in order of priority based on inherent quality)

1. Representative, national data on patterns in real fires (i.e., NFIRS national estimates).

2. Well-designed laboratory studies

    a. Giving fire properties of items.
    b. Giving likely behavior of occupants faced with fire.
    c. Giving lethal impact of various fire effects.
    d. Giving physical relationships during fire development and smoke spread.

3. Well-designed special studies of patterns in real fires (e.g., field studies by the Consumer Product Safety Commission).

4. Representative, national data on patterns in the general population (e.g., U.S. Census Bureau data).

5. Well-designed special studies of patterns in the general population (e.g., industry surveys).

6. Opportunity data bases on patterns in real fires (e.g., subjective impressions after review of a handful of cases assembled through a process that is not statistically designed).

7. Opportunity data bases on patterns in the general population.

8. Estimates by experts.

Note: NFIRS national estimates are estimates using the U.S. Fire Administration's National Fire Incident Reporting System (NFIRS), calibrated by the NFPA survey, as combined using statistical methods developed by analysts at the National Fire Protection Association, the U.S. Fire Administration, and the Consumer Product Safety Commission.

1.3 Case Studies

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

The methodology evolved as refinements based on the experiences of application were incorporated. This report documents the "final" structure which, in itself will continue to evolve with the capabilities of fire modeling and data collection. The four case studies are documented in detail in separate reports [5-8].

It is important to emphasize that the four case study reports represent approximations to a complete fire risk assessment of the selected product and occupancy. Rather they serve as:

- examples of the application of the risk method to a problem of interest,
- a focus for expanding the technology into areas of special interest to the project team and sponsors,
- a test of the capabilities of the method to deal adequately with the specific issues related to these products and occupancies,
- a demonstration of the different analytical techniques to be applied under different, case-specific circumstances, and
- simplifications of actual risk assessments since some scenarios and calculations were not done where they did not detract from what was learned, but which must be done for a complete analysis.

For Case 1, upholstered furniture in residences, the case represents the best possible combination of breadth of incident data and technology squarely within the scope of the original method. That is, HAZARD I as the core of the risk method is particularly well suited to the analysis of fires involving the contents of residences. Thus no extensions of the technology were needed for the first case.

Upholstered furniture represented a product which is susceptible to both smoldering and flaming ignitions, and is (voluntarily) regulated as to its ignitability by cigarettes. This regulation went into effect recently enough that an apportioning of current stock was necessary, and thus was demonstrated.

The fire incident data on residential fires is by far the most detailed, and non-fire data (e.g., Census data) provided a rich data base for the definition of scenarios. Thus case 1 demonstrated how an abundance of data should be grouped to maintain a reasonable number of computer runs.

Finally, the rich data base and large number of incidents (and fatalities) provide an observed fatality rate for every scenario. This gave data against which to calibrate and validate the method, and allowed the report to demonstrate the best way of presenting the copious amount of data obtained (i.e., stacked bar graphs organized around the usual demographic categories used to analyze the incident data).

In many ways Case 2 (carpet in offices) represented the antithesis of Case 1. The incident data showed no fatalities, and the product seldom burns by itself. The occupancy involves a large building occupied by a sufficiently large number of people that congestion problems during evacuation are expected.

The combination of no fatalities and only secondary product involvement meant that there was no incident data against which to calibrate the method. The product burning characteristics required the development of a means to quantify the degree of involvement as a function of measured properties, and the occupancy required a different approach to evacuation simulation.

The report demonstrated how some degree of confidence in the results could be obtained with a total lack of calibration data. In addition, it showed how the method can be used to analyze the potential impact of a reduction in regulation.

Case 3 (concealed combustibles in hotels) involved a product which represented both an ignition source and a fuel load. The major challenge was that it was located within the structure rather than in a traditional room. The particularly small volume of the stud cavity made ventilation a major determinant of how the product burned, and thus a technical challenge for the team to address. And the occupants represented a mixture of the family groups of Case 1 (in the guest rooms) and the larger groups of Case 2 (in the function rooms).

The incident data showed fatalities in some but not all of the identified scenarios, and the incident (statistics) data only showed fatalities when the fires started outside the concealed space and where concealed combustibles, although involved, made only a minor contribution to the deaths. Thus the report needed to show yet a third way of analyzing and presenting the results. Here we chose to group the scenario classes by whether there were fatalities predicted (by the method) and observed (in the incident data), no fatalities both predicted and observed, and fatalities predicted but not observed and vice versa. Also since the number of scenarios were much fewer than in Case 1 and to present the numbers with which the user of the method must work, the data were presented in tabular form in contrast to the histograms of Case 1.

Case 4 (interior finish in restaurants) brought additional challenges in dealing with the subject of flame spread on interior finish in an occupancy which was harder to define than any other due to a large variability. Here the incident data showed a small number of fatalities (more than offices and fewer than hotels) and a product which can range from only secondarily involved (like carpet) to fast burning like furniture.

Case 4 exhibited similarities to the product of Case 2 (carpet) and the occupancy of Case 3 (for the function room fires). The fact that the method predicted no fatalities required a presentation of results similar to Case 2 but much more sensitive to the assumed burning properties of the product and to the assumed characteristics of the occupants. Thus while Case 2 might indicate a significant safety factor extant with carpet meeting current regulation, Case 4 shows that good finish materials are safe while poorly performing materials can be hazardous under certain circumstances.

2. COMPONENTS OF A FIRE SCENARIO

The method defines a fire scenario as a detailed description of a specific fire incident related to a building, a fire involving specific items in that building, and the persons occupying the building at the time of the fire. These details are drawn from a review of incident data from the national databases, focussing on:

1. buildings where fires originate,

2. rooms described as the "area of origin",

3. combustible contents of the room (area) of origin, described as the set of items first ignited within that room,

4. heat sources igniting the first item (flaming or smoldering),

5. final size of the fire expressed as extent of flame damage,

6. factors contributing to fire spread, and

7. location of any fatalities relative to the fire.

These descriptors are tied to specific data elements in the NFPA 901 Standard, so that the probability of occurrence for each scenario can be estimated from the national databases. The descriptors are also associated in the method with a set of physical parameters used in the models to assess the development of hazard within the building and the eventual outcome of the fire event.

2.1 Buildings

The method considers the classes of buildings used to report fire experience (e.g., residential, office, mercantile). The presence and operational status of detectors also can be measured in probability form directly from fire data bases for those property classes. Also required are more specific building characteristics -numbers, types, and layouts of rooms and floors; and the sizes of the openings connecting them. Sources of information related to these factors are listed in Table 2.

Table 2 - Data Sources for Parameters Used to Model Buildings

Parameter	Data Source
1. Probability of fire in class of buildings.	1. (a) NFIRS national estimates of annual average number of fires. (b) U.S. Census Bureau or other sources for data on number of buildings (or other suitable denominator, such as square foot area).
2. Number and types of rooms and floors.	2. U.S. Census Bureau or other sources for data on the general population of buildings are preferred for probabilities.
3. Dimensions of rooms.	3. The room heights will generally be given by common industry practice. Lengths and widths will be estimated by type of room by an expert panel. There are no plans to use several sizes, with probabilities, for any particular type of room.
4. Layouts of rooms.	4. Expert judgment is likely to be needed. A single, average layout may be used unless data are available to suggest what the probabilities of different layouts should be.
5. Sizes of openings connecting rooms.	5. Common industry practices often mean that the average values are also the actual values in most buildings. In this case, the use of one average scenario is defensible, and openings between rooms will be defined once as part of the specified floor plans of the benchmark buildings.

6. Whether openings connecting rooms (principally doors) are open or closed, and if closed, how much do they leak. (Also applies to status of openings out of buildings (e.g., windows).	6. There are no data available on this point, which affects the spread of fire effects to rooms other than the room of fire origin. Expert judgment will be needed to establish probabilities as functions of time of day, and it may prove essential to do sensitivity analyses on this point.
7. Probability that operational detectors are present.	7. NFIRS national estimates, given a fire large enough to activate operational detectors.

Note: It is assumed that at each step if finer distinctions are needed than are possible with the best general data sources, then special studies or expert judgment will need to be used to fill the gaps.

2.2 Rooms

Within these buildings, the rooms and other areas defined by the categories used to report fire experiences (e.g., living room, dining room, office, meeting room) are related to descriptions of the materials and assemblies which constitute the walls, ceilings, and floors of each room. Also associated with room descriptors is a list of items first ignited and their associated ignition sources. The former is a surrogate for an inventory of typical, combustible contents and the latter helps define the early stage of fire development in the first item. Table 3 gives an example of the NFIRS data available for upholstered furniture as the first item ignited in various rooms of a dwelling. Table 4 summarizes information sources from which we can obtain required data on rooms.

2.3 Fires

A room fire is specified in terms of:

- whether the product was the first item ignited;
- if not, whether the product was secondarily ignited during the fire, and
- if so, at what point.

Table 3 - Where Home Fires Start--Total and Upholstered Furniture

Exploratory Analysis of 1980 - 1984 Structure Fires Reported to Fire Departments in Dwellings or Mobile Homes

	Percentage of Fires	
Selected Areas of Origin (901 code)	Upholstered Furniture Ignited First	All Fires
Living room, den, lounge (14)	66.7	10.5
Bedroom (21-22)	11.8	11.6
Storage areas, crawl space (41-49, 71)	6.2	9.2
Dining room (23)	2.2	1.0
Exterior balcony, open porch (72)	1.7	1.1
Unspecified function area (39)	1.5	0.3
Kitchen (24)	1.4	20.6
Heating room (62)	1.0	3.6
Laundry room (26)	0.4	3.2
Concealed roof/ceiling space (74)	0.2	2.3
Library or office (16, 27)	0.1	0.1
Chimney (57)	0.0	20.9
Exterior wall surface (76)	0.0	3.0

- Additionally, whether other items in addition to the first item and the product were ignited, and
- if so, at what points and in what quantities, and
- whether the room reached flashover.

Table 4 - Data Sources for Parameters Used to Model Rooms

Parameters	Data Source
1. Probability that fire begins in rooms given origin in specified building.	1. NFIRS national estimates.
2. Probability of final extent of flame damage, given specified building and room of origin.	2. NFIRS national estimates.
3. Estimated peak upper layer temperature, given final extent of flame damage.	3. Expert judgment of project technical team.
4. Deaths per fire in fires beginning in rooms where product is rare, differentiating fires beginning with product and with other items.	4. NFIRS national estimates.
5. Grouping of areas of origin based on similarities of size, fuel load, occupant use, and product use.	5. Expert judgment of user of method.
6. Peak rate of heat release, given peak upper layer temperature.	6. Result from FAST model.
7. Flashover mass burning rate per unit area given room.	7. Equation (2), which assumes a ventilation-controlled fire.
8. Probability that the product is in the room.	8. Estimated by expert panel but only for rooms in which product is found with some frequency.
9. Fire load of combustible contents in the room.	9. Surveys and expert judgement.

This is done by grouping all possible scenarios into one of the six classes shown in Table 5. With these specifications and those for the first room and the full building, the hazard assessment method predicts the production of heat, smoke and toxic gases as time lines in every part of the building, using physical laws and the burning properties of the specified involved items. The hazard assessment method also will estimate the lethality of the heat and toxic gases to persons in the rooms.

Table 5 - Overview of Fire Scenario Groups

Scenario Group	Is Product First Item Ignited	Final Extent of Flame Damage	Is Product Secondarily Ignited?
1	Yes	Confined to object, area, or room of origin.	Not applicable.
2	No	Confined to object of origin.	No
3	No	Confined to area or room of origin.	Yes, because product is close enough to first item ignited, given product ignitability and peak rate of heat release of first item.
4	No	Confined to area or room of origin.	No, because product is not close enough to first item ignited, given product ignitability and peak rate of heat release of first item.
5	Yes	Extended beyond room of origin.	Not applicable.
6	No	Extended beyond room of origin.	Yes

Note: All scenarios are further distinguished by flaming versus smoldering ignition heat source and by time of day (day, evening, night). All scenarios involving a first item ignited other than the product are distinguished by three curves giving rate of rise in rate of heat release and (except in Scenario Group 6) peak rate of heat release for the first item ignited.

A fire may need to be specified in terms of spread beyond the first room, in which case it may be necessary to specify which rooms became fire-involved, whether the product became involved in those rooms, and what other items became involved. At this stage in its development, the risk method can only model fire development up to flashover in the first room. This is sufficient to model all fire consequences in nearly all fires in small buildings (like dwellings), but it is not sufficient for larger buildings and will need to be extended later.

The representative, national fire data bases can provide probabilities in terms of three dimensions:

- the form and type of material first ignited, which provides an initial set of classes for the first item,

- the form of heat of ignition and equipment involved in ignition, which may be used to infer whether the fire had a smoldering phase, and

- the final extent of flame damage (confined to object of origin, area of origin, room of origin) which may be used to estimate the size and severity of the fire at its peak.

The likelihood of secondary ignition of the product under consideration is estimated in part using the extent of flame damage. First, it is assumed that any fire confined to an object of origin that is not the product was a small fire that did not ignite the product and, in fact, would not ignite the product however it might be changed. Second, it is assumed that any fire spreading beyond the room of origin was a fire that reached flashover in the first room and, therefore, involved the product, if it was there to be involved. Third, it is assumed that any fire spreading beyond the object of origin but confined to the area or room of origin might have ignited the product, depending on the interaction of:

- the peak rate of heat release of the first item involved,

- the relative ignitability of the product, and

- the distance separating them.

This approach should work well if the area of origin is a room; its assumptions are less satisfactory and will need to be modified for some concealed spaces.

The extent of flame damage is related to the peak rate of heat release for the entire room fire as a means of obtaining a representative fire size. This constraint on energy released will indicate either that other items besides the first item and the product must have been involved or that the first item and product could have produced an even larger fire than occurred and must have been prevented from doing so.

2.4 Occupants

The representative, national fire data bases provide no information on the characteristics (e.g., age or sex) of building occupants unless they are injured or killed. Therefore, with one exception, one must use data bases produced by Census surveys or demographic data developed in marketing studies for the general population to infer the nature of the occupants of the building at the time of the fire. These assumptions are adjusted where possible by data from special studies of fires. The one exception is time of day, which is available for fire incidents and can be used to condition the probabilities of fire and which also serves to imply location probabilities for occupants, based on available data on activity by time of day.

As part of each scenario, we specify the number and initial locations of occupants, the waking capability status of each (i.e., asleep, awake, impaired by handicap, drugs, or alcohol), and some information on ages, sexes, and relationships as they relate to assumed speeds of movement and behavioral decision rules. To a limited extent, some information can be inferred from the location of fatalities relative to the fire, particularly for those "intimate with ignition", or "on another floor".

2.5 Sequence of Calculation in Method

Figure 1 illustrates the sequence of modeling activities used in the risk assessment process. As previously described, the universe of possible fires is divided into a set of well defined scenarios. Thereafter, the method follows the sequence:

- Select one or more versions of a product and an occupancy class in which that product is found.

- Select a fire scenario and compute the probability of its occurrence from the fire data. Then specify the type of building; the room of origin; whether the product is part of the room's fuel load; the class (NFPA 901 category of first item ignited) from which the first item ignited is drawn, based on burning properties; a distribution for the distance between first item and product, given the room; whether the fire had a smoldering phase, based on its form of heat of ignition; the time of day; and whether an operational detector was present.

- Select an occupant set and compute the probability of its occurrence from data on the general population, specifying the number of occupants; their relationships; their capabilities; inferred from their sleep statuses, ages, handicaps, and impairments; and their initial locations, inferred from their likely activities based on time of day. Probabilities for other characteristics and the values of those other characteristics are also estimated from data on the general population.

- Convert the fire scenario specifications to an assumed fire growth curve.

- The hazard assessment method is used to develop a time line for heat, smoke density, and toxic gases in all modeled rooms. (In HAZARD I for example, this is the FAST portion.)

- If an operational detector is present, its activation time is derived from the physical fire effects in its vicinity. (In HAZARD I for example, this is the DETACT portion.)

- Either the activated detector or the fire effects are estimated to cause alerting of the occupants, each of whom then begins to act and move in accordance with behavior rules abstracted from past studies of human behavior in fires. (In HAZARD I for example, this is the EXITT portion.)

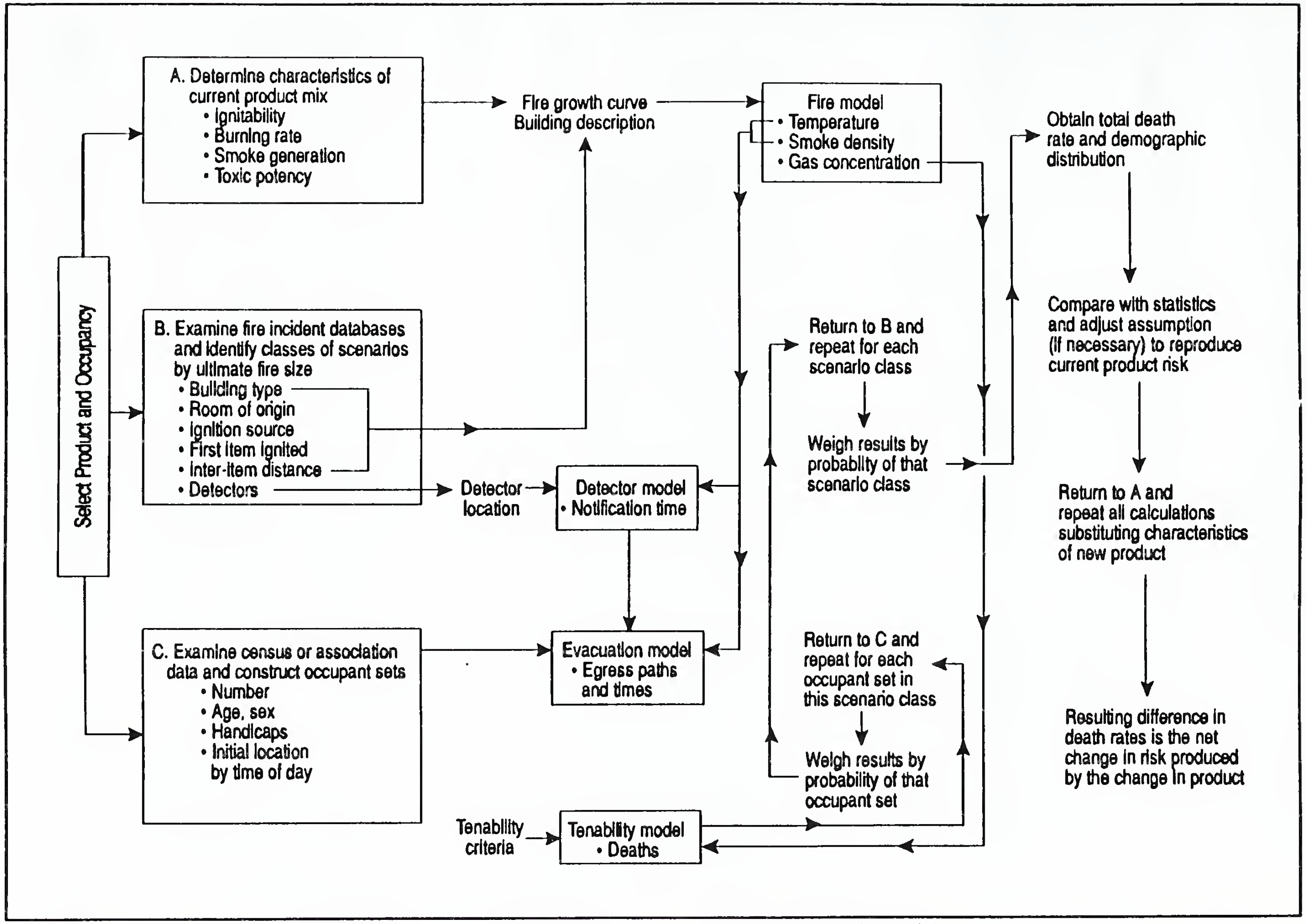

Figure 1 - Modeling Sequence to compute Fire Risk

- With a time line now developed showing both fire effects by location and occupant locations, the method uses available data on tenability thresholds to determine whether, when, and where each occupant died or escaped. (In HAZARD I for example, this is the TENAB portion.) This provides the number of deaths per fire for that fire scenario and occupant set.

- The next occupant set is selected and the EXITT and TENAB models are repeated with the previous output results for the fire's effects from FAST as inputs.

- The deaths-per-fire results for that scenario are estimated using the probability for each occupant set.

- Using the fire scenario probability and the total number of fires, one obtains the number of fires for that scenario. This is combined with the deaths-per-fire estimate for the scenario to obtain the number of deaths.

- These results are combined with similar results for all other scenarios to produce a sum that gives the estimated risk.

- This procedure is conducted twice. The first computation is to produce a baseline of fire risk associated with the mix of versions of the product now in use. Such a computation is done either using the product's average characteristics or, if possible, by conducting runs for the versions of the product in use and weighting the results by the share of product in use. The second computation is done using the characteristics of the new product - its peak rate of heat release, its relative ignitability, etc. Comparison of these two computations then produces a measure of the change in risk achievable by changing to the new product.

3. COMPUTATION OF FIRE DEATH RISK

3.1 Computing Risk of Death in Building Fires

The assessment of risk involves the calculation of the expected severity (in deaths per fire) and the relative likelihood (as fire probability) of each of a large number of fire scenarios which may or may not involve the product of concern. A summary equation for the computation of risk of death in building fire for a specified occupancy is:

$$E\ (\text{deaths}) = \sum_{TD} F_{TD} \sum_{i} P(S_i | TD) \sum_{j} D_{ij}\ P(O_j | TD) \tag{1}$$

where:

- E (deaths) = expected number of deaths
- F_{TD} = total fires by time of day
- $P(S_i | TD)$ = probability of combination of fire and building (i), given time of day
- D_{ij} = deaths per fire given i and j, based upon the hazard model result
- $P(O_j | TD)$ = probability of occupant set j, given time of day

Note that this assumes the probability of a fire scenario is not influenced by the occupant set that is present, except for the dependence that both may have on time of day.

3.2 Factor Evaluation

The first factor in the equation, F_{TD}, breaks down the total fires expected in a building occupancy by time of day. A source for F_{TD} is the NFPA annual stratified survey of fire departments in the United States [4]. The second factor, $P(S_i | TD)$, can be derived from the detailed NFIRS reports collected by the U.S. Fire Administration. The NFIRS reports use the NFPA 901-1976, *Uniform Coding for Fire Protection* which includes information necessary to classify fires (scenarios), by building type, room of origin, first item ignited, and extent of flame damage. The proportion of the total fires for each scenario can be estimated from analysis of NFIRS. This implies that the probabilities do not change for the new product case (see section 6.6).

The third factor, D_{ij}, is an estimate of the number of deaths per fire for a specific fire scenario calculated using the deterministic model HAZARD I. The fire scenario includes both the elements necessary for fire development in the building, as well as the location and capabilities of the occupants. HAZARD I simulates the fire's spread through the building and the occupant exposure to the fire effects, and results in a prediction of the number of deaths. This involves a three step process. First the fire's effects (heat, smoke and combustion product distribution in the building as function of time) are predicted using the FAST model. Second, this result is used for evaluating the evacuation response of people in the building, for the many occupant sets which are representative of this building occupancy in the U.S. The evacuation model EXITT is run for each occupant set to track occupants in the building as the fire develops. Data from FAST provide smoke conditions to which the occupants are exposed and which affect their travel speed and route selection. For example, in the residential cases EXITT was run over 200 times to include all the combinations of occupant sets. In the third step the outputs of FAST and EXITT are combined with a tenability model (TENAB) to predict the number of deaths.

Finally $P(O_j|TD)$, the probability of occupant set j is derived from U.S. Census data and sources which describe occupant activities by time of day. It should be noted that the fire statistics do not relate information on persons exposed to fires unless they are casualties. Therefore, the Census data and other data have been used as a surrogate for exposure.

The formulation of the term $\sum_j D_{ij} P(O_j|TD)$ in equation (1) indicates that the expected deaths per fire from a fire scenario i is determined by weighting the results from exposing each representative occupant set j by the relative fraction that occupant set j represents in the United States population.

4. MODELING THE BUILDING OF ORIGIN

4.1 Defining the Building

The building (or class of buildings) of interest must be defined first in terms of the NFPA 901 standard categories of fixed property use. In some cases, the categories of mobile property type (e.g., to distinguish mobile homes from conventional homes) or building complex may also be necessary or useful. Then data on actual fires can be used to estimate the average number of fires per year (reported to fire departments in the U.S.) that occur in that class of buildings. This is the first place where it may be necessary to deal with the handling of fires that are coded with incomplete information. For example, if one were interested in products used in court rooms, one would find that there are fires coded as court room fires (fixed property use 155) but also fires coded as occurring in library, museums, or courthouse properties not further specified (fixed property use 150).

The use of an average value for a particular characteristic like room layout is a substitute for analyzing all room layouts separately. If the relative probability of each layout were known, and if these analyses were recombined, then the average fire severity (deaths per fire) would be the same as the number of deaths per fire computed in one analysis using the correct average room layout. Sensitivity analysis can be done to check these assumptions. The assumption will be true in two special cases - the case of building characteristics that have no effect on fire severity and the case of building characteristics that are numerical in form and for which the number of deaths per fire goes up (or down) linearly as the value of the characteristic goes up. As an example of the first, if the number of doorbells in a home would have a negligible effect on fire hazard, then that variable can be captured by the average number of doorbells (or simply ignored if the hazard method does not require it for computation). As an example of the second, if the number of occupants would produce a proportional increase in fire hazard (proportionally more people to be killed by fires), then again the use of the average will produce the desired results.

By contrast, if one knows that the expected number of deaths per fire is actually related to some building characteristic in a distinctly non-linear fashion, then one should use two or more benchmark cases. In essence, each of these cases is used to capture a range of the building characteristic in hopes that, within that range, the assumption that the average fire severity equals the severity of the average case will be more reasonable.

4.2 Illustrating the Procedure With Dwellings

There is a nearly infinite variation of styles and floorplans in the existing stock of US housing. But Census data can be used to identify a few broad categories of housing, thus eliminating the need to examine such a large number of arrangements. At the most fundamental level, we have identified two building types: a five-room, one-story home (statistically representing 70% of the total) and a six-room, two-story home (representing 30% of the total). These selections are based on the following background information.

Data from the *Statistical Abstract* [9] indicates that the **median** number of rooms per occupied housing unit is 5.1. This value has remained nearly constant for some time (range of 4.9 - 5.1 since 1960) and appears to be a stable measure. When one-household homes are isolated, the median is somewhat higher. Also, the **mean** number of rooms would be slightly higher than the median. At the same time, fires occur proportionally more often in poorer households, which probably tend to have smaller homes on average. Therefore, the average is in the range of 5 - 6 and probably close to 5.

In 1970, 74% of new detached housing was in the form of the one-story house. The rest was split-level housing or had two or more stories. This percentage has declined to 65% in 1975, 60% in 1980, and 54% in 1984. Given that these percentages apply to new housing only and that percentages for homes built more than 15 years ago are not as generally available, it seems reasonable to estimate that roughly 70% of existing one-household housing is one-story housing and the rest is two-story housing. (3 or more story homes are negligible.)

The two benchmark homes, then, may be defined as a five-room, one-story home (equivalent to a ranch house) and a six-room, two-story home (equivalent to a colonial house). The former would be weighted 0.7, the latter 0.3, which would give the proper weighting for the number of floors and the right range for the average number of rooms. They would have three bedrooms which is consistent with specific *Statistical Abstract* data on numbers of bedrooms that shows the mean and median number of bedrooms per house is roughly 3. Each would have a living room and a kitchen. The colonial would have a separate dining room. The colonial would have its bedrooms upstairs and its other rooms downstairs, based on common industry practice. Each would have two bathrooms (ignoring the realtor's distinction between 1 1/2 and 2 baths), again supported directly by *Statistical Abstract* data, although this information may not be used. Each would have the indicated hallways, stairways, and closets normal for the layout. The ranch house would have a garage, the colonial would not, again based on available data which show the majority of dwellings have garages.

These two benchmark homes are similar to, but somewhat smaller than, the prototype homes identified by the Center for Fire Research (CFR) for the exercise of its hazard method (HAZARD I). The prototype colonial house has eight rooms rather than six, the ranch house six rooms rather than five.

A key parameter for evacuation is the presence or absence of an operational smoke detector. It is assumed that a code-complying arrangement is used. We include an estimate of the probability that the detectors are working. NFPA analysis of data from actual fires [10] indicates that, as of 1984 (the latest year available), the probability of having a detector, given a fire in a dwelling, was 0.284. Note that this was far lower than the probability that a dwelling in the general population would have a detector (around 0.75). The probability that the detector was operational, given a detector and a dwelling fire, was 0.674. Therefore, the probability of having an operational detector, given a fire in a dwelling, was 0.190 = 0.284 x 0.674.

5. MODELING ROOMS

The modeling of rooms and other areas principally involves the modeling of the room of fire origin. The current hazard assessment method treats the rooms other than the room of fire origin as volumes of space to be heated and filled with smoke and toxic gases, based on the size and dimensions of the volumes and the sizes of the openings connecting these volumes to room of fire origin. (As noted earlier, the spread of fire to secondary rooms is not modeled yet). The data sources from which these parameters can be estimated are listed in Table 4.

5.1 Ignition Probabilities

For each of the nearly 100 rooms or areas defined by the NFPA 901 standard categories of area of origin, statistics from actual fires can be used to calculate the base case probability that a fire occurred in the room, given a fire in that type of building. It will be desirable, however, to aggregate rooms and areas (defined by the NFPA 901 standard categories for area of origin) into groups of rooms and areas that would be expected to behave similarly in the model (e.g., similar size, similar fuel load, similar pattern of occupant activity). This is necessary in order to avoid an over-emphasis on this dimension of scenario definition which, if used in all its available detail, would either preclude the use of most other dimensions in scenario definition or produce an unmanageable total number of scenarios.

5.2 Grouping Areas of Origin

To group areas of origin, it is useful to begin by identifying the area of origin where most fires beginning with the product occur, then adding, if necessary, any other areas where the product typically is found. Table 3 shows the results of an exploratory exercise of this type, done for the first sample case used in developing the method, upholstered furniture in dwellings. The first two area groupings - living rooms and bedrooms - account for over three-fourths of the primary ignition of upholstered furniture. The next three - storage areas, dining rooms, and kitchens - account for nearly all the other areas where one might expect upholstered furniture to occur, but where it is not often a "first item ignited". These are, therefore, primary candidates for fires involving secondary ignition of upholstered furniture.

The other areas are presented as illustrations of the judgments one must make. Libraries and offices account for few fires, but the rooms are so much like living rooms and dens that they might as well be grouped together. Heating rooms, laundry rooms, and concealed roof/ceiling spaces (a category that includes attics) are other areas that sometimes are used as storage areas and on that basis might be included with the more traditional storage areas already grouped together. Alternatively, one might argue that the storage area grouping shown here, which combines closets, garages, crawl spaces, and other areas, should be broken apart. The percentages of total fires accounted for by area are presented because these will determine how many fires will be available that might cause secondary ignition of upholstered furniture. As may be seen, the secondary ignitions in kitchens could be as important to overall risk as the primary ignition in bedrooms. Chimneys are the prime example of an area that is not a room but has a great many fires. Upholstered furniture is not stored in chimneys, and a chimney fire that spreads to upholstered furniture is, by these definitions, a multi-room fire, which the method does not yet address. Similarly, exterior balconies, open porches, and exterior wall surfaces, as exterior areas, are not well handled by the hazard method and are, therefore, not captured by the risk method as yet.

Once this grouping exercise is completed, then the method proceeds as follows:

- Identify all rooms and areas in which the product is rarely found and for which only primary ignitions of the product will be considered. Calculate the probability of fire originating in any of these areas, given a fire.

- For this special group of areas, separate the probability just calculated into the probability that the product is in this area and the product is the first item ignited and the probability that the product is in this area with anything else as first item ignited. Calculate deaths per fire based on the national fire data bases, not the hazard method. For the latter group, treat this as an element of risk that no change in the product will affect since nearly all fires in these areas will not involve the product.

- For the former group (primary ignitions of the product in unexpected places), calculate the overall average number of deaths per fire involving primary ignition of the product in places where the product is expected to be. Use this as the estimate of severity for fires involving primary ignition of the product in unexpected places.

- Now take the rooms and areas where the product typically is found and group the rooms by reasonable similarities, as discussed earlier. For these rooms only, the remainder of the modeling decisions regarding rooms will be relevant.

5.3 Relating Extent of Flame Spread to Peak Upper Layer Temperatures for Room Fire

The fire model requires quantitative estimates of the peak energy released in the room of fire origin. Since this cannot be obtained directly, the method uses information in the incident data bases on the final extent of flame damage in real fires as an indicator of the peak severity of the fire. This is done by assigning a characteristic peak upper layer temperature to each category of final extent of flame damage. The assignments made by the technical team with discussion and concurrence of the Advisory Committee are:

- A fire coded as having extent of flame confined to object of origin is assumed to have had a peak upper layer temperature of no more than 100 °C. This upper layer temperature assumption takes precedence over the information that only one item was involved and may mean that the fire will be allowed to grow further than the one item could allow, for example if the product is incapable of raising the room temperature to this level. Because the fire is coded as confined to object of origin, if the object of origin is not the product, then this fire is assumed not to have involved the product.

- A fire coded as having extent of flame confined to area of origin had peak upper layer temperature of 200 °C.

- A fire coded as having had extent of flame confined to room of origin is assumed to have had peak upper layer temperature of 450 °C. This assumes that a fire confined to room of origin but not to area of origin nearly reached flashover, with 600 °C being a temperature value commonly found in laboratory tests at the onset of flashover.

- A fire coded as having extent of flame beyond the room of origin is assumed to have reached flashover in the room of origin. As such, it will burn at a rate of heat release characteristic of the room contents until the fuel load is exhausted. Therefore, if the product is in the room, it will be involved in the fire, and it is assumed that it will be involved however the product is changed, although changes in the product may be enough to prevent room flashover if the rest of the room's fuel load is small enough. This is discussed more in Section 6.

In each case, the selection of upper layer temperatures as surrogates for the extent of spread codings are major assumptions on which there is no direct evidence.

5.4 Using FAST to Relate Scenarios to Hazard Development

The method uses the FAST model to compute heat build up from ignition through flashover and fuel burn out in the room of fire origin, based on the user input fire. Using the FAST output for upper layer temperature it is possible to identify the time during the fire when each of the extent of spread criteria is met. The user should remember that FAST is a zone model with all of the attendant limitations, as discussed in reference 2.

Since FAST determines the quantity of fuel burned within the room of origin and that which is transported through openings and burned in other rooms, the input structure must specify mass loss rate rather than rate of heat release. While this is a straightforward conversion using the appropriate heat of combustion value, at flashover (600 °C upper layer temperature) the high flux is vaporizing all available exposed surfaces. Therefore, at the time corresponding to flashover the mass loss rate changes and it is necessary to determine for the specific room how much fuel is vaporizing. Also, since oxygen may become limited, the fuel which is not burned in the room is transported elsewhere in the building where it will burn if the oxygen is adequate. This phenomenon contributes to both the toxic and thermal impact outside the room of origin. Therefore, the FAST input structure must consider how much fuel is vaporized at flashover, so that the FAST model can determine where it is burned.

The computation is made using a well-known formula for the mass burning rate per unit area exposed at flashover

$$\dot{m}'' = \frac{\dot{q}_f''}{Lv} \qquad (2)$$

where, $\dot{m}''$ = mass burning rate per unit area

$\dot{q}''_f$ = total heat flux on material per unit area and

Lv = heat of gasification.

Typical post flashover values for computing the mass loss rate until fuel burn out are listed in Table 6.

Table 6 - Typical Post Flashover Parameter Values for Computing Mass Loss Rate

	Parameter	Typical Value
$\dot{q}f''$	Imposed flux above smoke interface	80 kW/m^2
	Imposed flux below smoke interface	25 kW/m^2
Lv	Heat of gasification	~5 kJ/g
	Exposed surface area vaporized	~2/3 floor area
	Fire load of combustible contents for typical residential rooms	23kg/m^2

The less severe fire hazard conditions are derived from the complete FAST output by noting the conditions at the appropriate time. This is equivalent to assuming an intervention which immediately stops the fires. The intervention assumption eliminates the need to run FAST for each extent of spread to capture the die-out portion of the fire. Ignoring die-out sacrifices additional detail, but gains a substantial reduction in the computational burden. This trade off was made recognizing that the die-out portion of a fire of less severity than flashover is not significant, that these fires are not the major contributors to death totals, and that fires which are interrupted prior to flashover are most likely discovered and extinguished. Discovery assures a strong possibility of assistance to those still in the house. This last point is important since an assumption is made that no one dies after the fire terminates.

5.5 Fuel Load

Because a flashover fire will consume all the room's fuel load, this quantity will need to be obtained, possibly from field surveys or if necessary from expert judgment. It will normally be expressed as two terms -- the fuel load per square meter (normally expressed as an equivalent weight of wood) and the effective heat of combustion (the value assumed in deriving the equivalency). When multiplied by the room area the fuel load per square meter converts to the entire fuel load of the room.

6. MODELING FIRE DEVELOPMENT BY SCENARIO, GIVEN THE ROOM OR AREA OF ORIGIN

At this point, the method has a specified building and fire room and a constraint on the peak rate of heat release, based on the final extent of flame damage. What is required in the scenarios is a more complete description of the fire, including its growth curve to the peak, what happens at and after the peak, and whether the product is involved. The method is designed to provide appropriate benchmark curves when nothing is known about the fire or the contents of the room except the final extent of flame, summary properties of the room and item first ignited, whether the product is present, whether the product was the first item ignited, and how far the product is from each of the potential items ignited.

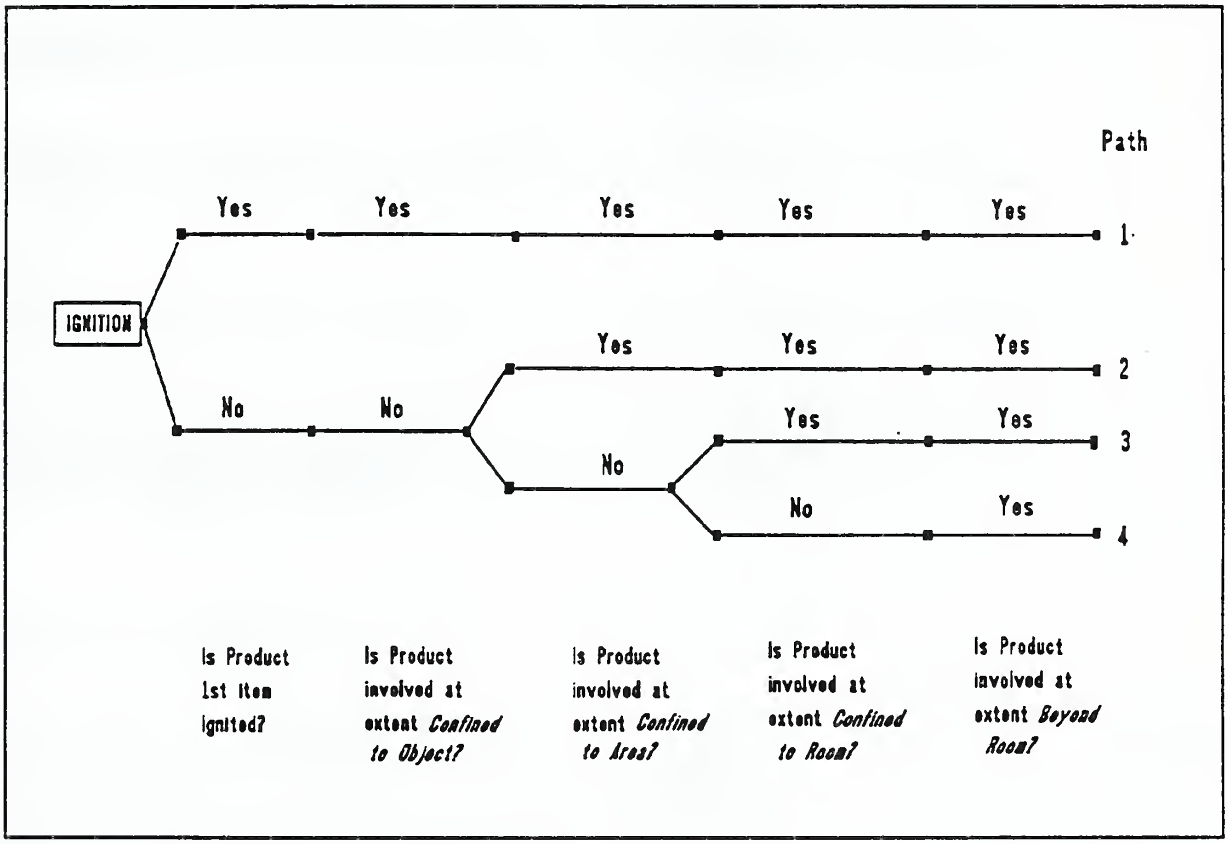

Figure 2 - Event tree indicating at what *Extent of Spread* the product becomes involved.

As described in section 5.4, the fire is modeled in FAST as a continuous curve from ignition through flashover and burn out of the fuel in the room of origin. Figure 2 is a generic event tree which indicates there are four possible paths a fire scenario can take for a particular first item ignited and time in the fire growth (extent of spread) when the product becomes involved (in any given case, not every path will be followed). Determination of which path applies to a specific product in a particular room depends upon several factors including: the dimensions and thermophysical properties of the room, the first ignited item's peak and rate of rise in heat release rate, the separation distance between the first item ignited and the product, and the product's ignitability. Appendix C gives the detailed procedures for determining the appropriate path and for developing the fire growth curve using the material from the rest of this section. The fire may involve more than one burning item. Therefore, in this section, we show how to determine whether and when one item will ignite others. The steps are:

- Determine the maximum size of the fire for each burning item. (Section 6.1)
- Determine the shape of the fire growth curve for each burning item. (Section 6.2)
- Determine the maximum separation distance from a burning item at which ignition of a second item will occur (Section 6.3, Table 8)
- Determine the typical spacings of combustible items in the application being considered. (Section 6.4)
- Combine the latter two distances to determine the average separation distance for which ignition will occur and the probability of ignition. (Section 6.4, Tables 9 & 10)
- Use these data to determine how long it will take the first item to ignite the second. (Appendix C)
- Insert these values into MLTFUEL to construct the total fire profile for the combined burning objects. [Note that if the probability of ignition is zero or the spacing need for ignition is larger than the anticipated real spacing, the second object will not ignite and the first item alone is the fuel package.]

Table 7 - Burning-Characteristic Item Classes for Dwellings

Growth Rate	Peak Heat Release Rate	Classes of Items First Ignited Included*
Slow	Low	18, 43, 44 Thermal insulation; books, magazines, paper
Slow	Medium	None identified
Slow	High	None identified
Medium	Low	22, 33-38, 45, 61 Non-upholstered chairs; soft goods other than mattresses, pillows, bedding; toys and games; wire or cable insulation

Medium	Medium	21 Upholstered furniture
Medium	High	15, 17, 23, 24, 29 Interior wall coverings; structural members; cabinetry, including tables; ironing boards; unclassified furniture
Fast	Low	14, 16, 42, 46-48, 51-57, 71-78, 85, 87 Floor or ceiling coverings; decorations; awnings; tents; supplies and stock except cleaning supplies; pelletized or rolled materials
Fast	Medium	25, 31-32, 41, 58, 62-68, 81-84, 86, 88 Appliance housings; mattresses, pillows and bedding; cleaning supplies; power transformer equipment; fuels and other combustible or flammable liquids or gases, dust or lint; explosives; adhesives
Fast	High	None identified

*Numbers refer to NFPA 901 standard code (1976 edition) for form of material first ignited.

Exterior forms of material first ignited (11-13) are excluded from analysis of indoor products.

Unspecified and unknown type items, except where shown above, are proportionally allocated over the classes they belong to.

6.1 Peak Heat Release Rate

All items defined by the NFPA 901 standard categories of form and type of material first ignited were classified by the project team as low, medium or high energy emitters. Table 7 summarizes these assignments for dwellings. The benchmark values for the three classes are based on patterns in laboratory testing [e.g., 11] and the ranges were defined by boundaries estimated as the geometric means of successive benchmark values. These are used when the first item ignited is not the product.

- A low energy emitter is estimated to have a peak heat release rate of less than 0.35 MW. The benchmark peak heat release rate value for an unspecified item in this class will be 0.25 MW.

- A medium energy emitter is estimated to have a peak heat release rate of 0.35-0.71 MW. The benchmark peak heat release rate value for an unspecified item in this class will be 0.5 MW.

- A high energy emitter is estimated to have a peak heat release rate of at least 0.71 MW. The benchmark peak heat release rate value for an unspecified item in this class will be 1.0 MW.

The assignment of items to these three classes requires that assumptions be made about both the heat of combustion and the mass of material represented by the item in the room. The actual assumptions made for each case are presented in the reports on those cases. However, it is clear that these are major assumptions made with little supporting evidence.

6.2 Fire Growth Curves and Rates of Rise in Rate of Heat Release

The fire growth rate (heat release) curves for any item can be represented by a curve proportional to time squared, where the curve is defined by its peak heat release rate and the time required for it to reach a particular heat release rate value.

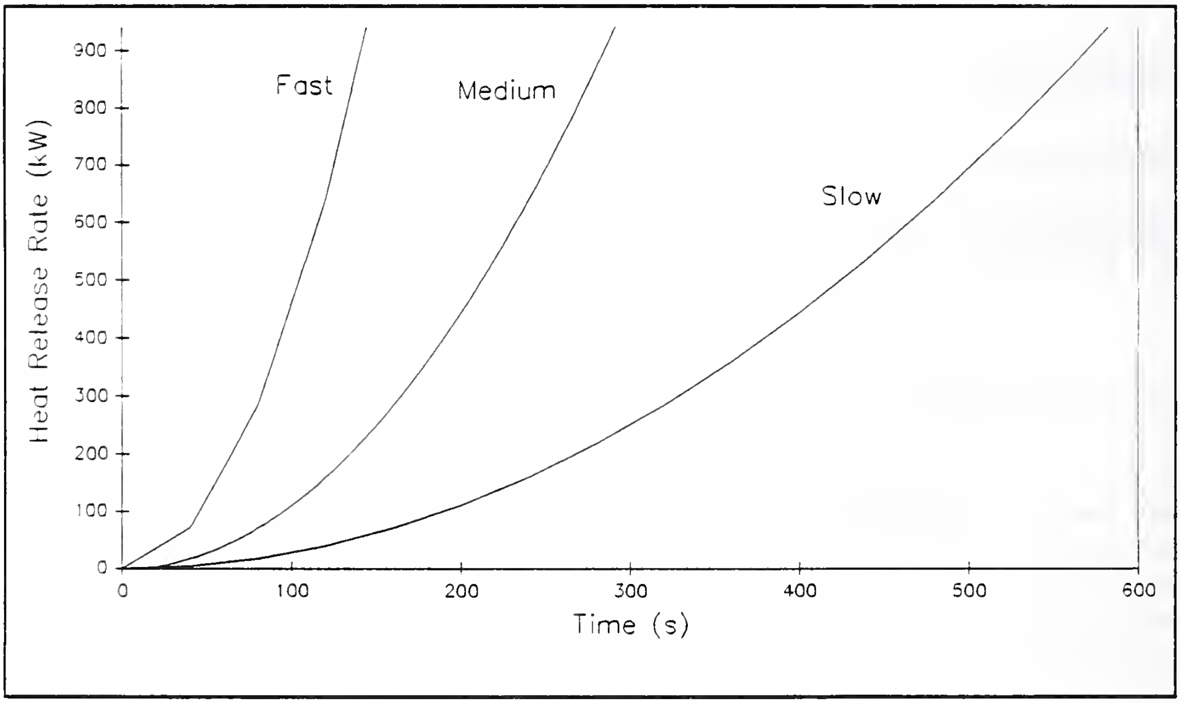

Figure 3 - T-square fire growth curves

Three growth rate curves are employed -- slow, which grows to 1055 kW in 600 s; medium, which grows to 1055 kW in 300 s; and fast, which grows to 1055 kW in 150 s (see Figure 3). All items defined by the NFPA 901 standard categories of form and type of material first ignited were classified by the project team as slow, medium and fast items (see Table 7). These curves (along with an Ultrafast curve) are being used by the NFPA Committees on Detection Devices and Automatic Sprinklers, within design systems that require similar assignments of general burning items to classes. Some such assignments are tabulated in Appendix C of the Standard on Automatic Fire Detectors (NFPA 72E) [12].

In the absence of an intervention, it is also assumed that the rate of heat release declines from its peak value according to a linear curve that requires the same time to decline to zero as was required to reach the peak rate from zero.

Ignition of an item by a smoldering heat source is assumed to produce an initial period of smoldering prior to the onset of the flaming function. In the residential cases, soft furnishings (upholstered furniture and mattresses) are assumed to smolder for 45 minutes prior to flaming combustion. If the ignition source is by a smoking material there is a two step ignition process which is represented by a constant mass loss rate of 0.00006 kg/s for 1000 s, which represents the burn through of the cover fabric, followed by constant mass loss rate of 0.0003 kg/s for the remaining 1700 s, which represent the foam [13]. If the heat of ignition is a non-smoking material source the initial stage is represented by a 720 s constant mass loss rate of 0.0003 kg/s. This applies to soft furnishings only. At this point, the heat release rate curve for the item subjected to a flaming source is used.

Smoldering ignition is assumed to involve ignition by smoking materials (i.e., tobacco products, not matches or lighters). The recognized mechanism of smoldering initiation by overloaded electrical wire and extension cords is not yet addressed in the method.

6.3 Product Ignitability

Results of tests by V. Babrauskas [14] indicate it is reasonable to assign all items to three classes - easy, normal and hard -- in terms of the heat flux from a flaming heat source required to ignite them. The benchmark values developed by Babrauskas for easy, normal and hard to ignite items are 10, 20, and 40 kW/m^2, respectively. The use of these categories offers a simplified approach to the handling of the product's ignitability in the baseline case.

Since the benchmark values are separated by factors of two, boundaries for the classes can be defined by geometric averages of consecutive benchmark values.

- Thus, the easy (to ignite) items would require heat flux values in the range of 0.0 - 14.1 kW/m^2, with benchmark value of 10 kW/m^2.
- The normal(ly difficult to ignite) items would require heat flux values in the range of 14.1 - 28.3 kW/m^2, with benchmark value of 20 kW/m^2.
- The hard (to ignite) items would require heat flux values in the range of 28.3 or more kW/m^2, with benchmark value of 40 kW/m^2.

Table 8 has been developed from the data in Reference 14 giving the maximum distance at which an item of a particular emitter energy level (low, medium or high) will ignite an item of a particular ignitability level (easy, normal or hard).

Table 8 - Maximum Ignitability Distances (inches) [14]

	Emitter Energy		
Ease of Ignition (Critical Flux)	Low (0.25 MW)	Medium (0.5 MW)	High (1.0 MW)
Easy (10 kW/m^2)	31	47	55
Normal (20 kW/m^2)	12	24	35
Hard (40 kW/m^2)	4	8	16

In practice, one should use Table 8 only as a framework for the development of a table showing the average farthest distance at which ignition will occur, based on peak rate of heat release, that are specific to the baseline and new-product versions of the product. These averages, if used in actual modeling, could blur the effects of important changes in product ignitability. Appendix A describes the procedures for addressing changes in the ignitability of the product.

6.4 Distances from Product to Other Items

Ignition of one item by another takes place when the flames from the first touch the second, or when radiant energy from the flame over the first item and upper layer gases in the room heat the surface of the second item to its ignition temperature. Thus, for cases when the product is secondarily ignited by items other than the product, the distance separating these items is critical to determine the time at which the product becomes involved.

Inter-item distances must be developed for the "First Item Ignited" classes defined by the NFPA 901 standard. In most scenarios, analyses use larger item class groupings (e.g., all basic item classes involving high peak rate of heat release, slow rate of rise in rate of heat release items). To avoid the need to run the hazard method once for each basic item class, an average distance to the product is computed for the larger item class groupings. That average is calculated using weightings reflecting, for each basic item class, the relative probabilities that basic item class contributed the first item ignited, given the room, given that the item first ignited was from the larger item class grouping, and given that the item was close enough to ignite the product. In this way, the formulas from Tables 9-10, which give effective distances for basic item classes, can be used to compute effective distances for larger item classes.

When the method refers to the product in a room, it refers to every object in the room that is an example of the product. All are treated as one item. Thus, upholstered furniture in a living room would represent a single chair or a multiple item set as a single upholstered item.

Table 8 indicates the maximum distance a product can be from another item and still be secondarily ignited by radiation from that item, as a function of the intensity of the initiating item and the susceptibility of the target. To use this, one needs to estimate typical distances separating the product from specific other items. What are required then are estimates of the distribution of distances between the product (at its nearest point to the fire-involved portion of the first item) and the fire-involved portion of the first item (at its nearest point to the nearest part of the product). This can be complicated by the relative size and orientation of items as identified in the fire incident data. For example, a piece of furniture may be in contact with a wall covering at one point, and still be some distance from the section of the wall covering where the fire might be most frequently ignited (e.g., near a fireplace).

Since these data have not been collected and are not easily obtained, we use an expert panel to estimate both a maximum and average distance from the product to each item first ignited as defined by the NFPA 901 standard form. These distances need to be estimated separately for each room or area (or group of rooms or areas) where the product is considered eligible for secondary ignition. An example of the outcome of such an exercise can be found in the main project report [16].

It is recognized that this estimation procedure involves some distances that are difficult to imagine in a realistic context (e.g., average distance from upholstered furniture to dust - which is a "first item ignited" on the 901 form). Therefore, sensitivity analysis will be particularly important for providing some confidence in these estimates.

It is also recognized that in some cases, account must be taken of the <u>variation</u> in distance that occurs in practice. Table 9 shows an example of a simplified histogram distribution which we developed to capture at least some of the variation that would be expected in actual item-to-product separations in the real world. [This example is similar to a normal (Gaussian) distribution with a standard deviation of 6 inches.]

The meanings of the entries in Table 9 may be illustrated as follows: Suppose the expert panel estimated that, on average, the product of interest (e.g., sofa) will be separated from an item (e.g., table) by 5 inches. Table 9 says that there is a 0.17 probability that the actual separation is 6-12 inches greater than 5 inches, implying a total separation in the range of 11-17 inches. At the other end, Table 9 says that there is a 0.17 probability of a separation 6-12 inches *less* than 5 inches (a negative distance which is impossible) giving a separation of zero.

To estimate the total probability that an item will be close enough to ignite the product, begin with Table 8. Categorize the item as low, medium, or high under "Emitter Energy" and the product as easy, normal, or hard under "Ease of Ignition." (If more specific information is available on the product's ease of ignition, that may be used to produce an even more appropriate set of values for Table 8.) These two classifications will result in a maximum igniteabilty distance.

Next, subtract the panel's estimate of the average distance between the item and product from this maximum distance. Find the row in Table 9 that corresponds to that difference. Then add the probabilities for all the rows above the one selected, and this is the probability that the item will ignite the product.

Table 9 - Distribution of Distances Separating Product from First Item Ignited

Actual Distance vs. Average Distance	Probability of that Range of Actual Distances
More than 12" less than average	0
Less than average by more than 6" but not as much as 12"	.17
Less than average by up to 6"	.28
Equal to average	.10
More than average by up to 6"	.28
More than average by at least 6" but less than 12"	.17
More than average by at least 12"	0

The following definitions are for terms in Table 9:

Average Distance: The typical spacing between two combustible objects, as estimated by the panel of experts.

Actual Distance: The spacing between any two items. In this example, these are grouped into ranges of 6", and there is a Gaussian distribution of the likelihood of these groups occurring.

Probability: The likelihood that the two objects will be separated by that distance.

For example, if the average distance is 6 inches but the item could ignite the product from 24 inches away, [24 - 6 = 18] which is "more than the average by at least 12 inches", or the last row. The sum of the probabilities for all rows above is 1.0, which means that the item is sure to ignite the product.

However, if the average distance were 6 inches but the item could only ignite the product from 4 inches away, [4 - 6 = -2] which is "less than the average by up to 6 inches" which is the third row. The sum of the probabilities for all rows above the third row is 0.17, which is the probability that the item will ignite the product.

Next, one must estimate the average distance from the item to the product for only those cases where the item is close enough to ignite the product. Table 10 provides formulas to make this estimate. Table 10 comes from replacing the probability distribution of ranges in Table 9 with a probability distribution of exact values.

Table 10 - Formulas for Average Distances from Product to Items Close Enough to Ignite Product

(X-Y)	Probability that Item Will Ignite Product*	X>12"	9"≤X≤12"	6"≤X≤9"	3"≤X≤6"	X≤3"
>12"	0.00					
>6,<12"	0.17	X-8.65"	.765X-5.82"	.353X-2.12"	0"	0"
>0,<6"	0.45	X-5.20"	.911X-4.13"	.756X-2.73"	.489X-1.13"	.111X
X=Y	0.55	X-4.25"	.927X-3.38"	.800X-2.24"	.582X-0.93"	.273X
>-6",<0	0.83	X-1.77"	.952X-1.19"	.867X-0.43"	.723X+0.43"	.518X +1.05"
<-6"	1.00	X	.960X+0.48"	.890X+1.11"	.770X+1.83"	.600X +2.34"

Note: X is the panel's estimate of the average distance from item to product, and Y is the maximum distance at which ignition of the product could occur.

*From figures in Table 9.

Consider a case where the experts decide that two items are an average of 12 inches apart, and can be as close as 5 inches or as far as 19 inches. Thus the difference from the average can be as much as seven inches. From Table 9, these involve the first two rows, totaling an 0.17 probability. The first row has a probability equal to zero. Therefore, to create the distribution of actual distances, we need only consider row two.

If the product has a normal ease of ignition and the initial item is a medium emitter, Table 8 tells us that the maximum separation at which ignition will occur is 24 inches. Table 10 then tells us that (for X=12 and X-Y=-12) the average distance at which ignition will occur is 12 inches with a probability of 1.0. If the ease of ignition were hard and the emitter low, Y=4, X=12 and X-Y=8. Applying the formula 7.65 x (12) - 5.82 (from Table 10), the average separation where ignition would occur would be 3.36 inches and the probability of ignition would be 0.17.

We now have the average separation distance for which ignition will occur and the probability of ignition. The procedures in Appendix B use these data to determine how long it will take the first item to ignite the second.

6.5 Multiple-Item Fires and Terminating the Fire

Based on Section 6.4, one may establish whether the product was ignited by the first item involved. Thus, the model must include different items, igniting at different times, and burning at different rates. In HAZARD I, the rate of heat release curve for a fire involving multiple items is a time-curve whose value at any point in time is the sum of the heat release rates for the individual items. This curve can be calculated from the times at which each of the various items begin burning. The hazard assessment method can calculate when the product was ignited, given the fire growth curve for the first item ignited and the average distance to that item when it is capable of igniting the product. However at this point in time, only the interaction of two items at a time can be considered because the calculations are done manually. These calculations are discussed in Appendices B and C.

If the peak rate of heat release calculated for the entire room is assumed to represent the final extent of flame damage for this scenario class (group of scenarios intended to represent a single category of extent of flame spread), it may be found that the item(s) known to have been ignited would not have been sufficient to produce this size of fire. The method then assumes that other items with a medium rate of rise in heat release rate were also involved and provided the necessary additional energy. They are modeled by extending the fire growth curve to the peak rate of heat release value for the room.

On the other hand, the item(s) known to have been ignited may have been more than sufficient to produce the peak rate of heat release for the room. It is then assumed that an intervention (i.e., manual or automatic suppression) occurred to suppress the fire at the time when the rate of heat release just reached the peak value allowed for the room fire. The intervention is assumed to reduce the rate of heat release to zero immediately.

Later, when the new product is compared with the base case it is usually assumed that the unspecified other items begin burning at the same time as in the baseline case, they are the same medium rate-of-rise in rate-of-heat-release items as before, and they contribute for the same length of time. The intervention, if there was one, also occurs at the same time as it did before. This treatment is best suited to fires occurring during the daytime and evening where random discovery might be the expected trigger of the intervention. However, other possible options have been suggested, including the intervention occurring at the same total energy (area under the heat release rate curve) released or at the same upper layer temperature. These options are best suited to discovery based on the fire's effects such as by an alarm system signaling the fire's presence or a sprinkler system.

Changes in the product can dramatically alter the course of the fire. Intervention could now occur after flashover or after the fire has already died out. If an item known to have been involved in the fire could have ignited the product, then it is assumed that it did ignite the product.

6.6 Computing Scenario Probabilities

The baseline probabilities can be derived directly from national fire incident data, because the scenarios are defined entirely by classes defined by categories in the NFPA 901 Standard -- final extent of flame damage, form and type of material first involved, and form of heat of ignition. Therefore, the base case probability of each scenario is calculated as the probability that those items were the materials first ignited, given the extent of flame damage and the room of origin. To support the needs of the evacuation analysis, the probabilities are computed individually for each time-of-day category used in the analysis.

These probabilities will be changed in the new-product case if the new product's resistance to ignition is changed. This could involve changes in both primary ignition probabilities and in secondary ignition probabilities.

The handling of changes on primary ignition probabilities is a complex but self-contained procedure shown in Appendix A. Most product fire risk analyses in the past have focused on this aspect alone.

Assumptions discussed earlier in Section 5.3 regarding the handling of fires confined to object of origin and fires extending beyond room of origin showed that changes in secondary ignition of the product involve only scenarios in scenario groups 3 and 4 (Table 5) -- those where the product is not the first item ignited and where the baseline fire was confined to the area or room of origin. In these scenarios, the method shifts non-product items between the two scenario groups in a balanced way so that the sum of the probabilities remains constant. What changes is that some items that had been close enough to ignite the product no longer are, given the changes in the product, and/or some items that had not been close enough to ignite the product now are close enough. Therefore, calculation of the new-product scenario probabilities requires, for all scenarios in scenario groups 3 and 4, the recalculation of which items are and are not close enough to ignite the product. Based on this recalculation, the assignment of non-product items to specific scenarios may be affected.

6.7 Predicting Exposure Impact

HAZARD I can assess toxic impact on building occupants in two different ways. One uses a concentration-time product of the fuel mass lost, called species Ct. The other evaluates the combined effects of the primary toxic gases released, using a formula called Fractional Effective Dose (FED). The former is a generic method which does not differentiate among the constituent products within the "smoke" or the combustion chemistry of the fuel. The latter is more detailed in that it can account for both, allows for the toxicity of multiple items (or items constructed of multiple materials) to be added together properly, and can account for components of the "smoke" which react or condense out with time and/or distance (such as $HC\ell$ which will be added to the next revision of HAZARD I).

The use of FED requires a knowledge of the specific materials of construction and their release rates of the gases included in the model (currently CO, CO_2, low O_2, and HCN). Thus, this method could be employed for the "new" product, where such information can be measured or estimated, but cannot be readily applied for the mix of products in the baseline, let alone for the less well defined first items ignited and the largely undefined other items ignited. One should not attempt to make direct comparisons between Ct and FED as their interrelation has not been established. Thus, Ct becomes the default toxicity indicator for the method.

For the present therefore, the risk method uses species Ct as the toxicity determinant. The following steps are used to calculate toxic impact of the product:

1. Separate the rate of heat release curve (as a function of time) into a curve for the product and a curve for all other burning items.

2. Use a standard reference value for the effective heat of combustion to convert these two rate of heat release curves to rate of mass loss curves.

3. Estimate a ratio of (LCt_{50}(product))/(LCt_{50}(average)), where LCt_{50}(product) is the cumulative concentration-time exposure for the product being analyzed that will just kill half the animals in a standardized combustion toxicity test. The LCt_{50}(average) is the corresponding benchmark value for the "average" toxic gas output of an average fire. This ratio is an estimate of how much more or less toxic the product is than other items.

4. Take the ratio from step 3 and multiply it by the mass loss time-curve for the product, then add the revised curve to the mass loss curve for all other items.

5. This revised curve will be compared to LCt_{50}(average) to determine when conditions become lethal in any room.

The method is able to use this species Ct approach because it requires only one assumption (the effective heat of combustion) and one estimate of an average toxicity parameter, LCt_{50}(average) to perform the calculations. If FED were used, several average toxicity parameters would be needed and several more assumptions would be needed to produce the required toxic-gas time-curves for the average items. The use of species Ct still enables the method to incorporate the interaction between mass loss rate and toxic potency in the creation of toxic hazard. Sensitivity analysis, which is highly desirable for this phase, can be concentrated on measuring the effects of changes in the two assumptions.

Thermal effects are modeled using a modification of a relation developed by Purser, as presented in the HAZARD I documentation [2]. The equation for human incapacitation by convected heat was derived from literature sources, and is a function of the temperature rise over a threshold level to an exponent of exposure time.

In some cases, a separate calculation conducted outside of HAZARD I may be necessary to address fatal injuries that occur rapidly to persons very close to the fire (called "intimate with ignition" in the data bases. HAZARD I inflicts fatal injury only through exposure to room conditions, not through the kind of burns that might occur if the fire spreads directly to the victim (e.g., clothing ignites). This type of injury accounts for a modest fraction of structure fire deaths overall, but can be a significant component or even a majority for some property classes.

The side calculations required to address this gap are simple. For each scenario involving the product as first item ignited, calculate the number of intimate-with-ignition deaths per 1000 fires based on incident data, and assume this rate is constant regardless of product changes. This means that only product changes which affect its probability of ignition will effect this component of the product risk.

6.8 Data Sources and Assumptions

Table 11 summarizes data sources for the parameters used in modeling scenario fires. Table 12 summarizes the assumptions used in the fire risk assessment method.

Table 11 - Data Sources for Parameters Used in Modeling Scenario Fires

Parameter	Data Source
1. Probability of first item ignited (form and type of material first ignited), given fire in room of particular extent of flame.	1. NFIRS national estimates.
2. First item's peak rate of heat release.	2. Project team estimates, using laboratory tests where available and a simplified grouping approach.
3. First item's rate of rise in rate of heat release.	3. Same as #2.
4. Product ignitability.	4. Estimate by user of method, expressed as maximum distance for ignitability, given peak rate of heat release of primary flaming heat source.
5. Distance from first item to product.	5. Expert panel estimates of averages, refined by a standard distribution of actual distances around the average.
6. Benchmark value of effective heat of combustion.	6. Project team estimate.
7. LCt_{50}(average).	7. Midpoint of range of values derived in laboratory for most materials tested.

Table 12 - Summary of Assumptions and Limitations in Fire Risk Assessment Method

General

1. Sources for test data are as shown in Table 1. We must assume that use of the best data available from any of these sources produces acceptable results.

2. Fires reported with certain characteristics unknown (often a significant portion of the total) are handled by allocating them proportionally over the fires for which those characteristics were known. The sequence in which this is done can make a difference in the results. The recommended sequence follows the perceived importance of the variable to the analysis. Thus, (a) allocate the total number of partially unknown building-type fires (e.g., office building of unknown type) over the fully known building type fires; (b) allocate the total number of unknown and partially-known area of origin fires (within the residential or non-residential structure group) over the known area-of-origin fires; (c) do all other allocations in terms of the full matrix of dimensions of interest, allocating form of material first ignited, then type of material first ignited, then extent of flame damage, then form of heat of ignition, then time of day.

Building

1. All buildings of a class can be modeled by a small number of representative arrangements and constructions.

2. Flame spread beyond the first involved room is not modeled in this version of FAST. Spread of heat, smoke, and toxic gases is modeled.

3. Spread of fire effects is modeled only for spread through openings between rooms. This means spread in HVAC ductwork, elevator shafts, and the like, sometimes important, must be omitted. It also means spread out windows is not available as a means of spread of fire effects back into other parts of the building, but this is seldom an important factor.

Room

1. To achieve computational practicality, areas of origin defined by the NFPA 901 standard may be grouped by the user of the method, according to patterns of room size, fuel load, occupant use, and product use.

2. Rooms in which the product rarely is found may be designated as ineligible for secondary ignitions of the product. Also, fires involving primary ignitions of the product in those rooms will be modeled by hazard assessments of the fires involving primary ignition of the product in rooms where the product is more typically found. Rooms in which the product is found with some frequency will have expert panel estimates of how often the product is in that room and available for secondary ignition.

3. Final extent of flame damage may be used to estimate a characteristic peak upper layer temperature for the room fire. This may then be used to estimate the peak rate of heat release for that room fire.

4. Fires coded as confined to object of origin and not originating in the product may still have involved other items (because those items may be required to reach the peak upper layer temperature), but the model assumes that these fires did not involve the product and will not involve the product no matter how it is changed.

5. Fires coded as extending beyond the room of origin reached flashover in that room and therefore consumed all fuel in that room. Changes in the product cannot prevent its involvement in these fires but may prevent flashover by reducing the available fuel. Thus, for the new product case the method must assume that all items *except* the product still ignite. If this results in sufficient energy for flashover, the product change has no effect on the scenario. If, however, flashover is no longer predicted, this scenario moves to another (lower extent of spread) class and the product change is credited.

6. If flashover occurs, it proceeds as a ventilation-controlled fire, whose rate of heat release is therefore solely a function of the dimensions of the room and its openings.

<u>Fires</u>

1. Burning of first items ignited can be characterized by one of three benchmark values of rate of peak heat release. These assignments are made for item classes defined by the NFPA 901 standard categories of first items ignited in fire. The assignments use the project team's best judgments using laboratory test results where they exist. Assumptions must be made for each item class as to the effective heat of combustion and the mass of the item.

2. First items ignited can be characterized by one of three benchmark curves showing rates of rise in rate of heat release, where the curves are time-squared curves. These assignments are made for item classes defined by the NFPA 901 standard categories of first items ignited in fire. The assignments use the project team's best judgments, using laboratory test results where they exist.

3. Smoldering heat sources are assumed to produce a smoldering phase characterized by a linear increase in rate of heat release with fixed slope for all items. The length of the smoldering phase is estimated by the project team. Upon transition to flaming, the assigned t^2 curves are used, with the transition point as time zero and the rate of heat release at the transition point as a constant to be added to the rate of heat release curve, throughout its growth phase.

4. Product ignitability as secondary items ignited must be characterized in terms of the maximum distance at which ignition can occur, given a fire-involved item with low, medium, or high peak rate of heat release. In a simplified analysis, assignment of the product to one of three benchmark classes - easy, normal, and hard - may be used.

5. The average distance from the product to an average fire-involved item must be estimated by an expert panel for each class of items first ignited and each class of rooms in which secondary ignition is possible. A fixed-variance distribution is used to convert these average distances into a distribution of actual distances.

6. If an item could have ignited the product, it is assumed that it did ignite the product.

7. If the first item ignited and the product (if it is involved) would not produce a peak rate of heat release equal to the estimated peak rate of heat release for the full room fire, then additional items are added to the fire to bring it to the peak value. These other items are assumed to have medium rate of rise in rate of heat release and to begin contributing to the fire when the fire growth curve for the known items reaches its peak. In the new-product analysis, these unspecified other items are assumed to become fire-involved at the same time and to contribute in the same way.

8. If the first item ignited and the product (if it is involved) could have produced a fire more severe (higher peak rate of heat release) than the entire room fire was estimated to have had, then an intervention is assumed to have occurred, suppressing the fire and instantly reducing its rate of heat release to zero at the time its rate of heat release had reached the peak rate for the room. In the new-product analysis, an intervention is assumed to have occurred at the same time during the day or total energy at night. These assumptions ignore the possibility of significant compartmentation effects on the growth curve of the fire.

9. Fires involving the product are assumed to involve all the items in the room that are classified as the product. All are treated as one item.

10. The toxic impact of a product is estimated by (a) using the product's rate of heat release to estimate its mass loss rate and an effective heat of combustion; (b) revising that mass loss rate-time function by multiplying it by a ratio of the product's LCt_{50} to an estimated LCt_{50} for burning items in fires; (c) using this to produce a modified effective mass loss rate curve for the product with other items; and (d) determining when this revised curve reaches the average LCt_{50} value in each room. This approach lacks an analysis of individual toxic gas components and does not address synergistic effects among toxic gases or between toxic effects and heat results.

Occupant Assumptions

1. U.S. Census and other sources used to determine general occupant composition and activity patterns also represent households that have fires.

2. Occupant composition does not influence ignition likelihood.

3. During the daytime, able-bodied occupants (adults, elderly and older children) are combined into one class and during the evening adults and older children are also combined as a class.

4. Occupants are assumed not to re-enter the building to perform rescues.

5. The maximum household size in residential analyses is limited to five people.

6. Critical tenability criteria for heat and smoke toxicity do not vary by occupant type.

6.9 Observations on Computational Burden

Table 5 showed six scenario groups, but if all variations affecting the fire growth (FAST) portion of the hazard assessment inputs are considered (i.e., all those listed except time of day), then this approach may require 104 scenarios to be examined for each room of origin or grouping of rooms and areas of origin where the product is typically found. The large number of scenarios reflects the need to consider various combinations of characteristics -- particularly rate of rise in heat release rate and peak heat release rate -- of the myriad non-product items that may be the first items to be ignited. Only 8 of the 104 scenarios apply to the post-flashover fires which appear to account for the overwhelming majority of deaths in actual fires. There may be interest, therefore, in (1) considering of a less precise, less accurate, but computationally simpler version that uses data from actual fires for the low fatality rate fires and sets bounds on the impact of product changes for those scenarios and (2) limiting use of the hazard method to those scenarios producing the most fatalities.

For fires confined to object of origin, it is possible to use available information to set the peak heat release rate of the room fire at the minimum of the peak heat release rate of the one item known to be the only object burning and the benchmark maximum for a confined-to-object fire. This approach uses more of the available information and is therefore more accurate even though it is less consistent in format with the approach used for larger fires (where the collection of objects involved is not known in detail). However, this more accurate approach would require more scenarios and they would be concentrated on the smallest, least consequential fires, so this refinement does not appear worthwhile.

7. MODELING OCCUPANTS

7.1 Modeling Occupant Exposure

The impact created by the fire depends upon the exposure of the occupants to the products of combustion and heat. Exposure evaluation requires locating the occupants at ignition and modeling their response to the cues (e.g., detector alarm and smoke) from the fire. The method uses a deterministic evaluation model with decision rules which depend upon occupant characteristics, building layout and fire conditions [15] . These characteristics are used in the evacuation model to simulate behaviors such as alerting, assisting or requiring assistance and evacuation speed. An occupant set is defined in terms of the number of persons, their characteristics (sex and age), location (within and outside the house) and condition (asleep, awake, or incapacitated by physical impairment or due to drugs or alcohol) at ignition. Once an occupant set is specified, the model will trace the expected pattern of movement during the time from ignition to the time of evacuation or to the time individuals become trapped by smoke.

The risk calculation requires an estimate of the probability of each occupant set given a fire scenario. The national fire data provide no information on building occupants unless they are injured or killed. Information is provided on likelihood of fire by time of day, which can be used to imply location probabilities - based upon information available from the U.S. Census or other sources on occupancy composition and activity patterns. This procedure conditions occupant set probabilities by time of day ***without regard for the influence a particular occupant set might have on ignition likelihood***. When and where better information is available - tying together occupant sets with the fire - it should be used.

7.2 Occupant Set Construction

The method requires characterization of occupant sets and their associated probabilities by time of day. Each occupancy will have its own unique aspects for evacuation modeling, occupant characterization and sources of information for estimating occupant exposure. However, the following provides a step-by-step guide for the process of establishing occupant sets and is applicable to most occupancies.

- Determine the total number of occupants per unit area, individual unit, room or building - ultimately these numbers will be subdivided into occupant sets exposed to fire.

- Evaluate the occupant characteristics which influence evacuation -this depends not only on the occupancy but also the evacuation model. Characteristics include age, condition (asleep or awake, or functional limitations due to disabilities or impairment by drugs or alcohol) and location within the building. The key consideration in simplifying the calculation is to identify those characteristics which result in insignificant differences in evacuation behavior.

- Locate the occupants within the building by the time of day. Location can be inferred for occupants with defined characteristics from activity pattern information by time of day.

- Merge together occupant types sharing common locations expected to behave in a similar manner by time of day.

- Based upon the results of the previous analyses, subdivide the occupants into sets for evacuation modeling. The number of sets required may vary greatly from occupancy to occupancy. In the one- and two-family residential occupancy, one can imagine a large number of combinations of family members with different characteristics in a number of rooms interacting with each other during a fire. This would require a large number of occupant sets. Each occupant set would have an integer number of members and represent the U.S. household with this structure. U.S. Census data and other sources are used to estimate the fraction of the total households represented by each occupant set. In this way, all of the households are represented by an occupant set and weighted by the fraction of the households having this structure.

8. PUTTING IT ALL TOGETHER

The application of the risk method to the analysis of the impact of changes made to a product on its life-safety risk is relatively straightforward. One goes through the process defined in this paper to compute the "base case," representing the current risk of the product in the target occupancy. Once the base case is run and calibrated against the fire incident data, the "new product" case is run by substituting the properties of the new product and repeating all of the calculations. This leads to a direct estimate of the change in risk associated with the modified product in terms of the increase or decrease in the fire death rate. The comparisons are thus direct, and can be made not only on the basis of overall deaths, but also on the supported demographics such as time of day, room of origin, type of ignition, or characteristic of victim.

This process is demonstrated for each of the four case studies performed as a part of the development of the method, and documented in the four case study reports [5-8]. By reviewing these case studies, the abstract nature of the methodology as presented in this paper is made significantly clearer.

9. INTERPRETING SIGNIFICANT RESULTS

It is very difficult to make global statements regarding the accuracy of the method when it is so dependent on the availability of good data, judgement, and the ability of HAZARD I to address properly the science issues particular to the case under consideration. Since these issues were encountered and addressed in the four case studies performed by the project team, the reader is referred to the discussion in those reports.

In general, however, the risk method incorporates a built-in mechanism to measure its abilities for a specific case. This is the process of calibrating the "base case" against the fire incident data. The degree to which the base case matches the demographic distribution of fatalities in the "real world" is the measure of its accuracy. While you should not expect perfect agreement, the case studies showed that most comparisons to statistics were within 50%, with some within 10%.

As also demonstrated in the case studies, confidence can be improved by conducting sensitivity studies on parameters which are not soundly based to determine their impact on the results. If wide variation in the estimate has little impact on the result, it doesn't matter that the parameter might be off.

Finally, the authors feel that the mere existence of this risk method will influence improvements in both the underlying science and the quality of data. It will create a "demand pull" for such because of the improved safety, and the reduced cost of product development and marketing.

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Appendix A

Modeling Changes in Probabilities of Primary Ignitions of the Product.

A.1 Product Share.

First, estimate how much a share the product has of the item class it is part of. In most cases, the answer will be that everything in the item class is an example of the product. For example, upholstered furniture belongs to an item class that is just upholstered furniture. By contrast, tables share an item class with desks, filing cabinets, and bookcases, among other objects. Let P_{ip} be the estimate of the proportion of initial ignitions of the product.

Note that this step is used only for primary ignitions. Because of the way the method works, if anything in an item class is secondarily ignited, then everything in that room in that class is secondarily ignited, because all are modeled as having the same properties and the same location relative to other objects.

A.2 Propensity for Ignition.

With a product or item class, it may be necessary to estimate the relative propensity of the various versions in use to be initially ignited. These propensities (call them f_i, where i is a particular version of the item or product) represent the proportion of the initial ignitions attributable to the baseline mix of versions of the item or product now in use. To calculate f_i, several elements are required:

- A set of versions of the item (labelled i);
- A set of potential heat sources (labelled j) for initial ignition of the item;
- The proportion of all of the item in use that are version i (q_i), which is to say share of total usage or market;
- The probability of ignition for each heat source, given that the first object ignited was a version of the item (p_{ij}), where the probabilities must sum to one (over i for each j), thereby requiring all heat sources (defined by the NFPA 901 Standard categories of form of heat of ignition and possibly equipment involved in ignition) to be grouped into classes with each class having exactly one benchmark heat source from the set of potential heat sources; and

- A series of tests of the items and heat sources in combination, so that each item i is tested N_{ij} times against heat source j and is ignited n_{ij} times in those tests.

Then n_{ij}/N_{ij} should be proportional to the relative propensity of heat source j to ignite item version i, given contact between them. Similarly,

$$\sum_i q_i n_{ij}/N_{ij}$$

should be a measure of the propensity of heat source j to ignite a representative version of the item, given contact between them.

Since contact between heat source and item may occur more often with some heat sources than with others, one must calibrate

$$\sum_i q_i \; n_{ij}/N_{ij}$$

by p_j, the actual proportion of ignitions of the item by heat source j. Thus, the ratio $p_j \,/\, \sum_i q_i \; (n_{ij}/N_{ij})$ is a calibration term applicable to the (n_{ij}/N_{ij}) values.

Putting this all together, the relative propensity of heat source j to ignite item version i is given by $(p_j \; n_{ij}/N_{ij}) / \sum_i q_i \; (n_{ij}/N_{ij})$, and the overall

relative propensity of item version i to be ignited is given by:

$$f_i = \sum_j \left[p_j (n_{ij}/N_{ij}) / \sum_k q_i (n_{ij}/N_{ij}) \right] \tag{2}$$

A.3 Defining Heat Source.

Standard test methods include detailed ignition sources, some of which were designed to represent specific accidental sources. For example, the "pill" used for testing carpet ignitability represents a match and the gas burner in the Furniture Calorimeter represents a wastebasket. In the simplest cases, only two generic heat sources are defined -- flaming and smoldering. For correspondence with the NFPA 901 categories, smoldering fires are identified with smoking material (but not matches or lighters) fires and flaming fires are defined as everything else.

A.4 Estimating the Ignitability of New Products.

For new products, the calculation of f_i must be preceded by a baseline analysis like that described above. Then the new version of the product must be subjected to the same battery of laboratory tests. Call the new product I. Then n_{Ij} will be the number of ignitions of the new product in N_j tests against heat source j. Thus:

$$f_I = \sum_j \left[p_j (n_{Ij}/N_j) / \sum_i q_i (n_{ij}/N_j) \right] \qquad (3)$$

Note that the denominator continues to be a sum based entirely on existing versions of the product and so will not include product I. The new product's test results are shown only in the numerator.

A.5 Adjusting for the Baseline Mix.

Using these formulas, calculate P_{new}, the ratio of the new product's overall propensity to be ignited to the overall propensity for the baseline mix of products.

$$P_{new} = f_I / \sum_i f_i \, q_i$$

A.6 Interfacing With the Risk Method.

Identify the scenarios where the product's item class provides the first item ignited. These are the scenarios in scenario groups 1 and 5 and one of the two scenarios used to analyze the class of rooms and areas where the product does not typically appear. For each such scenario, replace the baseline probability (call it Z) with a new value, Z $(1 - P_{ip} + P_{ip}P_{new})$. Note that if $P_{ip} = 1$ (indicating the product accounts for the entire item class), then this is equivalent to replacing Z by $Z(P_{new})$.

A.7 Computing New Conditional Probabilities.

After A.6 has been completed, the scenario probabilities for any room or class of rooms may no longer sum to one. Thus, they no longer represent the conditional probabilities of their scenarios, given fire in the room. What this means is that the scenario changes have produced a change in the overall probability of fire in a particular room, and the probabilities need to be revised to reflect this. Sum the new values from A.6 for the conditional probabilities of scenarios in the room, given fires in that room. Call that sum S. Now divide each of the new values by S. (These ratios will be the new conditional scenario probabilities.) Then, multiply the old conditional probability for the room, given a fire in the building by S.

At this point the conditional room probabilities, given a fire in the building, may not sum to one. Therefore, divide each of them by the sum of the new room values calling the sum Q. (These ratios will be the new conditional probabilities of each room or room groupings, given fire in the building.) Multiply Q by the old overall probability of fire in the building to get the new overall probability of fire in the building. (If buildings have been subdivided into sub-classes, with conditional probabilities for each building sub-class given fire in a building from any sub-class, then this adjustment procedure will need to be repeated. The last adjustment should be to the figure giving the unconditional probability of fire in the building or buildings of interest.)

Table A.1 Data Sources for Parameters Used in Estimating Changes in Primary Ignitions of Products

Parameter	Data Source
1. Usage or market shares of versions of the product.	1. Surveys by manufacturers of the product.
2. Probabilities of heat sources, given ignition of the product.	2. NFIRS national estimates.
3. Ignitability tests for product versions versus heat sources.	3. Laboratory tests.

Appendix B
Secondary Ignition of a Product

B.1 Background and Purpose

An important factor in the quantification of a product's risk is understanding when it becomes involved in fires in which it is not the first item ignited. Since the fire incident statistics in the U.S. do not include secondary ignition as a data element, it was necessary to devise an approach which used laboratory results to infer product involvement from other information. This general approach which based product involvement on ignitability and separation distance from the item first ignited, was explained in Sections 6.3 and 6.4.

The purpose of this Appendix is to explain the derivation of the equations used to compute the mass loss rate required to ignite a product of a given ignitability at a known distance from the radiating source (first item ignited).

B.2 Derivation of the Ignitability Equation

The data used in this Appendix were taken from the experimental work of Babrauskas [14]. During his study, Babrauskas addressed the problem of fuel interactions -- will the second item ignite by radiation? One aspect of the work involved mapping several ignition flux levels. This irradiance mapping provided a set of maximum radial distances where the flux was reached, together with the corresponding peak mass loss rates generating the radiation.

Table B.1 contains results for 20 kW/m^2 and 40 kW/m^2 ignition flux levels. These data are plotted in Figures B.1 and B.2, and a linear expression for mass loss rate was determined for each of the ignition flux levels. These expressions are of the form:

$$\dot{m}_{ign} = K\, D_{ign} + C \qquad (1)$$

where,

$\dot{m}_{ign}$ is the peak mass loss rate of the product
D_{ign} is the radial separation distance
K is the slope and
C is the $\dot{m}_{ign}$ intercept

The parameter values are shown in Table B.2.

Table B.1 Ignition Distance and Mass Loss Rates for 20 kW/m^2 and 40 kW/m^2 Ignition Flux Levels

Ignition Flux Level			
20 kW/m^2		40 kW/m^2	
Ignit. Dist. Meters	Peak Mass Loss Rate for Ignition g/sec	Ignit. Dist. M	Peak Mass Loss Rate for Ignition g/sec
0.0	1.9	0.0	6.2
0.16	6.2	0.10	18.0
0.29	12.0	0.12	12.0
0.43	18.0	0.40	47.0
0.88	47.0		

Table B.2 Parameter Values for Products Ignitable at 20 kW/m^2 and 40 kW/m^2 Flux Levels

Ignitability I_e(kW/m^2)	Slope K(g/m-sec)	Intercept C(g/sec)
20	37.9	1.2
40	103.5	4.7

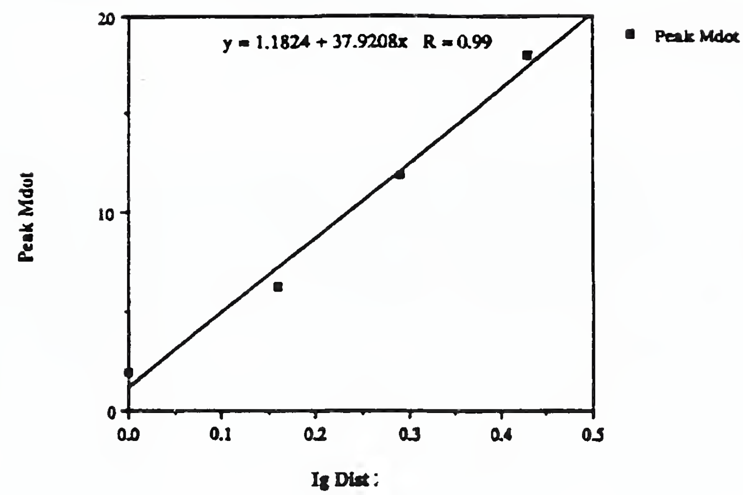

Figure B.1 - Relationship between ignition distance and peak mass loss rate at 20 kW/m^2 ignitability

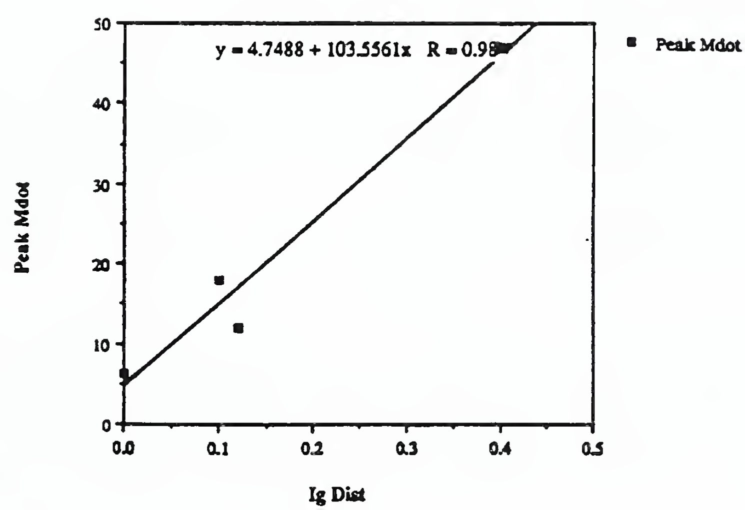

Figure B.2 - Relationship between ignition distance and peak mass loss rate at 40 kW/m^2 ignitability.

Based upon the parameter values in Table B.2, equations (2) and (3) can be used for linear interpolation of values for K and C between 20 kW/m^2 and 40 kW/m^2.

$$K(g/m\text{-}sec) = 37.9 + (Ie - 20)\ 3.28 \quad (2)$$

$$C(g/sec) = 1.2 + (Ie - 20)\ 0.17 \quad (3)$$

Since it does not make physical sense to have a negative $\dot{m}_{ign}$, the C values have been constrained to yield non-negative values. Solving for the ignitability value when C = 0 in equation (3), yields I_e = 12.9 kW/m^2. Therefore, below an ignitability of 12.9 kW/m^2, the C value is constrained to zero; the slope (K) at 12.9 kW/m^2, by substitution into equation (2), is 14.7 g/m-sec.

Assuming that the slope changes linearly with changes in ignitability values below 12.9 kW/m^2, yields equation (4).

$$K = 1.14\ I_e \text{ for } I_e < 12.9\ kW/m^2 \quad (4)$$

In summary,

$$K = 37.9 + (I_e - 20)\ 3.28 \text{ if } 12.9 \leq I_e \leq 40 \quad (5)$$
$$K = 1.14\ I_e \quad \text{if } I_e < 12.9 \quad (6)$$
$$C = 1.2 + (I_e - 20).17 \quad \text{if } I_e \geq 12.9 \leq 40 \quad (7)$$
$$C = 0 \quad \text{if } I_e < 12.9 \quad (8)$$

B.3 Application of the Equations

It should be noted that since Babrauskas used a mix of items which had an effective heat of combustion of 29.2 kJ/g, it will be necessary to adjust the $\dot{m}_{ign}$ depending upon the heat of combustion (HC) for the item-first-ignited.

$$\dot{m}_{ign} = [K\ D_{ign} + C]\ \frac{29.2\ kJ/g}{HC} \quad (9)$$

Also, since Babrauskas' work was based on radiation effects, flame impingement was not considered and distances closer than 0.05m were excluded from the study.

Figure B.3 displays a family of curves for ignitability based upon the equations derived in this Appendix.

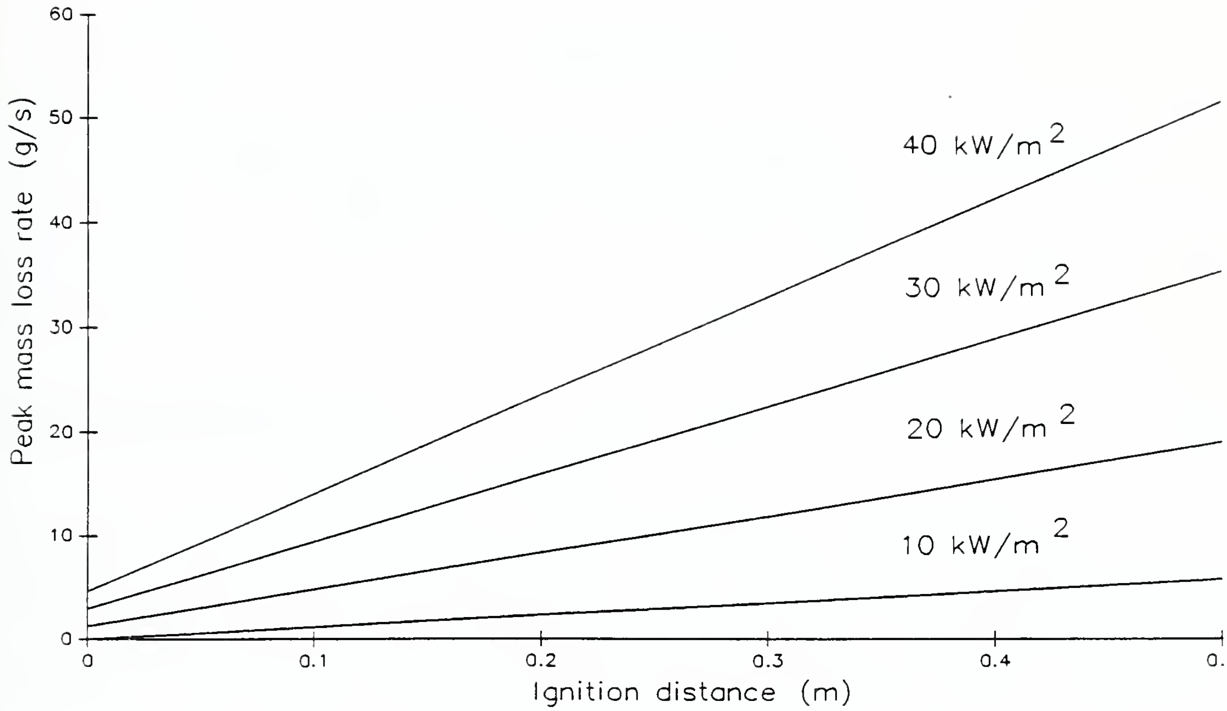

Figure B.3 - Relationship between ignition distance and peak mass loss rate at various ignitability values

The case of upholstered furniture is worked here as an example. If we know the ignitability (I_e) is 20 kW/m^2, we can use equation (5) to compute K

$$K = 37.9 + (I_e - 20)\ 3.28$$
$$K = 37.9 \text{ g/m - sec}$$

and since the I_e value is ≥ 12.9 kW/m^2, equation (7) can be used to compute C

$$C = 1.2 + (I_e - 20).17$$
$$C = 1.2 \text{ g/sec}$$

therefore, using equation (9) $\dot{m}_{ign} = [37.9\ D_{ign} + 1.2]\ \frac{29.2\ kJ/g}{HC}$

Now given any distance, D_{ign}, between the product and the item first ignited, the $\dot{m}_{ign}$ can be computed and used in the generation of the input fire for the FAST model.

Appendix C

Rules for Construction of Scenario Fires to Interface with the Hazard Method

C.1 Purpose and Background

HAZARD I requires that the heat of combustion and the time functions for mass loss rate or heat release rate of the fuel be defined and provided as input data. HAZARD I then takes this defined fire and uses the FAST model to compute the level of heat, smoke, and toxic products developed in the prescribed building as a function of time. This Appendix will describe the rules used to determine the inputs for the FAST portion of the HAZARD I model.

The scenarios used by the risk method are defined relative to a particular room in a particular type of building. Scenarios are also defined by the type of ignition (smoldering or flaming), by the first item ignited, and by the extent of flame spread.

Using HAZARD I, all fires in a particular room must follow one of the paths depicted in the event tree in Figure 2. The rationale for this structure is discussed in Section 5.4. All fires are modeled as if they reach flashover and pyrolyze the entire contents of the room. The rules in this Appendix specify how to compute the heat release rate curve need to run FAST from ignition until all the fuel is pyrolyzed in the room of origin. The risk software has been designed to interface with these fires, as they are run in FAST, and to derive the hazardous conditions which apply to a specific scenario when the extent of spread is less than beyond room of origin (flashover).

Products are evaluated both for fire scenarios which initiate with the product and for those fires which start with each of the nine classes (see Table 7) of first item ignited which eventually involve the product. For fires which initiate with the product, the rules specify when other items in the room become involved in order to reach flashover. For fires initiating with an item other than the product, the rules specify at which extent of spread the product is secondarily ignited, and when the rest of the room contents become involved.

C.2 Construction Rules

The terminology used in the discussion which follows is based upon Section 6 of the report. We will start with a known building and room configuration. To evaluate multiple buildings and multiple rooms within those buildings, it will be necessary to cycle through the process for constructing the heat release rate curves for each room in each building.

C.2.1 Definition of Terms

Each first item ignited will have a characteristic peak rate of heat release and a growth rate. RHR_x is used to refer to a peak rate of heat release value of the item x. RHR_{prod} is the peak heat release rate characteristic of the average version of the product involved in fire in the baseline case. RHR_{new} is the peak heat release rate for the new product being analyzed. Slope is the parameter value for the growth rate, giving the ratio of the rate of rise in the rate of heat release to time squared (t^2), as defined in Section 6.2. $Slope_{prod}$ is the slope for the average version of the product involved in fire in the baseline case. $Slope_{new}$ is the slope for the new product being analyzed.

RHR_{prod} is the characteristic peak rate of heat release for the baseline mix of products in use today and involved in fire. A crude estimate of this value might be the median of the peak rates of heat release of typical products in use or the actual peak rate of heat release of the dominant example(s) of the product. A more sophisticated estimate would require the following.

- A set of versions (numbered i) of the product representing all products now in use;
- Each version's share of all products in use (q_i), with the q_i values summing to one;
- Overall relative propensities to be ignited for each version (f_i); see Appendix A for the derivation of these values; and
- Each version's peak rate of heat release (RHR_i).

Then $$RHR_{prod} = \sum_i q_i \, f_i \, RHR_i \Big/ \sum_i q_i \, f_i . \qquad (2)$$

RHR_{nprod} and $Slope_{nprod}$ are the peak heat release rate and the growth rate, respectively, for a class of items, n, first ignited (other than the product), as illustrated for residences in Table 7. The RHR_{nprod} can take on one of the three heat release rate values (250, 500 or 1000 kW) indicated in Table 8. The Slope $_{nprod}$ can take on one of three t^2 growth rate curves - slow, which grows to 1055 kW in 600 sec; medium, which grows in 1055 kW in 300 sec; and fast, which growths to 1055 in 150 sec.

t_{FO} is the time when the FAST results indicate that the flashover criterion has been met; the upper layer temperature reaches 600 °C in the room of fire origin. t_{FO} is determined by entering the prescribed RHR value into the FAST model and noting when the upper layer temperature exceeds 600 °C.

$RHR_{smolder,\ x}$ is the rate of heat release value reached at the end of the smoldering phase of a fire that begins as a smoldering fire in an item x.

$t_{smold,\ flaming,\ x}$ is the time required for item x that was ignited in the smoldering phase to transition to the flaming phase. t_x is the time it takes an item to reach its peak heat release rate. If there is no initial smoldering phase, then

$$t_x = \sqrt{RHR_x / Slope_x}$$

If the item has an initial smoldering phase, then

$$t_x = t_{smold,\ flaming,\ x} + \sqrt{(RHR_x - RHR_{smolder,\ x})/Slope_x}$$

$\dot{m}$ is the mass loss rate at flashover as explained in section 5.4. At t_{FO} it is assumed that the fuel is pyrolyzed at this rate until it is exhausted.

t_{end} is the time when the fuel is exhausted at the end of the flashover phase of the fire. It is calculated for a particular room and fire scenario using the formula:

$$t_{end} = t_{FO} + \frac{(\text{room area} * \text{fuel load/unit area}) - \text{mass burned prior to } t_{FO}}{\dot{m}_{FO}}$$

$\dot{m}_{ign}$ is the mass loss rate of the item first ignited required to ignite the product (given the product's ignitability and separation distance from the item). Secondary ignition of the product is discussed in section 6 and the equations used to compute $\dot{m}_{ign}$ are described in Appendix B.

t_{ign} is the time when $\dot{m}_{ign}$ is reached, thereby igniting the product. t_{ign} is calculated based on the heat of combustion value (HC) input to FAST, the $\dot{m}_{ign}$ and the $Slope_{nprod}$:

$$t_{ign} = \left(\frac{\dot{m}_{ign}\ HC}{Slope_{nprod}} \right)^{1/2}$$

C.2.2 Logic for Construction of Heat Release Rate Curves

All fires are modeled as if they reach flashover and py olyze the entire contents of the room of origin. The criterion for flashover is an upper layer temperature of 600 °C. The shape of the heat release rate curve is defined using the following logic:

- The heat release rate curve for a single item burning has the functional form $Slope_x t^2$, where t is time from item ignition until the peak heat release rate is reached. The curve then declines linearly (in t) to zero, taking the same period of time to decline to zero that it took to reach the peak from zero.

- The heat release rate curve for the first item ignited is input to the FAST model to determine if 600 °C is achieved.

- If the temperature falls short of 600 °C, then other items must have been ignited to reach flashover. These other items are represented by one or two additional heat release rate curves which provide the energy to reach flashover.

- At flashover the high flux level in the room of origin is vaporizing material at all exposed surfaces and a fundamental change occurs in the fuel available to the combustion process. The fuel, represented by a constant mass loss rate ($\dot{m}_{FO}$), is determined for the specific room using the procedure outlined in section 5.4. This mass loss rate represents the pyrolysis process from flashover until the fuel is exhausted.

C.2.3 Product as First Item Ignited.

For fires in which the product was the first item ignited, Figure C.1 depicts the logical structure for defining the heat release rate curve up to flashover. Since the product is involved at each extent of spread, this curve corresponds to path 1 in Figure 2.

$$RHR = (Slope_{prod})\ t^2\ ,\ \text{for } 0 \le t \le t_{prod} \qquad (1)$$

$$RHR = 2RHR_{prod} - (\sqrt{RHR_{prod}\ Slope_{prod}})t,\ \text{for } t_{prod} \le t \le 2t_{prod} \qquad (2)$$

The product's heat release rate curve is input to FAST to determine if the flashover criterion is met. If 600 °C is reached the time, t_{FO}, is noted and FAST is rerun using equations (1) and (2) up to t_{FO}. At t_{FO} the room specific mass loss rate at flashover (m_{FO}) is used until the fuel is exhausted at t_{end}.

If 600 °C is not reached, than other items must have been ignited. At the time t_{prod}, when the RHR_{prod} is reached, another curve is added with the following functional form:

$$RHR = (Slope_{med})\ t^2\ ,\ \text{for}\ t_{prod} \leq t \leq t_{FO} \qquad (3)$$

Now, the combined heat release rate curves for the product and the other items are input to FAST, and the time t_{FO}, when 600 °C is reached, is noted. FAST is run again with the combined curves used until t_{FO}. At t_{FO} the mass loss rate $\dot{m}_{FO}$ is used until t_{end}.

C.2.4 Item First Ignited Not the Product

For fires in which the product is not the first item ignited Figure C.2 depicts the logical structure for determining: the heat release rate curve, the time when the product becomes ignited, and if additional items were required to reach flashover. The RHR curve initiates with the item first ignited.

$$RHR = (Slope_{nprod})\ t^2\ ,\ \text{for}\ 0 \leq t \leq t_{nprod} \qquad (4)$$

$$RHR = 2RHR_{nprod} - (\sqrt{RHR_{nprod}\ Slope_{nprod}})\ t, \quad \text{for}\ t_{nprod} \leq t \leq 2\ t_{nprod} \qquad (5)$$

Depending on the separation distance and the product's ignitability, the product will become involved at different stages in the fire's growth (extent of spread). Comparison of t_{ign} with the time when each of the extent of spread criterion (upper layer temperature in the room of origin) are met enables mapping the fire to one of the paths 2-4 on the event tree shown in Figure 2. If the product ignites before the temperature criteria for extent of spread confined to area (200 °C), the fire follows path 2 on the event tree. If the product ignites after 200 °C but before the room temperature criterion (450 °C), the fire follows path 3. And finally, if the product ignites after 450 °C is reached it is assumed to be involved only at flashover, which corresponds to path 4 on the event tree.

Initial computations are made to determine the $\dot{m}_{ign}$ and the corresponding t_{ign}. These computations use information which is specific to the room, the item first ignited and the product. The next step involves inputting the heat release rate curve and running FAST. Results from FAST are used to compare t_{ign} with the time each of the extent of spread criteria are met and to determine if the combined heat release rate curves for the item first ignited and the product have sufficient energy to reach flashover.

The heat release rate curve initiates with the item first ignited (equations 4 and 5). When the product ignites (t_{ign}), its heat release rate curve (equations 6 and 7) is added.

$$RHR = (Slope_{prod})\ (t - t_{ign})^2, \quad \text{for } t_{ign} \le t \le t_{ign} + t_{prod} \qquad (6)$$

$$RHR = 2\ RHR_{prod} - (\sqrt{RHR_{prod}\ Slope_{prod}})\ t, \qquad (7)$$

$$\text{for } t_{ign} + t_{prod} \le t \le t_{ign} + 2\ t_{prod}$$

If the FAST results indicate that the combined curves yield an upper layer temperature of 600 °C, then this time (t_{FO}) is noted. Under these circumstances, a final FAST run is made using equations 4, 5, 6 and 7 until t_{FO} at which time $\dot{m}_{FO}$ is used until t_{end}.

If, on the other hand, 600 °C is not reached a third curve (equation 8) is added to represent additional items contributing to the heat build up.

$$RHR = Slope_{med}\ (t - t_{ign} - t_{prod})^2, \quad \text{for } t_{ign} + t_{prod} \le t \le t_{FO} \qquad (8)$$

FAST is run once again to determine the time (t_{FO}) when 600 °C is reached. FAST is run for a third and final time, using equations 4-8 up to t_{FO}, and using $\dot{m}_{FO}$ from t_{fo} until t_{end}.

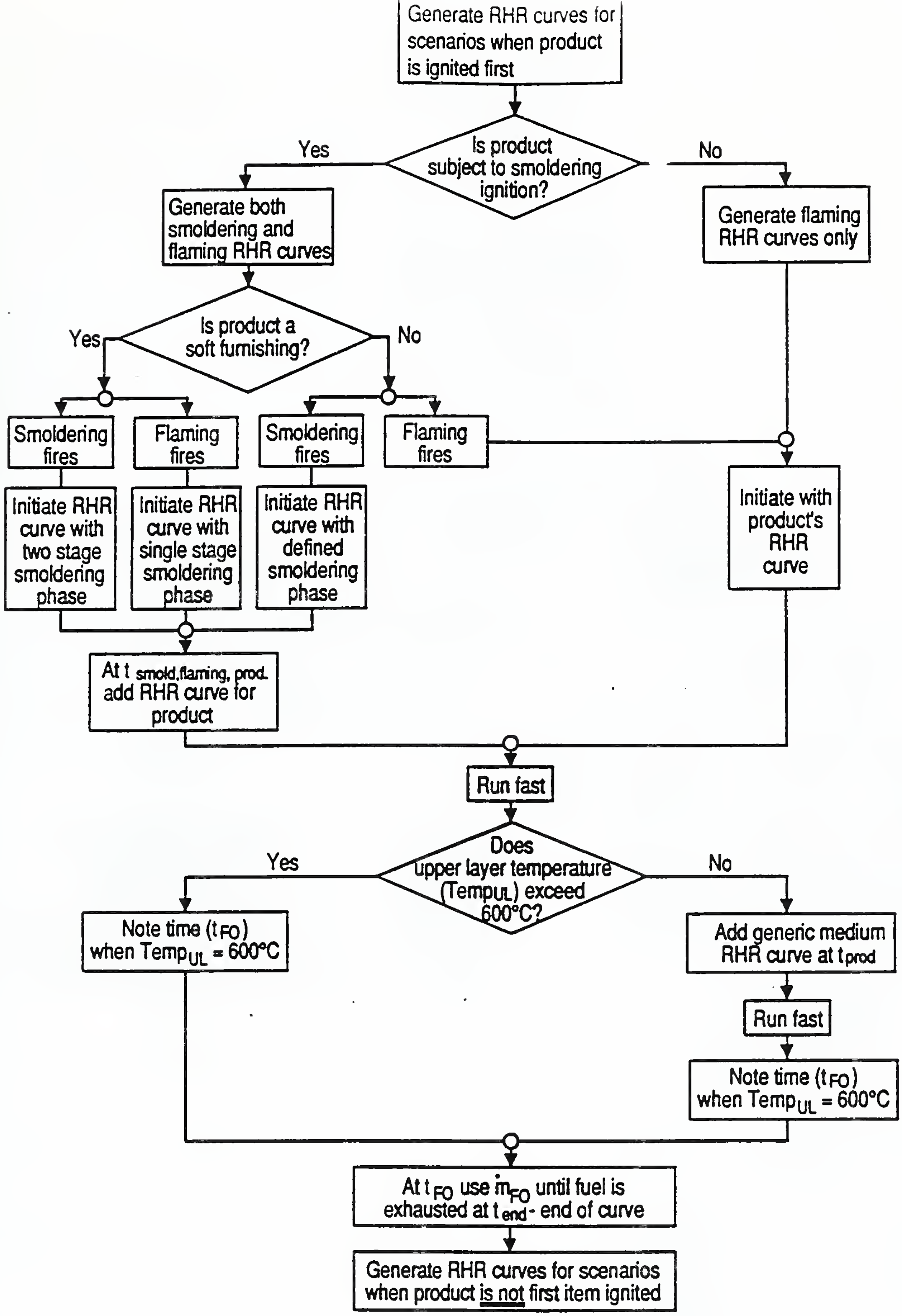

Figure C.1 - Procedure for generating heat release rate curves for scenarios where the product is ignited first.

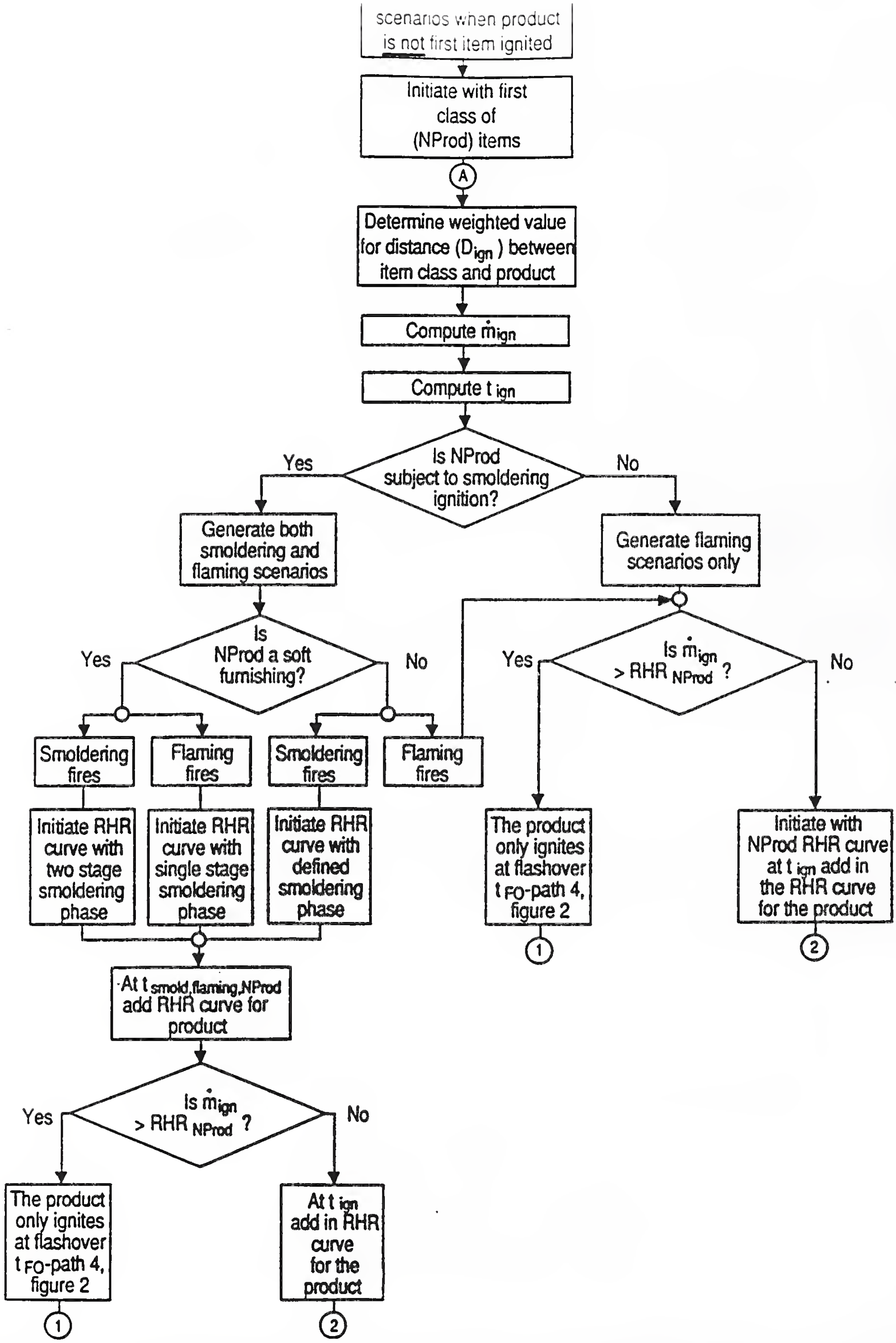

Figure C.2 - Procedure for generating heat release rate curves for scenarios where the product is not ignited first.

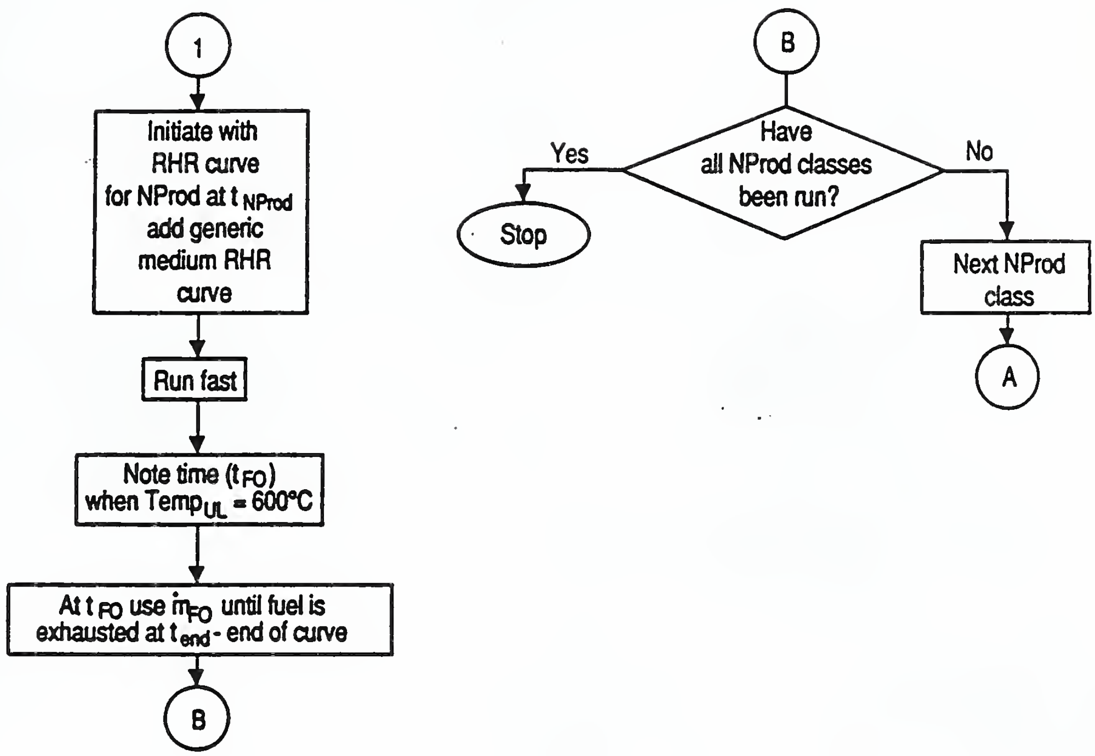

Figure C.2 (continued)

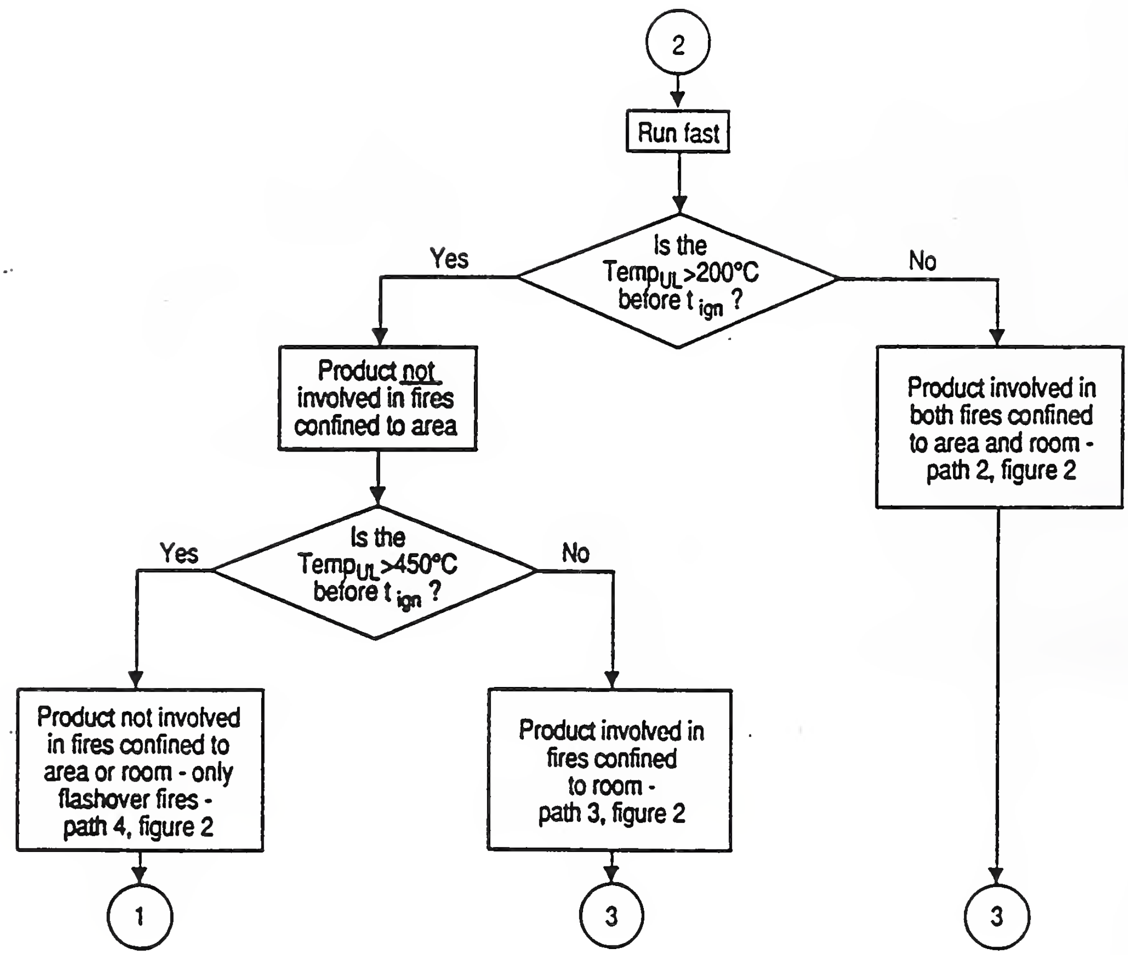

Figure C.2 (continued)

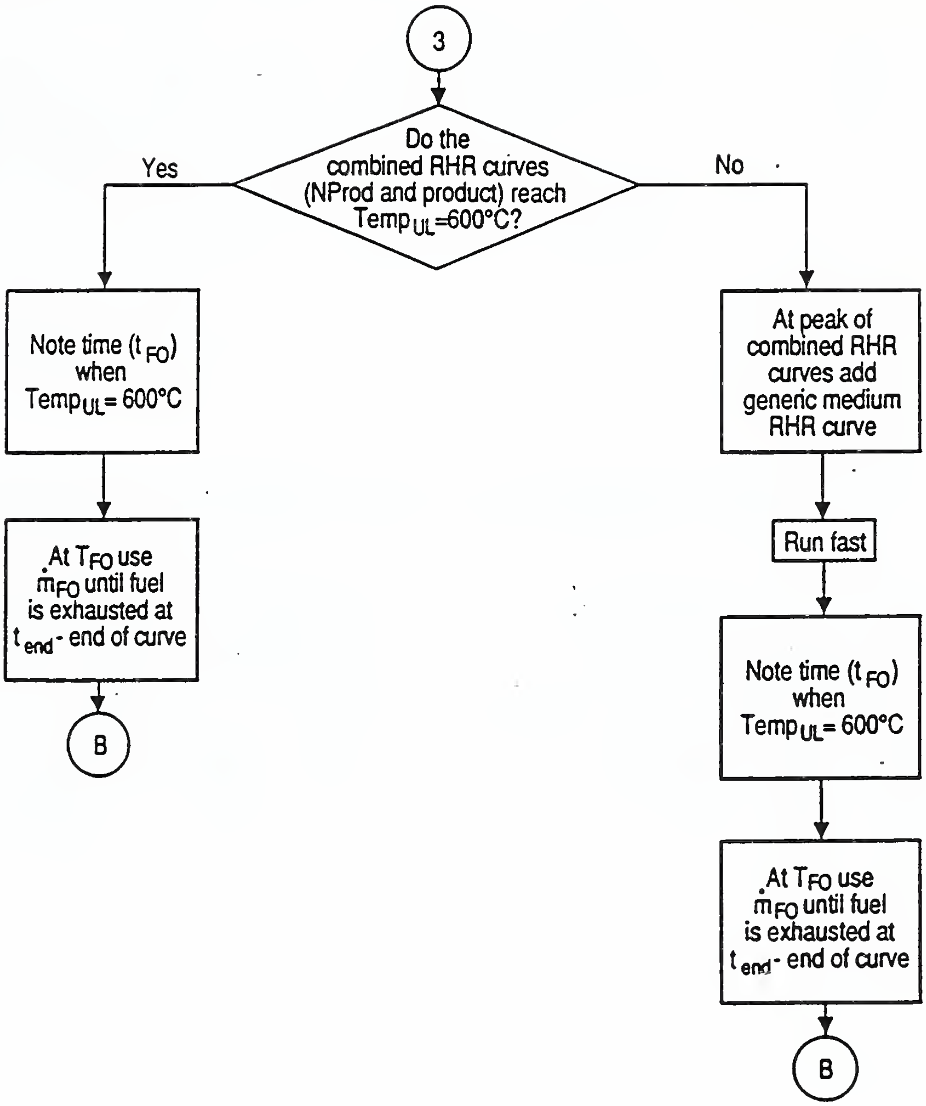

Figure C.2 (continued)

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[ ] 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.)

Traditional methods of assessing fire risk are based on probabilistic treatment of fire incident data. Recent advances in the ability to make deterministic predictions of the consequences of specific fire scenarios, presents an opportunity to reduce this dependency on incident data and greatly improve the ability to assess the risk associated with new products for which such data do not exist. This paper presents a risk assessment method developed for such a purpose, and provides the essential documentation for the methodology to be understood and applied by others. There are also four associated reports detailing trial applications of the methodology to specific products in specified occupancies.

12. KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)

computer models; fire statistics; hazard assessment; ignitability; probability; risk assessment

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