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FIRE RISK ASSESSMENT METHOD: CASE STUDY 3, CONCEALED COMBUSTIBLES IN HOTELS

S. W. Stiefel
R. W. Bukowski
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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FIRE RISK ASSESSMENT METHOD CASE STUDY 3: CONCEALED COMBUSTIBLES IN HOTELS

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1. Introduction

1.1 Purpose of this Report

This report describes results from a test case application of a recently developed, generally applicable method for the assessment of life safety fire risk associated with new and existing products. As part of this effort, the method was applied to several test cases, resulting in modifications to the method followed by limited reapplication to the cases. The methodology report [1] should be read prior to reading this and other case studies, both for a full rendition of the method and a clear understanding of terms.

To describe fire risk and the fire risk assessment process, it is necessary to define some terms [2].

- *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 NFPA 901, *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.

Described in this report are the procedures used to exercise the fire risk assessment method for the third developmental case: fires involving concealed combustibles (further specified as wire and cable insulation within wall and floor-ceiling void spaces) in hotels. Numerical results are also provided. This case study provided a "test bed" for application of the method using available and expert judgment in place of in-depth studies. Therefore, the descriptions and results presented should not be viewed as definitive, but rather as demonstrating the technique.

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 The NFPRF Risk Assessment Method Approach

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) [3]. 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 being studied. As a consequence of the current state-of-the-art of fire science, the fire risk assessment methodology is constrained to predicting death and not injury to exposed occupants, nor does it consider property damage.

While a more complete explanation of this process can be found in the documentation of the methodology, the step-by-step approach employed in each of the case studies, follows. The first five steps establish the structure and set-up the method for the life safety risk assessment performed in the last three steps.

1. Select the product and occupancy pair.
2. Identify and specify the physical characteristics of the building(s) representing the occupancy.
3. Develop a scenario structure with associated probabilities which uses a set of scenario classes drawn from the universe of all possible fires.
4. Adapt the fire model to fit the needs of the product and occupancy pair.
5. Specify occupant sets (groupings of people) at risk, their associated probabilities and relevant tenability criteria to judge survivability to toxic and thermal hazard.
6. Perform the risk calculation for the base case (status quo) and compare the results (deaths/fire and predicted deaths) by scenario with the expected results derived from the national fire database.
7. Perform the risk calculation for a "new" product case and compare the results with the results for the base case to obtain the impact on life safety risk.
8. Interpret the outcome.

1.3 Scope of this Case

Concealed combustibles in hotels were selected as the third product/occupancy pair to be analyzed using the prototype risk assessment method. Considerable controversy surrounds questions of the risk posed by combustible materials located within wall and ceiling spaces of buildings. One side argues that these materials represent a concentrated fuel load located in a space from which combustion products can spread through unseen and unplanned passages. The other side counters that ignition sources within the concealed spaces are rare, and the material is protected from exposure to the effects of room fires by finish materials which are often part of a fire-rated assembly.

With respect to the objective of challenging the prototype risk method, concealed combustibles in hotels presents several benefits. First, like the dwelling furniture case (case 1), the statistics show that there are fatalities from fires beginning with the product and spreading to the product in hotels. Thus unlike the office carpet case (case 2), there is non-zero fire fatality experience against which we can calibrate the risk prediction.

Second, as in the carpet case, modeling a fire in a confined space like a stud cavity within a wall involved an additional computational challenge to the HAZARD I fire model, FAST. When the case was selected, the FAST model could not automatically account for the effect of reduced oxygen on the combustion process. While this was not an unsurmountable problem in the first two cases, the very limited volume of the concealed space leads to rapid vitiation with an attendant reduction in burning rate and production of unburned fuel. Thus, this modeling limitation had to be addressed in order to properly handle this case.

Third was the new challenge to the evacuation modeling approach. In the first case the method had to deal with family groups of five or fewer persons, awake or asleep, who exhibited a significant degree of interaction. The second case involved a large group of always awake persons who did not interact at all. Hotels are mixed occupancies with the potential for both. In the guest room area we find individuals or small groups who again might be asleep, but with little interaction. Additionally, there are function rooms (e.g., ballrooms, meeting rooms, or other "assembly occupancies") in which you find persons like the office occupants. Thus, we need to combine the two evacuation modeling approaches in some way.

This combination of national fire experience data showing relevant fire fatalities, the opportunity to make additional enhancements to the fire and evacuation models, and the strong interest in questions of the risk of concealed combustibles, made this a good choice to extend the fire risk assessment methodology relative to the first two cases.

2. Description of Method Implementation - Set Up for Concealed Combustibles in Hotels

2.1 Selection of Product Characteristics

In the first step, we need to define concealed combustibles in terms of NFPA 901 categories. In examining the incident data categories of form of material first ignited and type of material first ignited, we find that there are three major "products" identified. These are wooden structural members or components (form of material category 17 with type of material categories 63 or 65), thermal insulation (category 18 with type categories 86 and 67) and electrical insulation (category 61 with type 40-49). Since these represent three distinctly different products, we needed to focus on only one for this case. We chose wire and cable insulation (henceforth referred to simply as cable) because of past concerns about the potential hazards of PVC and PTFE insulation and prior calculations thereon [4].

Once we settled on the product, we needed to characterize the population of cable now in use in terms of fire properties, type, and location within the target occupancy. We establish in this step the coding link between the national fire experience data and the cable as it is coded in the NFPA 901 codes under form of material first ignited. We will use statistics derived for cable using this coding to determine the frequency of fire scenarios involving cable and to validate the method's fire severity predictions in terms of deaths per fire. We will also specify a set of fire properties representing current cable in hotels.

We contacted the American Hotel and Motel Association (AHMA) to determine what information they could supply. This contact was quite fruitful in that they had detailed information on typical room contents, services, occupancy rates, occupant characteristics, and building (construction) characteristics, many by class of property (which they classify as economy, first-class, or resort) or by size (number of guest rooms). The data obtained here will be presented throughout this report in the sections to which it applies.

It is important to note that the characteristics assumed were those for typical, code-complying hotels, whereas the fire statistics show that fires - particularly fatal fires - are disproportionately found in older buildings that do not comply with current codes and may not even comply with the codes in force when they were built. As in Case 1, there is little opportunity to develop data to compensate for these deviations from typical practices occurring in hotels that have fires, because the same level of detail is not available on them. Nevertheless, the point should be kept in mind when considering these cases.

With respect to the cable properties, an AHMA supplied article [5] states that the typical electrical requirement per guest room is 18 to 22 amperes, implying a single (#12 AWG) circuit. For any hotel taller than 3 stories the codes would require non-combustible construction and this circuit would be in tubular metal conduit or armored cable. With 3 or fewer stories, combustible construction is allowed, and the cable would generally be non-metallic sheathed cable (NMSC). In order to be able to deal directly with the burning behavior of the cable, and since most questions of the safety of cable as a fuel relates to NMSC, we chose to restrict the analysis to 2 or 3 story hotels with 2 parallel runs (one per room) in the common wall between two guest rooms. This is not a bad assumption since the AHMA data showed that 73.4% of the nearly 45,000 hotels of their members have fewer than 75 rooms [6].

Previously, we discussed the fact that hotels represent a mixed occupancy with both residential and assembly areas. To represent the latter, we considered function areas (ballrooms and meeting rooms) as another class of scenarios for the case study. Here, the rooms are larger and the wiring is normally above a suspended ceiling. This wiring generally serves several types of lighting fixtures with multiple controls - resulting in significantly more cable. So for these scenarios we assumed a total of 300 feet of NMSC cable in the ceiling space above the room.

From tests of NMSC conducted in the Cone Calorimeter [7] and the Lateral Ignition and Flamespread Test Apparatus [8], the burning characteristics of such cable were obtained for the guest room and function room fires. Table 1 presents the assumed, "base case" properties for all cable currently installed in these locations. The risk associated with a more flammable cable will be examined for the "new product" case (see Section 4).

Table 1 - Flammability Properties of Existing (Base Case) Cable

	Stud cavity within wall	Void space above ceiling
Quantity of Cable	4 pieces, 15 inches long	6 pieces, 50 feet long
Peak Rate of Heat Release (RHR) per unit surface area	250 kW/m^2	250 kW/m^2
Rate of Rise in RHR (flame spread rate)	1 kW/s (1 in/s)	1kW/s (1 in/s)
Toxic Potency (Ct)	900 $g\text{-}min/m^3$	900 $g\text{-}min/m^3$

In the case of power cable in void spaces, we assumed that for fires originating within the space, the cable would generally be involved early in the fire, so we treated it as the first item ignited. However, the limited fuel load in the void (particularly in a stud cavity) limits the impact of such a fire unless it spreads to the adjoining space. So this will be the first class of fire spread scenarios considered, and it does not involve radiative transfer or separation distances.

The other class of relevant scenarios would involve fires originating in adjoining spaces that spread into the void space and involve the cable. These typically occur in flashover fires when the protective membrane (the gypsum board or ceiling tile) fails. This is the other class of fire spread scenarios to be considered in this case, and it too does not involve radiative spread. This eliminates the need for the procedure used in Case 1 for calculating a distribution of separation distances.

In summarizing this first step in the method, we have:

- used national fire experience to identify cable as a major concealed combustible in hotel fires,
- estimated fire properties for typical cable, and
- identified two classes of fire spread scenarios appropriate to cable in void spaces.

2.2 Identify and Specify the Physical Characteristics of the Hotel

In the second step, we will describe one or more representative buildings in the terms necessary to run the hazard model. This consists of a geometric configuration, physical arrangement of the rooms, and the materials of construction needed to run the hazard model. We also specify for the building the "areas of origin" - rooms where fires start, and any fire safety features provided in the design. To do this, we used data from the U.S. Census and from the American Hotel and Motel Association (AHMA).

We must match the building specification with the level of detail required by the hazard model, HAZARD I. The rate of development of the fire depends on the size of the room in which the fire starts, the thermal properties of the walls and ceilings, the fire load in the room, connections to and total volume of other rooms, and openings to the outside. After a review of two articles supplied by AHMA [5,9] on hotel design and discussion with representatives of several large chains, the technical team agreed upon the two building layouts presented in Table 2 and figures 1 and 2.

Table 2. Hotel Building Characteristics

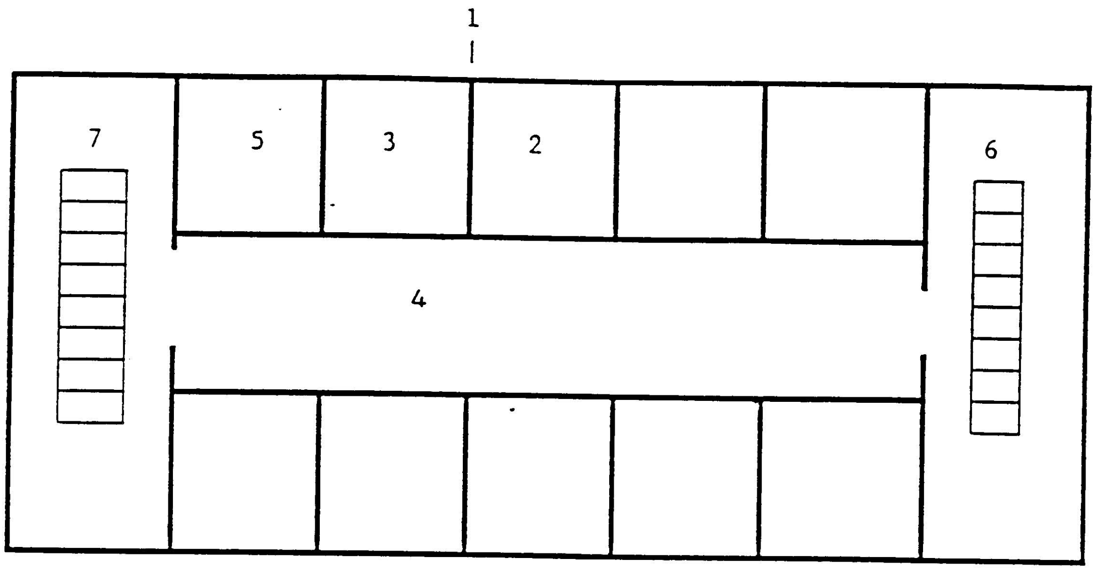
Guest Room Dimensions	13' x 25 'x 8'
Function Room Dimensions	26' x 25' x 8'
Corridor Dimensions	8' x 8' x 100'
Stairwells	13' x 7' x 16'
Doors	3' x 6' 8"
Stud cavity (in common wall between rooms)	14 5/8" x 3 3/8" x 100"
Ceiling void (above function rooms)	52' x 25' x 1'
Wall construction	5/8" gypsum on 2 x 4 wood studs, 16" OC
Floor construction	6" concrete slab
Ceiling construction	5/8" mineral tile, suspended ceiling

The building itself is a two or three story, protected combustible construction with double-loaded interior corridors, divided into 100 foot sections by stairwells. Both open stairways (which would only be allowed connecting two floors) and enclosed stairways were considered. The function rooms were always on the first floor, with guest rooms above. Guest rooms could have either guest rooms or function rooms below. Floorplan drawings of the room layouts, with the room numbers from the FAST runs, are shown in Figures 1 and 2. Note that the stud cavity is modeled as a room (#1 on figure 1) and that the ceiling space extends over two function rooms (#1 on figure 2).

The articles supplied by AHMA [5,9] contain considerable data on typical contents of guest rooms in economy, first-class, and resort properties. From these data, the technical team "furnished" the guest and function rooms as follows:

Table 3 - Potential fuel items other than the product

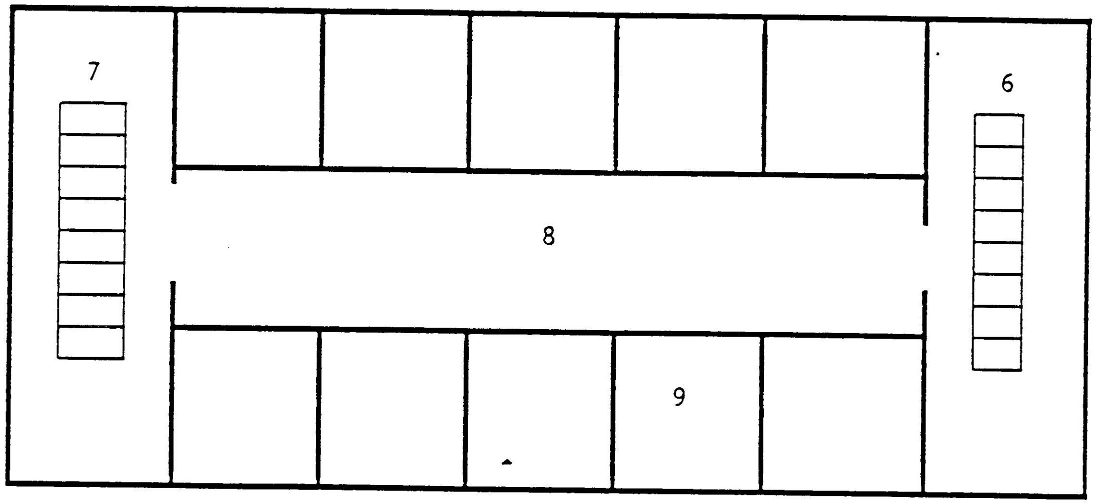
Guest Room	Wall	Function Room	Ceiling
2 beds (54"x80")	#22/4 phone cable	4 tables (3'x6')	2x10 wood joists
headboards	R59U TV coax cable	12 stacking chairs	3/4" plywood
dresser	2x4 wood studs	carpet	duct insulation
night tables			
desk and chair			
2 lounge chairs			
luggage			
carpet			



FIRST FLOOR

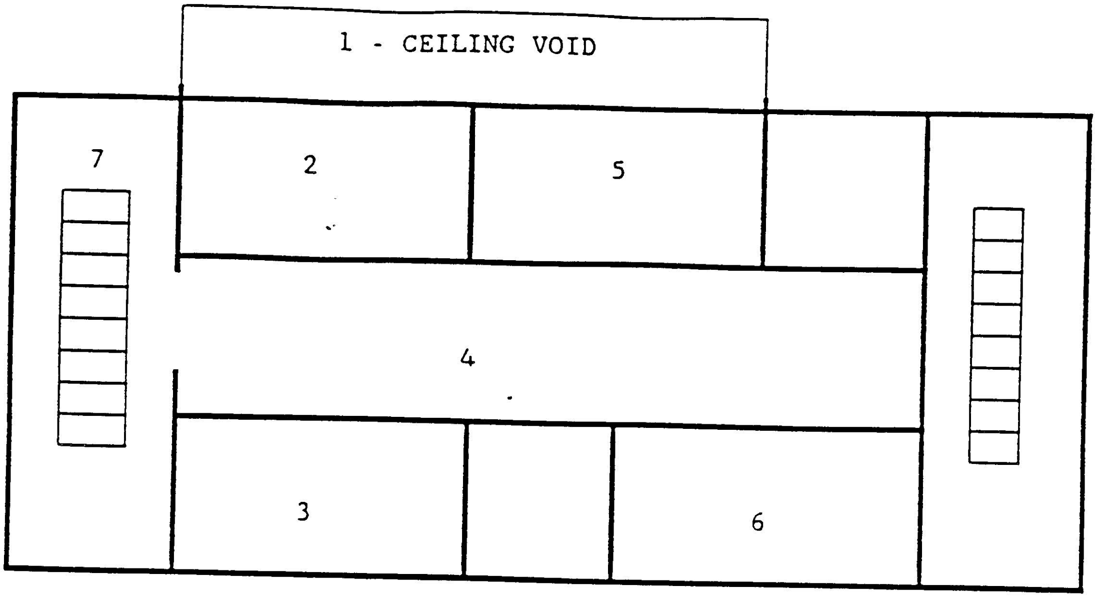
Room Dimensions - 13' x 25' x 8'
Corridors - 8' x 100' x 8'
Wall Space - 14 5/8" x 3 3/8" x 100"

Stairs - 13' x 7' x 16'
Doors - 3' x 6' 8" (1/16" crack)



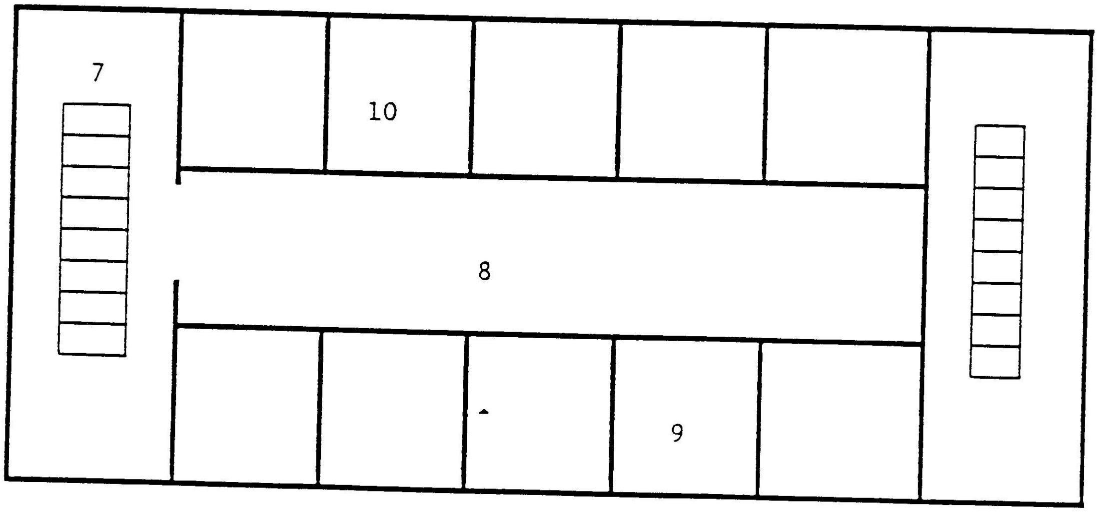
SECOND FLOOR

Figure 1 - Floorplan and room assignments for guest room fires



FIRST FLOOR

Conference Room Dimensions - 26' x 25' x 8'   Doors - 3' x 6'8"
Guest Room Dimensions - 13' x 25' x 8'   Doors - 3' x 6'8"
Stair Dimensions - 13' x 7' x 16'   all Doors w/ 1/16" crack
Corridor Dimensions - 8' x 100' x 8'
Ceiling Space Dimensions - 52' x 25' x 1'



SECOND FLOOR

Figure 2 - Floorplan and room assignments for function room fires

These contents items serve as the fuel load of the associated spaces, which are used with the assignments in Table 4 to specify burning rates whenever fires involve those spaces. Fires involving concealed spaces can originate there or originate in adjacent (occupied) spaces and spread there. The reader can see the frequency and probability data for these scenario groupings in the related Appendix in the main project report [1].

Summarizing step two, we have:

- specified two floorplans to be used in representing hotel fires originating in either guest rooms or function rooms.

- specified number, size, and construction of each room, corridor, and stairs, and

- identified the structure of the total fuel package for potential areas of origin.

2.3 Development of the Scenario Structure and Calculation of Scenario Probabilities

In the third step we develop the organizational structure for reducing the universe of all possible fire scenarios to a representative set, which the risk assessment method uses to assess life safety impact. We define a fire scenario in terms of a set of descriptors for the:

1. building where a fire occurs,
2. rooms for area of origin where fire originates,
3. burning characteristics of the item first ignited (growth rate and peak rate of heat release),
4. heat source igniting the first item (open flame or smoldering),
5. final size of the fire, measured as the extent of flame damage (confined to the object, area or room of origin or extended beyond the room of origin), and
6. extent of fire growth at the time when the cable contributes to the fire, for those fires originating with items other than cable.

These descriptors are tied into the NFPA 901 categories, so that we can estimate the probability of occurrence for each scenario using the national fire data base. The descriptors are also associated with a set of physical parameters, which we use in the modeling to assess the development of fire hazard within the building.

The first five items on the scenario structure list are data elements in the national fire database, collected using the NFPA 901 code. For the sixth item, secondary involvement, we will devise a special procedure which accounts for the cable's fire properties and its contribution to the fire after failure of the separation between the fire space and the void space.

In step 2, we selected the representative hotel buildings and "areas of origin." Our treatment of the last four scenario descriptors is explained in the remainder of this Section.

2.3.1 Burning Characteristics of the Item First Ignited

To compute risk for any product it is necessary to account both for fires initiating with the product and fires initiating with everything else, which could eventually involve the product. We assumed that fires always or quickly spreads to the product when the fire originates in the void space and, by definition start in something else when the fire originates outside the concealed space. Therefore, the former class of scenarios may be treated as primary ignitions and the second are all secondary ignitions.

The fire incident data specify only which items were first ignited. When hotel cable is not the first item ignited we need to model the burning behavior of what was first ignited. The risk method does this by assigning all combustible items identified in the incident data to one of nine burning characteristic classes. The classes are described by their rate of rise in rate of heat release (fast, medium, or slow) and by their peak rate of heat release (low, medium, or high). As an example, Table 4 indicates the item classes for dwellings with the items in each class identified using their NFPA 901 standard code. Since three classes had no items identified, the original nine classes reduce to six. The bases for the assignments made to the growth rate and peak heat release rate burning classification in the Table were either full-scale tests of an item of the same general description or small scale test (cone calorimeter) data on a sample of material of a type from which the item might be made. The documentation for these assignments can be found in Tables 5 and 6.

The numbers in brackets refer to the 901 codes for <u>form of material ignited</u>. Where wood (or natural) and plastic (or synthetic) are differentiated, these would be apportioned on the basis of the <u>type of material ignited</u> category.

Looking at Table 4, we see that all of the NFIRS first item ignited codes for residences correspond to items normally found in hotels. While some differences would be expected between residential and commercial items in these classes, the class assignments are broad enough that they were felt to be appropriate. These fire growth rate curves are identical to the assignments made of the burning rates of unspecified items by the NFPA Technical Committees on Detection Devices and Automatic Sprinklers [10]. These fire growth rate (of heat release) curves are represented as a curve proportional to time squared, where the curve is defined by the time required for it to reach a particular heat release rate value. The three growth rate curves used are:

- slow - which grows to 1055 kilowatts (1000 Btu/sec) in 600 seconds,
- medium - which grows to 1055 kilowatts in 300 seconds, and
- fast - which grows to 1055 kilowatts in 150 seconds.

The three peak heat release rate values are:

- low energy emitters - 250 kilowatts,
- medium energy emitters - 500 kilowatts, and
- high energy emitters - 1000 kilowatts (not used in this case).

Table 4 - 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 codes (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.

Table 5 - Tests of Actual Items

ITEM DESCRIPTION	NFIRS	REFERENCE
WOOD CABINETRY (plywood)	[23]	NBSIR 83-2787 (Fig 112,113)
WOOD CABINETRY (purchased)	[23]	NBSIR 83-2787 (Fig 126) and NBSIR 82-2469 (Fig 7)
PLASTIC APPLIANCE HOUSING		
(calculator)	[25]	unpublished data
(TV cabinet)	[25]	unpublished data
WOOD APPLIANCE HOUSING	[25]	unpublished data
MATTRESS (purchased, residential type	[31]	NBSIR 83-2789 (Fig 79)
PILLOW (purchased)	[31]	NBS MONOGRAPH 173 (Fig 20)
WEARING APPAREL (clothes on hangers)	[34]	NBSIR 82-2469 (Fig 8,9)
(metal wardrobe contents)	[34]	NBSIR 83-2787 (Fig 84)
BOOKS and MAGAZINES (box of files)	[43,44]	NBSIR 82-2469 (Fig 7)
BOX (container of paper trash)	[51]	NBSIR 85-3195 (Fig 8)
PACKAGING (trash fire)	[55]	NBSIR 85-3195 (Fig 12)
ELECTRIC CABLES (cables in a tray)	[61]	NBSIR 85-3195 (Fig 4,5,6)
FLAMMABLE LIQUID SPILL (fuel oil spill)	[62]	NBSIR 85-3195 (Fig 19)
COOKING MATERIAL (12" pan of cook. oil)	[67]	NBSIR 87-3604 (CKG001)
CURTAINS (cotton)	[36]	NBSIR 87-3604 (CUR001)

NOTE: Unpublished data are USFA tests of fuel pkgs. for QRS performance tests.

Table 6 - Small Scale Test Data

PLASTIC NON-UPH. FURNITURE	[22]	RIGID POLYURETHANE (RPU001)
WOOD NON-UPH. FURNITURE	[22]	PINE BOARD (PIN002)
PLASTIC CABINETRY	[23]	RIGID POLYURETHANE (RPU001)
IRONING BOARD	[24]	PINE BOARD (PIN002)
FABRIC AND YARDGOODS (synthetic)	[37]	RAYON (RYN001)
(natural)	[37]	COTTON (CTN002)
LUGGAGE	[38]	RIGID POLYURETHANE (RPU001)
DECORATIONS (synthetic)	[42]	ACRYLIC (MMA001)
(natural)	[42]	PINE (PIN002)

NOTE: All of these data are taken in the cone calorimeter and reported in NBSIR 87-3604. Small-scale data are reported on a per-unit-area (burning) basis. Thus, to arrive at a slope, a maximum rate of spread across the surface must be assumed. Likewise, a peak burning rate requires the assumption of a maximum surface area involved. The assumed mass of he item would relate to the total burn time.

In all cases, the peak energy release rate was limited to be consistent with the available ventilation, all of which entered through the two stairway doors at either end of the floor. After an item has reached its peak heat release rate it is assumed that the rate of heat release declines according to a *linear* curve that requires the same time to decline to zero as was required to reach the peak rate from zero. This approach was selected for simplicity in using HAZARD I. Based on the actual rate of heat release curves in reference [11], this is not expected to represent a significant source of error in the hazard calculation.

The last material property required by the hazard model is the production rate of smoke. This parameter results in the optical density which affects the occupants' speed of movement and potentially whether their egress path is blocked requiring an alternate path selection. Here, a review of the data shows that there is a distinct clustering of yield fractions for natural materials (cotton and wood) and synthetics (nylons and polyurethanes) about values of 0.003 and 0.03 respectively.

2.3.2 Heat Source Igniting the first Item

For fires originating in the cable, the ignition mechanism was assumed to be an electrical overload resulting in flaming combustion of the cable insulation. For fires originating in adjacent spaces, cable involvement did not occur until the separating barrier failed, after flashover. This group of fires was represented by a flaming ignition of the mattress on one of the beds for the guest room scenarios, or the ignition of a stack of chairs in the function room scenarios. Thus, for this case only flaming fire scenarios were modeled.

2.3.3 Final Extent of Fire Growth

The characterization of fire growth (final size of the flame spread) in NFPA 901 data used the following classes:

1. Confined to object of origin

2. Confined to area of origin but beyond object

3. Confined to room of origin but beyond area

4. Extended beyond room of origin (flashover)

While these classes are *subjectively* assessed by the fire officers collecting the data, we assigned to each of the classes a *specific* measure of peak severity to be used in the physical modeling. The measure is peak upper level temperature.

Extent of Flame Damage	Peak Upper Level Temperature
Confined to object of origin	100 °C
Confined to area of origin	200 °C
Confined to room of origin	450 °C
Extended beyond room of origin	>600 °C

These values were subjectively assigned without any direct scientific basis. They are, however, consistent with the concept that fire spread on or to an object is driven by radiant energy from its surroundings (flames and hot gases and room surfaces) which heat the surface and increase the volatilization rate. The higher the upper layer temperature, the higher the imposed flux and the more objects ignite and burn, thereby spreading the fire. Also remember that in this case, the "room of origin" can refer to the stud space or ceiling void.

2.3.4 Fire Spread Beyond the Space of Origin

A feature of this case unlike any of the others is the need to deal with the spread of fire beyond the space of origin. This occurs because the space of origin is not a room as classified in NFPA 901. Thus, we needed to create a means of handling spread to or from the concealed space.

The cable (along with other combustibles in the room) is assumed to become involved always in fires classified as spreading beyond the room of origin (because we assume that these all go to flashover). For fires starting in the guest room, spread to the cable assumes failure of the gypsum board on the wall, usually associated with the fasteners heating up and pulling out of the studs. When the guest room fire originates in the stud space, spread occurs when the oxygen in the stud space decreases such that unburned fuel exits around a power outlet, producing a small flame which ignites the mattress. Thus, all fires which spread to the room are represented by the mattress fire.

For the function room fires, we assume failure of the suspended ceiling is the source of spread to or from the ceiling void. Here, we considered three possible mechanisms:

1. The wires supporting the ceiling grid heat to failure. The estimated failure temperature is 550 °C.

2. Cellulosic ceiling tiles might ignite on the back side due to arcing associated with an electrical short in the cable or burn out due to a large room fire.

3. The metal grid supporting the ceiling expands from the heat, buckles and sags, causing tiles to drop out and the ceiling to collapse.

If the fire originates in the ceiling void, we assume that the ceiling collapses when the temperature in the void space reaches 550 °C. Where the fire starts in the function room, ceiling collapse occurs at room flashover.

2.3.5. Calculation of Scenario Probabilities

Baseline probabilities were derived directly from the national fire incident database. The general procedure followed is that described in the methodology report and illustrated in section 2.3.5 of the first two case reports. However, since this case involves fire spread beyond the space of origin, a logic for determining when and if this spread occurred was developed and is presented below:

1. If the fire began in a concealed ceiling or wall space (area of origin 73-75) and was coded as confined to *object* of origin, then it stayed in that space and involved the product (cable) only if the product was the first item ignited.

2. If the fire began in a concealed ceiling or wall space and was coded as confined to the *area* of origin, then it stayed in that space and involved the product, whether or not the product was the first item ignited.

3. If the fire began in a concealed ceiling space (area of origin 73-74) and was coded as confined to *room* of origin, then it stayed in that space and involved the product, whether or not the product was the first item ignited.

4. If the fire began in a concealed wall space (area of origin 75) and was coded as confined to *room* of origin, then it spread to the adjacent room. In that adjacent room, its ultimate size may have been confined to *object, area, or room* with probabilities of each given by the overall probabilities of being confined to object, area, or room for a fire that began in the room and not in the concealed space.

5. If the fire began in a concealed ceiling or wall space and was coded as *extended beyond room of origin*, then we assumed it spread to an adjacent room. Its final extent of spread may have been *confined to room* or *extended beyond room.* The probabilities of these two extents are given by the overall probabilities of being confined to room or extending beyond room.

6. If the fire began in a room that is not a concealed ceiling or wall space, then the fire entered the concealed spaces and involved the product **if and only if** the fire extended *beyond the room of origin* (i.e., reached flashover).

7. If the fire began on the building exterior or in an adjacent outdoor area, it was ignored for this case.

8. Since fires originating outside concealed spaces are assumed to involve the concealed combustibles only if the fire extends beyond the room, then it is further assumed that the calculations would be relatively insensitive to the presence or length of a smoldering phase at the start of the fire or to the speed of fire growth at the outset. Therefore, such details have been ignored for these scenarios.

9. Certain groupings have been made by the project team so that similar spaces are included with the spaces of interest. For example, ceiling voids include both ceiling space (73-74) and crawl space (71); wall spaces include wall space (75) and shafts (51-55); and guest rooms include bedroom (21-22), bathroom (25), and closet (42). For a complete list of these groupings, excluded areas (outdoor areas, see #7 above), and allocation of unknowns, see the related Appendix within the main project report [1].

We have now developed the fire scenario structure for modeling fires in hotels. This structure is based on the two assumed hotel arrangements and limiting the areas of origin to the concealed spaces or adjoining occupied areas. We have specified the properties of first items ignited as hotel contents based on typical burning characteristics. The heats of ignition have been limited to a flaming class, which is applicable to all first items ignited. We have described a procedure for determining the time of involvement of cable in fires initiating with other items and the time of spread to other items for fires originating in the cable. Finally we have calculated the probabilities associated with each fire scenario.

2.4 Adapting the Fire Model for Concealed Space Fires and Constructing Heat Release Rate Curves for Fire Scenarios

2.4.1 Adapting the Fire Model

As was previously mentioned, the principal enhancement to the fire model (FAST) required for this case was the accounting for the impact of the reduction in oxygen associated with burning in a confined space on the burning rate and product yields. This was addressed by the inclusion of a vitiated combustion algorithm into FAST Version 18.3, which was subsequently released with HAZARD I [3]. The details of the included physics and chemistry are presented in the documentation of both FAST and HAZARD I [12,3] and will not be repeated here.

2.4.2 Constructing the Heat Release Rate Curves for Fire Scenarios

Appendix C of the Methodology Report [1] provides the rules which specify how to compute the heat release rate curve needed to run FAST from ignition until all the fuel is pyrolyzed in the room of origin. The cable's contribution was evaluated for those fires which start with each of the scenario classes (see section 2.3.1) of first item ignited which eventually involve the cable.

All fires must follow one of the paths depicted in the event tree in Figure 3. Each path includes four fire scenarios by extent of spread. The method stipulates a maximum upper layer temperature corresponding to each extent of spread (section 2.3.3). We model the set of fire scenarios initiating with a specific item as follows:

1. Use FAST to model the fire scenario for extent of spread beyond room of origin (flashover). This scenario produces upper layer temperatures which extend through each of the upper layer temperatures for the less severe fire scenarios and pyrolyzes the entire contents of the room.

2. Use the risk software to derive the hazardous conditions which apply to the three fire scenarios with extent of spread less than flashover.

The risk software has been designed to use one run of FAST for each growth curve, and pick the three peak limits from that single curve to derive the hazardous conditions which apply to a specific scenario when the extent of spread is less than "beyond the room of origin" (flashover). The software uses the upper layer temperature criterion for each extent of spread, previously described, as the trigger for cutting off the fire. This significantly reduces the computational burden of making FAST runs, but does so by neglecting the die out portion of fires which do not reach flashover. However, an assessment was made that the die out portion of the fire of less severity than flashover is not significant, especially since these fires are not the major contributors to death totals. Also, fires which are interrupted prior to flashover are most likely discovered and extinguished, which assures a strong possibility of assistance to any persons still in the building.

In summary, the FAST model was modified to deal appropriately with the particular burning characteristics of cable. We have developed the heat release rate input curves for the fire scenarios associated with cable in certain concealed spaces of hotels. Moreover, we have applied a protocol in which FAST runs are carried out for flashover fires, and the less severe fire results are obtained from truncations of these runs.

2.5 Specification of Occupant Sets, Associated Probabilities, and Tenability Limits

For each area of building and each fire scenario, there are potentially different groups of people exposed to the fire's heat and toxic gases. Specifying these occupant sets, their likelihood of being in the building and their susceptibility to the fire is the fifth step in the procedure. An occupant set is defined in terms of the number of persons, their characteristics (e.g., age, sex, handicap), location (within and outside the house) and condition (asleep or awake and incapacitation by physical impairment or due to drugs or alcohol) at ignition. Some of these characteristics, particularly location

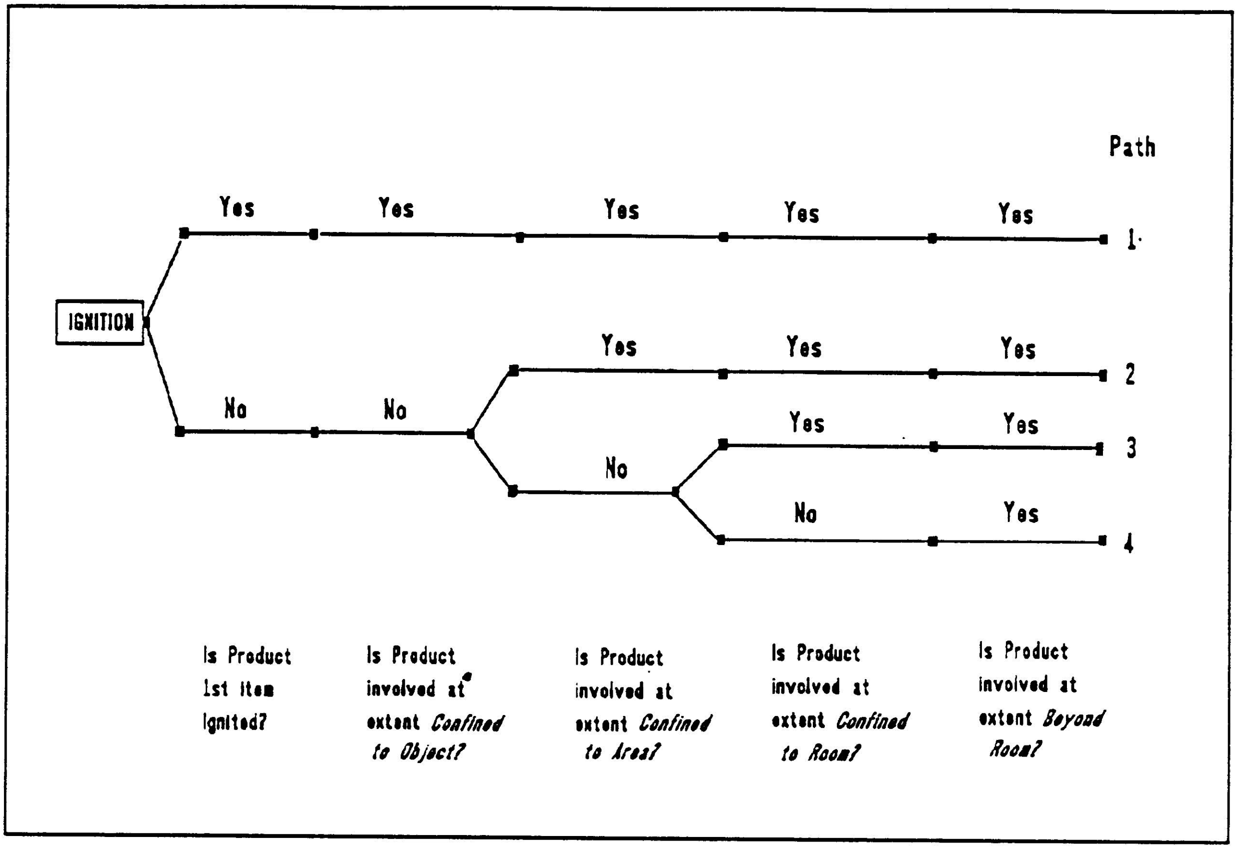


Figure 3 - Event tree indicating at what *Extent of Spread* the product becomes involved.

and condition, are strongly dependent on the time of day, and is how the time of the fire affects the result.

Hotel occupants can resemble residential occupants (i.e., family groups) in the guest room areas, and office occupants (adults, reacting independently) in the function room areas. Thus, we developed family-like occupant sets who could be awake or asleep as a function of time of day for the former, and we assumed awake adults able to evacuate without assistance for the latter. HAZARD I contains a deterministic evacuation model (EXITT) with decision rules which depend upon occupant characteristics, building layout and fire conditions [13]. These characteristics are used in the evacuation model to set evacuation speed and to simulate behavior such as alerting and/or assisting others or requiring assistance. The HAZARD I tenability program (TENAB) is then used to determine whether or not occupants succumb to the conditions to which they are exposed or successfully escape.

However, the EXITT model was not considered appropriate for hotel buildings where:

- the guest room occupants who might interact like family groups are present in sufficient numbers that queuing delays are important, and

- the function rooms contain large groups of persons who are expected to behave largely independently.

Thus, as in Case 2, we employed a simpler procedure developed by Nelson and MacLennan [14]. This is essentially a hydraulic flow model which estimates the escape time required in terms of horizontal or vertical movement, travel speeds, and building features such as corridors, doors, landings, and stairways, which may constrict occupant flow. These specific factors are related to constants applied in several equations to give an evacuation time. These equations use the *effective width* concept of Pauls [15], and model the queuing and congestion that occurs at doors and stairs when a large building is evacuated. Thus, this model is more appropriate to the hotel occupancy than EXITT. Behavioral interactions were limited to occupants of a single guest room, where they could be incorporated into the hand calculation method used.

2.5.1 Specification of Occupant Sets and Associated Probabilities

The risk calculation requires an estimate of the probability of each occupant set for each fire scenario. The national fire data provide no information on building occupants unless they are injured or killed. But Census data [16] and AHMA surveys [6] provide considerable detail on the characteristics of hotel guests as a function of class of facility. These data can be summarized as follows:

- The average occupancy rate for hotels is 66%.
- 52% of hotel occupants are on leisure travel and 56% of them are two to a room.
- 48% of hotel occupants are on business travel and 75% of them are single occupants.
- 9% of hotel occupants are over age 65 and
- 10% of the double occupancy rooms occupied by leisure travelers have children.

Based on these data and information developed for the residential case, the following demographics were developed for the guest room occupants:

- 27% of the rooms are double occupied, 39% are single occupied, and 34% are unoccupied.
- 10% of double occupied rooms have children.
- Children and incapacitated people travel with an able-bodied adult.
- 5% of the adults are intoxicated.

- In day hours (7 am to 6 pm),
  - 20% of the guests are in their rooms,
  - 10% of the children and handicapped are alone, and
  - 20% of the drinkers are incapacitated.

- In evening hours (6 pm to 11 pm),
  - 60% of the guests are in their rooms, and
  - 10% of the children and handicapped are alone
  - 20% of the drinkers are incapacitated.

- In night hours (11 pm to 6 am),
  - 90% of the guests are in their rooms, and
  - 5% of the children and handicapped are alone
  - 20% of the drinkers are incapacitated.

Table 7 presents all possible occupant sets for the guest rooms, along with their associated probabilities by time of day, computed from the data presented above according to the following relation:

Probability of Occupant type Given time of Day.	=	Probability of Room type (single or double occ.).	X	Probability of Occupant type Given room type.	X	Probability of Occupied room Given time of Day.

Table 7 - Occupant Set Probabilities for Guest Rooms

Occupant Type	Daytime Probability	Evening Probability	Night Time Probability
Adult	0.06782	0.20346	0.30519
Elderly	0.00670	0.02010	0.03015
Incapacitated	0.00047	0.00024	0.00003
Intoxicated	0.00069	0.01029	0.01544
Child	0.00108	0.00054	0.00007
2 Adults	0.03180	0.09540	0.14310
Adult, Intox.	0.00162	0.00486	0.00729
2 Intox.	0.00011	0.00162	0.00243
2 Elderly	0.00480	0.01440	0.02160
Elderly, Intox.	0.00024	0.00072	0.00108
Adult, Incap.	0.00119	0.00357	0.00535
Adult, Child	0.00270	0.00810	0.01215
2 Children	0.00108	0.00054	0.00007
2 Adults, 2 Child	0.00270	0.00810	0.01215
No Occupants	0.87700	0.62806	0.44390

Occupants of the function rooms have significantly different characteristics from guests, although some guests might be in the function area when not in their own room. Based on the above data and typical code requirements for allowable occupant loads and exits, the following description of the function room occupant sets was developed:

- There are 6 rooms, each with 625 ft^2 area.
- At a code allowed 15 ft^2 per person, the room will hold 40 persons.
- Thus for the 6 rooms, the total occupancy is 240 persons.

Since the function rooms are only occupied by adults, the only impact of time of day would be in the degree to which the facilities are being used. Assuming a facility utilization rate of 50% in the day, 40% in evening, and 10% at night, and occupant densities of none (room is empty, occupant set C_0), 1/3 (80 persons total in 4 rooms, occupant set C_{80}), 2/3 (160 persons total in 4 rooms, occupant set C_{160}), and full capacity (240 persons total in all 6 rooms, occupant set C_{240}), and assuming a utilization level when used of 30%, 50%, and 70% (day, evening and night) for C_{80}; 50%, 40% and 20% for C_{160}; and 20%, 20%, and 10% for C_{240}; we obtain probabilities for the occupant sets by time of day presented in Table 8.

Table 8 - Occupant Set Probabilities for Function Rooms

Occupant Set	Daytime Probability	Evening Probability	Night Time Probability
C_0	0.50	0.60	0.90
C_{80}	0.15	0.20	0.07
C_{160}	0.25	0.16	0.02
C_{240}	0.10	0.04	0.01

2.5.2 Tenability Limits

The tenability program (TENAB) is used to determine the impact of exposure of the occupants to the heat, and gases produced by the fire, and ultimately whether or not the occupants successfully escape [17]. If they do not, TENAB decides upon a *limiting condition* (toxicity or heat), when this occurred, and how far the occupant got before being overcome. The TENAB program compares the conditions in the dwelling over time as predicted by FAST and the occupant location over time as predicted by EXITT (or in this case, the alternate evacuation calculation) with tenability criteria (toxicity and heat tolerance) based on the work of researchers in fire toxicity. A detailed discussion of the criteria and the literature on which they are based is contained in the HAZARD I documentation [18]. For each type of criterion, two or more independent parameters are computed as a means of addressing the high degree of variability inherent in such physiological predictions. The toxicity measure used in this analysis was limited to the concentration-time product (Ct). This parameter represents a time-integrated exposure to the toxic products produced by the burning contents items relative to a small-scale combustion toxicity screening test. On this basis, a reference value of 900 mg-min/ℓ is typical for common materials. Ct is calculated in the FAST model by taking the cumulative mass of fuel lost and distributing it into the upper layers in each room. Unlike the more detailed fractional effective dose (FED) parameter also computed by TENAB the Ct measure does not require a knowledge of the specific materials of construction and their associated release rates of gases. Using the Ct parameter, a generic fuel can be characterized with an appropriate level of specificity. New products can be tested to determine their toxicity and the input to FAST (Ct) will reflect these results.

In a revision to TENAB included in the general release of HAZARD I but implemented after the initial processing of this case study, oxygen deprivation was included as lethality condition in addition to the Ct parameter. TENAB includes a formulation which accounts for oxygen deprivation as a time-integrated function, and allows for an occupant moving from a room depleted of oxygen into a room where oxygen is plentiful in a physiologically proper manner. However, as discussed in section 3.2.3, this was not an issue in this case.

Heat is assessed as an incapacitation measure in the analysis. Purser [19] has derived from various literature sources, a mathematical expression for tolerance time to convected heat. This expression was slightly modified to allow for a threshold temperature below which no impact occurs. This relationship produces a more realistic response prediction than simply a limiting temperature as was originally used, since it allows for the time-dependent nature of the heat transfer to the subject.

While heat is an incapacitation measure in the simulation, it is not differentiated from lethality. When convected heat is predicted to be the cause, the death may ultimately be from toxicity or oxygen deprivation, but only because the victims were prevented from escape by convected heat.

In the fifth step we have developed an occupant set to be exposed to the fire scenarios. We have introduced a new evacuation calculation to replace the EXITT model for non-residential occupancies. And we have selected the criteria for judging occupant survivability to exposure to the heat and gases produced by the fire.

2.5.3 Alerting Criteria

In case 1, the alerting of the occupants to the presence of a fire was done within the EXITT model using its internal criteria. In case 2, the occupants were always in the room of origin and saw the fire as it started. Here, we are not using EXITT and the fire sometimes starts in another room or space from the occupants, so some criteria must be established for when people are alerted and begin their evacuation.

As in residences, smoke detectors play a major role in this process in hotels. Codes typically require residential smoke detectors (which sound only within the room) in guest rooms and system smoke detectors (which activate the bells throughout the hotel) in all corridors and common use areas, including function rooms. But as in case 1, detectors have a finite probability of not working at the time of the fire. So again we compute the scenario outcome with and without detectors and weight the detector cases with the probability of a working detector given a fire. (The value of 0.19 from case 1 was assumed since no better value was available.)

For the guest room scenarios, the alerting criteria used for occupants in the fire room are (room) detector activation (13 °C temperature rise in the upper layer with a minimum layer thickness of 0.2 m, taken from the DETACT module in HAZARD I [3]) for detector cases, and a smoke layer 1 m above the floor for no detector. For occupants in rooms remote from the fire, the detector activation criteria above is applied to the corridor (since activation of the corridor detector sounds the alarm throughout the hotel), or 5 minutes after the layer reaches 1 m from the floor (in the fire room) if there is no detector. (This assumes that someone will see the smoke and alert people.)

For the function room scenarios, fires starting in the room are detected immediately in that room, and fires starting above the ceiling are detected when the layer drops to the level of the ceiling in that room, with or without detectors. For persons remote from the fire room, the same criteria are applied as for remote persons in the guest room scenarios.

3. Description of Method Implementation - The "Base" Case Risk Computation for Cable in Hotels

3.1 Sequence of Calculation in the Method

In Section 2, we described how we formulated the computation of the risk of current cable in hotels for each class of fire scenarios represented by a single case. Figure 4 indicates how we combine the fire scenarios and occupant sets to run the HAZARD I software and calculate an overall estimate for the annual deaths for all fire scenarios:

1. By running FAST for a specific fire scenario, the evacuation calculation for the occupant set, and TENAB to judge survivability, we obtain an outcome in deaths per fire.

2. We then run each occupant set in the scenario and weight the outcome by the probability of that occupant set.

3. Using the fire scenario probability and the total number of fires (estimated using the national fire database), we obtain the number of fires for that scenario, then combine this with the deaths per fire estimate for the scenario to obtain the number of deaths.

4. These results are combined with similar results for all other scenarios to produce a sum that gives the annual death rate for fires involving cables currently in use.

We can then compare these predicted results for the "base" case with the actual losses obtained from the national fire database. These comparisons in the first case study led to several adjustments, prior to establishing the final "base" case. These adjustments are discussed in the following sections.

3.1.1 Thermal Tenability Limit

The tenability limit used in this case for convected heat was based simply on a temperature limit of 100 °C. During the period that the release version of HAZARD I was being prepared, a new set of tenability criteria were published by Purser [19]. These were incorporated into the release version, including a time-dependent thermal limit which more closely matches data on heat tolerance in the literature. This measure was incorporated as a permanent part of the risk method, but was not revisited for this case. Thus, only the 100 °C limit was employed here.

3.1.2 Updated Version of FAST

The version of FAST used for this case was 18.3, the same version released with HAZARD I, and that used in the re-calculation of case 1 (see discussion in section 3.1.2 of the case 1 report).

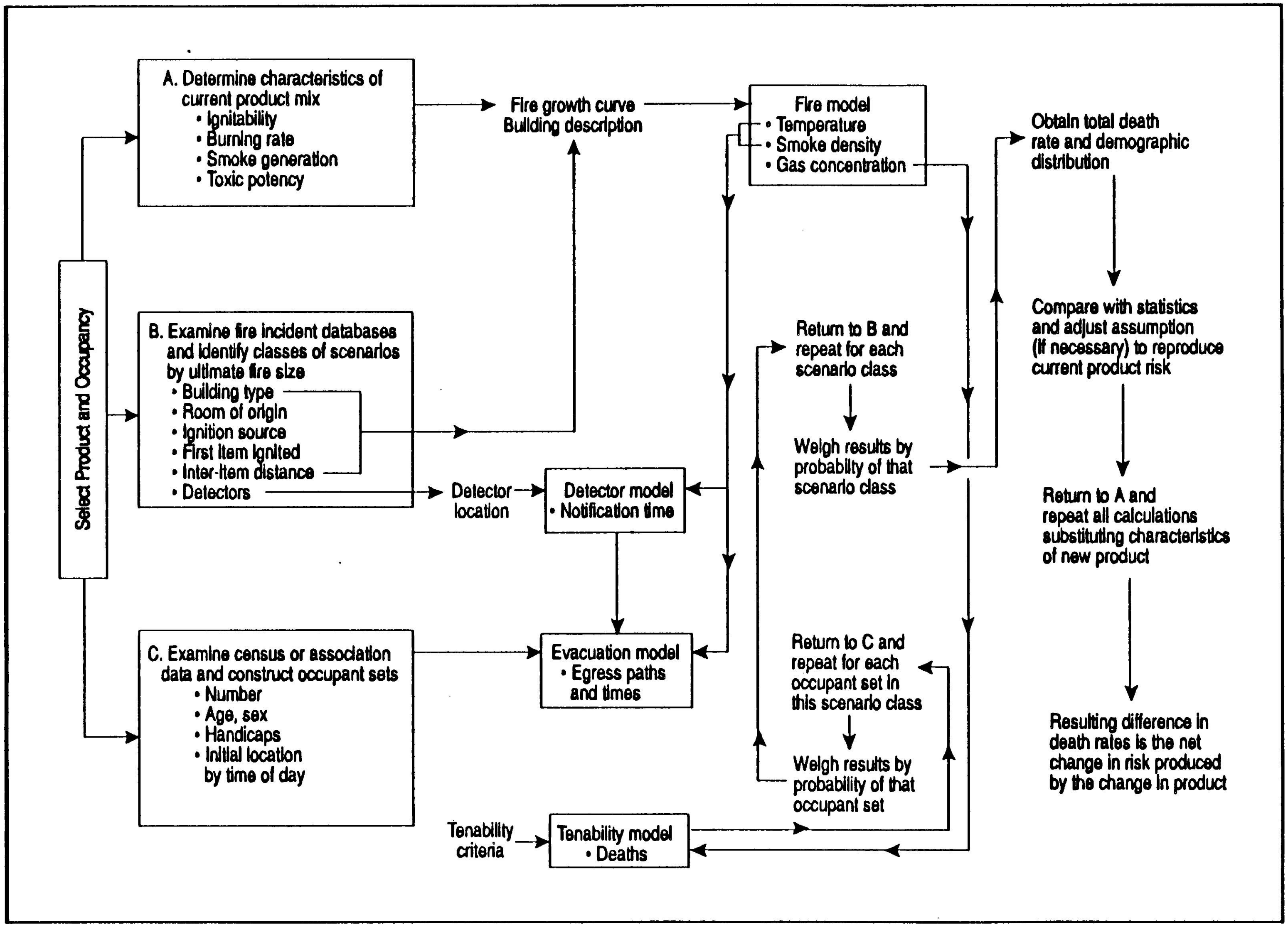


Figure 4 - Modeling Sequence to compute Fire Risk

3.2 Results of Base Case

3.2.1 Fire Performance of Cable

Since all fires which began in rooms and then spread to the concealed space (involving the product) were assumed to do so at or near flashover, the impact of the cable was negligible on both the temperature and gas levels, and on fatalities. This is because the fires are so large when the cable is first exposed. If, however, the cable is exposed (e.g., above a ceiling with tiles missing) the result might be different. But since we could not develop any reasonable estimates of how often this happens or how extensively the cable is exposed, we discounted such scenarios.

For the fires which begin within the concealed space, we found that the assumed quantities of cable and other combustibles could spread fire to adjacent spaces with fatal results. However, again, the majority of the fire's effects, and all of the occupant exposure, occur after the fire spreads to the room; therefore the relative impact of the cable is minimal. This can be quantified by comparing the burning (mass loss) rate of the cable to that of the rest of the fuel, at the point of flashover.

Table 9 - Relative Impact of Cable to the Total Rate of Fuel Mass Loss at Flashover

	Guest Room Fires	Function Room Fires
Burning rate of Cable	0.064 kg/s	0.04 kg/s
Burning rate of other fuel	0.93 kg/s	0.93 kg/s
Relative Impact of Cable	0.06	0.04

3.2.2 Required Evacuation Time

The time required for evacuation of any occupant is the sum of the time spent in the initial room (alerting time + reaction time), the time required to traverse the corridor (walking speed x distance, + and queuing time at the stairway door), and the time required to negotiate the stairs (horizontal or vertical walking speed x distance, + and queuing time at doors).

Based on the alerting criteria discussed in section 2.5.3 and the conditions predicted by the FAST runs, the following alerting times were obtained:

Table 10 - Occupant Alerting Times (Seconds)

	With Detectors		Without Detectors	
Scenario	Fire Room	Other Rooms	Fire Room	Other Rooms
Guest room fires: confined to wall	NA*	NA*	NA*	NA*
spread to room	35	176	80	380
In Guest room: confined to object	10	310**	90	390
confined to area	10	310**	90	390
confined to room	10	150	90	390
beyond room	10	150	90	390
Function room fires: confined to ceiling	180	480	300	480
spread to room	55	272	155	455
In function room: confined to room	90	250	230	530
beyond room	340	430	340	640

* NA= Not Activated

** Assume others are alerted 5 minutes after person in room is alerted, even though smoke detector in hallway is not activated.

Reaction times and walking speeds may vary for each occupant type included in the occupant set. Based on the values used in the EXITT module of HAZARD I [3], the values in Table 11 were used in this case.

Table 11 - Reaction Times (s) and Relative Speeds for Hotel Occupants

	Reaction Time (s)			% of Adult Speed*	
Occupant Set	Day	Evening	Night	Horizontal	Vertical
Adult	6	6	10	100	100
Elderly	6	6	10	70	70
Intoxicated	22	22	22	50	50
Child	6	10	22	70	70
2 Adults	6	6	10	100	100
Adult, Intox.	16	16	22	70	70
2 Intox.	22	22	22	50	50
2 Elderly	6	6	10	70	70
Elderly, Intox.	16	16	22	50	50
Adult, Incap.	16	16	22	35	35
Adult, Child	6	16	22	70	70
2 Children	6	10	22	70	70
2 Adult, 2 Child	6	16	22	70	70

* Adult Travel Speeds - Horizontal, 250 ft/min - Vertical, 40 ft/min

Based on the assumed characteristics, the evacuation of the building by the various occupants was simulated. This resulted in a series of tables locating individuals or groups of occupants as they moved throughout the building. Table 12 presents the times for the C_{240} occupant set evacuating the function areas, from which the times for the C_{160} and C_{80} occupant sets can also be derived.

Table 12 - Evacuation Times (s) for 240 Person Occupant Set

Time Person Left Room*	Time Person Left Corridor	Time Person Left Stairway
5	15	20
5	20	25
5	25	30
5	30	35
10	35	40
10	40	45
10	45	50
10	50	55
15	55	60
15	60	65
15	65	70
15	70	75
20	75	80
20	80	85
20	85	90
20	90	95
25	95	100
25	100	105
25	105	110
25	110	115
30	115	120
30	120	125
30	125	130
30	130	135

* The alerting and reaction times presented in Tables 10 and 11 must be added to these times to obtain total evacuation time for each occupant.

During each 5 second time period 9.6 people enter the stairway vestibules through two doors at opposite ends of the corridor. The 9.6 people per 5 seconds is based on the maximum flow through two doors when queuing has occurred.

3.2.3 Occupant Safety

The risk method predicts fatalities in some of the scenarios identified as potentially involving cable, and no deaths in others. The scenarios yielding no deaths tend to be the smaller extent of spread cases but include some larger fires. Causes of death include both temperature and toxicity, with the distribution varying with the scenario. Smoke detectors have some effect on reducing the death rate in some scenarios, but are not as significant as in the residential case. The numerical results obtained for the cases examined are presented in the next section.

One interesting observation is that this risk calculation indicated that persons outside the room of origin were typically killed during evacuation, receiving their primary exposure in the corridors or stairways. Conditions in the room from which they came remained survivable throughout the simulation. This suggests that the risk method might have utility in evaluating defend-in-place strategies. However, due to the level of uncertainty currently present in the risk calculation, one should not generalize that this calculation has verified this position.

3.3 Base Case Comparison with Statistics

As stated above, there were scenarios where the method predicted deaths, and those where it predicted no deaths. The statistics also predict deaths on only some of the scenario groups examined. Thus, the comparisons will be presented in groups where the method and statistics agree that there were deaths, and those where one predicts deaths and the other does not. To say they agree says nothing about the quality of that agreement (see section 3.3.5), but only that deaths did or did not occur in both. We should also keep in mind that the risk method cannot reproduce individual events. Thus, for example, one should not expect to see the Stouffer's [20] fire results duplicated here.

The data taken from the fire statistics are reported in Tables 13-16 to two decimal places to give the reader a feel for the numbers which obtain in the calculation. This probably represents more significant figures than the data uncertainties justify. Likewise for the method, numbers were rounded to one or two significant figures, although one is the most that can be justified.

The output of the method, and that which is compared to the statistics, is the death rate for fires involving the product. This death rate (and the number of deaths per year) can be fractional numbers because they represent *annual averages*; i.e., the statistical value is the average number of deaths per year for the years 1981 - 1985. Likewise the number of deaths per year will be less than the death rate (deaths per 100 fires) whenever there are fewer than 100 fires per year in a given scenario class.

3.3.1 Judging the Quality of Agreement

What is considered "good agreement" is often subject to argument or at least individual interpretation. As the risk method is applied, comparisons to incident data are made in developing and calibrating the "base case." The "new product case" involves comparisons to both the incident data and the base case. In each area, these comparisons can involve both absolute numbers (of deaths) and distributions (smoldering vs flaming or death from heat vs toxicity). This quality of agreement is a function both of the ability of the science to address properly the physics of the scenario, and the ability of the data to describe fully what occurs in the real world. Thus, some criteria are needed for judging the quality of the comparisons made, which are tailored *for the individual case under consideration.*

In terms of the intended use of the model, the degree of agreement should be sufficient that modeling errors are considerably less than the likely differences between the true base case risk and the true risk associated with a significantly better new product. This criterion may require better agreement than the "factor of two" criterion that is applied to several of the key models used in the risk method. The method consistently underpredicts fatalities everywhere except where there are no detectors, when the opposite is true. However, if you consider the fact that occupants die in large groups, then changes which cause a group to die or not, will have a major impact on agreement.

With respect to cause of death, we have limited data which suggests that 67% of fire fatalities die from toxicity. In most scenario classes with deaths, the method predicts 96% to 100% of the fatalities are from toxicity (Ct). This would be considered good agreement.

3.3.2 Scenarios Where the Method and Statistics Predict No Deaths

For guest room fires originating in the wall (product is first ignited), there were no deaths predicted or observed where the fire was confined to the wall space or where it was confined to the first object ignited in the room. For the function room fires, there were no deaths predicted or observed for scenarios where the fire started in and remained in the ceiling space and spread to the room but remained there, or where the function room went to flashover.

3.3.3 Scenarios Where the Method and Statistics Predict Deaths

Those scenarios where deaths are both predicted and observed include those beginning in the guest room and spreading beyond the room of origin, and those beginning in the function room and spreading beyond the room of origin. Note that in none of these scenarios is the product the first item ignited. The results of these cases is presented in Tables 13 and 14.

Table 13 - Summary Analysis for Guest Room Fires with Extent Beyond Room

	Statistics			Method		Cause of Death (%)	
	Prob. (x1000)	Deaths/ 100 fires	Deaths/ year	Deaths/ 100 fires	Deaths/ year	Ct	Temp
Daytime	16.20	2.56	4.2	1.0	2.0	96	4
Evening	9.04	3.06	2.8	0.6	0.6	96	4
Night	17.64	8.69	15.5	0.8	0.1	96	4
Totals			22.5		3.0		

Notes: 1. Method predicts identical results with and without detectors.
2. All victims are incapacitated (intoxicated or handicapped).
3. Ct deaths occur in rooms remote from the fire (1st floor at 840 s and 2nd floor at 984 s).
4. Temperature deaths occur in the fire room at 120 s.

In Table 13 we see that the method underpredicts annual fatalities by a factor of 2 in the day to a factor of 100 at night. By our criteria (section 3.3.1) this ranges from good to poor agreement with the total annual deaths in the "good agreement" category. We find this generally the case throughout the results from this case study.

Note that the only fatalities in these scenarios are incapacitated, and all fully-capable adults escape. This is not likely, and is not borne out by the statistics. This observation leads us to believe that the differences with statistics may be related to the alerting criteria and the response to fire queues assumed in the evacuation analysis.

Table 14 - Summary Analysis for Fires Starting in the Function Room, with Extent Beyond Room

	Statistics			Method With Detectors				Method Without Detectors			
	Prob $x10^3$	Dth/ 100 fires	Dth/ year	Dth/ 100 fires	Dth/ year	%Ct	%Te	Dth/ 100 fires	Dth/ year	%Ct	%Te
Day	17.38	2.98	5.24	0.7	1.2	100	0	1600	2800	0.03	99.97
Even.	11.13	2.44	2.75	0.3	0.4	100	0	750	850	0.03	99.97
Night	16.33	9.43	15.58	0.04	0.1	100	0	150	200	0.03	99.97
Totals			23.57		2.0				3900		

Notes: 1. The method predicts some deaths when operating smoke detectors are present.

2. All victims start from rooms remote from the fire and die from temperature, in the corridor.
3. Their evacuation starting time is 461 s (455 s alert time + 6 s reaction time).
4. Evacuation of the C_{240} occupant set takes 135 s, and the C_{160} set takes 90 s.
5. The victims all die at 521 s.
6. Thus, the C_{240} set require an additional 70 s of escape time, and the C_{160} set require 25 s.

Table 14 shows a similar level of agreement with statistics when smoke detectors are present as was evidenced in Table 13. However, without detectors the method grossly overpredicts the death rate compared to what is observed. For example, we noticed that the predicted deaths presented in Table 13 were all drunks. Thus we could bring the underprediction of fatalities in these scenarios into perfect agreement with the statistics if the percent of drunks were increased to 68% in the day, 8% in the evening, and 1.7% at night. This kind of adjustment is trivial in that it does not require any additional computer runs, but is accomplished simply by adjusting the weighting ratios for those occupant sets.

This result seems to derive from the high occupant load (40 would be an upper limit), conservative criterion for thermal fatality, and the zone modeling assumption of laterally uniform layers. In the corridors this leads to exposure of occupants to "lethal" conditions at a distance down the corridor from the fire room where the temperature would likely be lower than predicted. This gross overprediction also led to observations on sensitivity (see section 3.4).

3.3.4 Scenarios Where the Method and Statistics Predict Opposite Outcomes

In the guest room scenarios where the fire begins in the cable within the wall and the extent of spread is (1) confined to area, (2) confined to room, or (3) beyond room, the risk method predicts a small number of deaths where the statistics show none. These results are presented in Tables 15 and 16.

Table 15 - Summary Analysis for Guest Room Wall Space Fires Confined to Area or Room

	Statistics			Method		Cause of Death (%)	
	Prob. (x1000)	Deaths/ 100 fires	Deaths/ year	Deaths/ 100 fires	Deaths/ year	Ct	Temp
Daytime	2.18	0	0	0.05	0.01	0	100
Evening	1.50	0	0	0.02	0.003	0	100
Night	1.73	0	0	0.003	0.0005	0	100
Totals			0		0.01		

Notes: 1. All victims are incapacitated in the fire room at 140 s.
2. The method predicts identical results with and without detectors.

Table 16 - Summary Analysis for Guest Room Wall Space Fires with Extent Beyond Room

	Statistics			Method		Cause of Death (%)	
	Prob. (x1000)	Deaths/ 100 fires	Deaths/ year	Deaths/ 100 fires	Deaths/ year	Ct	Temp
Daytime	0.51	0	0	1.3	0.07	96	4
Evening	0.39	0	0	0.7	0.03	96	4
Night	0.59	0	0	0.08	0.005	96	4
Totals			0		0.1		

Notes: 1. All victims are incapacitated (handicapped, intoxicated).
2. Ct victims die in rooms remote from fire (1st floor at 782 s and 2nd floor at 920 s).
3. Temperature victims die in fire room at 161 s.
4. Method predicts identical results with and without detectors.

In Tables 15 and 16 we see very small numbers of deaths predicted where none are observed. These are scenarios of low frequency (probabilities on the order of 10% of that for other scenarios discussed), so they represent a small number of fire incidents.

3.3.5 Judging the Significance of the Results

It should be clear that the method will permit the calculation of differences in risk for a selected product/occupancy pair (e.g., new product vs. baseline), but not all differences can be safely interpreted as indicating real product differences. The accuracy and precision of the method will be functions of the quality of the input data, the adequacy of the many simplifying assumptions, and the coarseness of the scenario structure.

One way to assess the accuracy of the method is to calibrate the "base case", which will be based on real fire probabilities for a certain period, against actual fire death rates for the same period. The degree of correspondence between the predicted and actual fire death rates is a measure of the accuracy of the method. It has limitations, however. On one hand, high accuracy in predicting totals need not mean high accuracy in the underlying structure of the method. If an accurate tool is generated for the wrong reasons, that could mean an inaccurate answer for the new product. On the other hand, poor accuracy in predicting totals may be due to systematic errors that would have the same effect in other calculations. Therefore, one could do a poor job of predicting the total fire death rate in the baseline and still do an excellent job of estimating the relative change in fire risk between the baseline and new product.

Too little is known at present to do a truly satisfactory job of quantifying the degree on uncertainty in the method, overall or for a particular case. Instead, the authors have attempted for each case, to provide guidelines on how to judge the significance of differences in risk in that case. Sensitivity analyses and expert judgement play a large role in checking the confidence of these results.

This test case showed very poor agreement between statistics and method predictions. The method substantially underpredicts actual death rates for fires beginning in guest rooms, where the need for a side calculation of intimate-with-ignition deaths was probably a factor. The method substantially overpredicts actual death rates for fires beginning in function rooms without detectors, where the absence of a well-established base for assumptions about alternate alerting criteria and people behavior after alerting were factors.

Based on these results, the authors suggest that risk differences (e.g., between a new product and its baseline) would be considered to have statistical significance only if (1) the difference is at least 50% for each major scenario, guest room and function room, and (2) the relative difference is stable under sensitivity analysis, particularly with regard to alerting criteria and behavior. Annual hotel fire death rates are high enough that risk differences of well under 50% will still have practical significance. Since we cannot be sure that such differences have statistical significance at this stage, the authors suggest that the method be used sparingly on this property class until its stability and accuracy are further refined.

3.4 Sensitivity Analysis

The primary effort toward examining the sensitivity of the method to key assumptions was expended in case 1, since there the statistics presented the most detail for comparison. But each of the other three cases presented opportunities to make observations about sensitivity without performing large numbers of additional calculations.

It was observed that the predicted fatalities in this case tended to occur in large groups, all at the same time. This is not the way that fire deaths in hotels occur. Thus, the sensitivity analysis for this case was limited to some computations of changes that would be required to cause major changes in the outcome.

An even simpler sensitivity observation relates to the fact that large groups of function room occupants are predicted to die together, leading to the gross overprediction of fatalities in Table 14. This is not unusual in real fires to find a "pile of bodies" near an exit, locked or not. From the observation presented in section 3.3.4, an additional 70 s of alert time would have resulted in no fatalities within the C_{240} occupant set for one entire group of function room scenarios (or 25 s for the C_{160} set). This shows that assumptions related to alerting time, reaction delays, or walking speed of these occupant sets which could result in their evacuating a minute sooner will have a major impact on the fatality rate.

These analyses show that the method is highly sensitive to the construction of (e.g., fraction of drunks) and assumptions about (e.g., walking speed) the occupant sets used in this case. The results were not nearly as sensitive to the occupants in cases 1 or 2 (see the sensitivity analysis in those reports). This demonstrates that the sensitivity of the method is not inherent, but rather is case specific and should not be generalized.

4. Description of Method Implementation - The "New" Product Risk Computation for Cable in Hotels

4.1 Sequence of Tasks to Calculate Risk for the "New" Product

The "base case," once completed and calibrated against the fire statistics, becomes the mechanism by which the risk impact of changes in the product can be evaluated. In this context, the "new" product is any product item which incorporated one or more changed performance properties (e.g., ignitability, burning rate, toxic potency, smoke production) It is also important to remember that the "new" product must be assumed to **totally replace the existing product in use.**

To calculate the risk for the "new" product requires 1) measuring its fire properties (ignitability and burning characteristics); 2) running the risk procedure using the building(s) occupant sets and associated probabilities and the scenarios from the base case with the fire properties of the "new" product; and (3) comparing the risk calculation with the base case. It is assumed that the "new" cable is completely substitutable for the cable in use and that changes in the product do not affect who will buy it or what kind of hotel it will be in, etc.

4.2 Modeling Changes in the Fire Properties

Changes in the product's fire properties result in changes to the fire hazard and risk results. For this case, we chose to examine the effect of increasing the flame spread rate and peak heat release rate of the cable jacket. The values used are presented in Table 17.

Table 17 - Flammability Properties of New (New Product Case) Cable

	New cable	Base case cable
Quantity of Cable	6 pieces, 50 feet long	6 pieces, 50 feet long
Peak Rate of Heat Release (RHR) per unit surface area	375 kW/m^2	250 kW/m^2
Rate of Rise in RHR (flame spread rate)	2 kW/s (2 in/s)	1kW/s (1 in/s)
Toxic Potency (Ct)	900 $g\text{-}min/m^3$	900 $g\text{-}min/m^3$

The factor of two increase in flame spread rate chosen is consistent with cable jacketing materials found in use today. Appendix B of the methodology report describes how to construct the heat release rate curves for the "new" cable, given a measured set of fire properties. The risk method uses an upper level temperature as an intervention trigger for the base case to cut off the fire at each extent of spread before flashover (Section 2.3.3). When a new cable is analyzed for cases with interventions, the intervention is assumed to occur at the same *time* as in the base case scenario. This assumption is suitable for random discovery, which is most likely when people are awake and active, as in the function areas of a hotel.

4.3 Comparison of "New" Cable's Results with "Base" Case Results

Using the new cable properties, the function room scenarios were repeated, and new results obtained. These results are presented in Table 18.

Table 18 - Summary Analysis for New Product used in Function Rooms

	Method			Cause of Death	
	Prob (x1000)	Deaths/100 fires	Deaths/yr	% Ct	% Temp
Daytime	1.27	400	50	0	100
Evening	0.56	150	8	0	100
Night	1.08	400	40	0	100
Totals			100		

Notes: 1. These results are for fires starting in the new cable within the ceiling void, without detectors. The base case prediction was for no deaths (see section 3.3.1) so these are all new fatalities associated with the higher flammability cable. The method predicts no deaths with detectors for both the base case and the new product case.

2. All victims start in rooms remote from the fire room and die from temperature in the corridor at 661 s. They begin their evacuation at 536 s and require 135 s to escape. This means that they need an additional 10 s.

3. The conditions in the rooms from which the victims came remain survivable, so they would have survived if they had not evacuated.

5. Conclusions and Observations

In this report, we have described a third application of a quantitative method for the estimation of the fire risk associated with a specified product class in a specified occupancy. This third case study tested the prototype risk prediction method's capabilities to deal with significant differences in incident data, burning behavior of the product, and the way of addressing the occupants.

In particular, this third case demonstrated how the risk method might be modified to handle a product located *within a structural element of the building.* The risk method provided a means to examine a product whose involvement can be both as ignitor and a fuel, either as the first item ignited or secondarily ignited. And the fire model was enhanced to provide a mechanism by which an important interaction with the products environment (oxygen vitiation effects on burning rate and species yields) were accounted for. Properties of the product such as ignitability, flame spread, burning rate, smoke production, toxic potency, and total combustible mass are explicitly addressed as independent variables. In addition, the case demonstrated that the method was capable of producing a reasonable increase in deaths for a doubling of the assumed flame spread rate for the cable. A factor of two difference in flame spread rate is within the range of values observed for materials found in cable jacketing materials in use today.

The evacuation simulation provided a realistic treatment of two very different occupant groups. The guest room occupants had the demographic diversity of those in the residential case, while the function room sets were generic like the office occupants. With both sets, queuing was an issue that was addressed by the calculation.

The exercise of the method on this case study revealed a few areas where some enhancements to the hazard method were necessary (e.g., section 2.4.1). This was expected since this case was outside the scope of HAZARD I. The case identified areas where current data collection systems were lacking (e.g., information on hotel arrangements, construction, and guest characteristics, particularly fraction of handicapped). In some instances it may be possible to supplement the data collected to fill these gaps. In others, special studies may be necessary to attempt to capture the needed information. In still others, we may never be able to satisfy the needs of the system. But the identification of needs coupled with the potential value of the method should provide incentive for advances in these areas.

The remaining case study (interior finish in restaurants) was selected to stretch the method in yet another area of modeling - flame spread on vertical surfaces. Thus, the reader is invited to proceed to this case published in a separate report.

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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 trial application of a risk assessment method developed for such a purpose. A separate report provides the essential documentation for the methodology to be understood and applied by others. There are three other associated reports detailing trial applications of the methodology to other selected products and occupancies.

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