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USING FIRE TESTS FOR QUANTITATIVE RISK ANALYSIS

W. C. Teresa Ling and Robert Brady Williamson

March 1980

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ABSTRACT

Fires can be considered a causal chain-of-events in which the growth and spread of fire may cause damage and injury if it is rapid enough to overcome the barriers placed in its way. Fire tests for fire resistance of the barriers can be used in a quantitative risk assessment. The fire growth and spread is modelled in a State Transition Model (STM). The fire barriers are presented as part of the Fire Protection Model (FPM) which is based on a portion of the NFPA Decision Tree. An Emergency Equivalent Network is introduced to couple the Fire Growth Model (FGM) and the FPM so that the spread of fire beyond the room-of-origin can be computed. An example is presented in which a specific building floor plan is analyzed to obtain the shortest expected time for fire to spread between two points. To obtain the probability and time for each link in the network, data from the results of fire tests were used. These results were found to be lacking and new standards giving better data are advocated.

KEYWORDS

Fire Protection, Fires, Fire Resistance, Fire Tests, Fire Growth and Spread, Fire Safety, Probability Analysis, Risk Assessment, and Stochastic Processes.

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INTRODUCTION

The quantitative assessment of fire risk requires a rational framework to measure the "fire-safety" of a building or other structure. Harmathy[1] has defined a fire-safe building as one for which there is a high probability that all occupants will survive a fire without injury, and in which property damage will be confined to the immediate vicinity of the fire area. Under certain circumstances, such as for nuclear reactors, the criteria would need to be changed slightly, but, in general, the definition can be applied to many buildings or other structures and systems. Note, however, that this definition is conditional in the sense that it assumes that a fire will occur, and it is the impact of such a fire which is being minimized.

Friedman[2] starts his analysis of the threat from a rapidly growing fire at an early stage and he defines his framework as the product of two probabilities:

> "1. The probability of ignition, for a given ignition exposure specified by the scenario.
>
> 2. The probability of being unable to escape or be rescued from the fire before the escape route is blocked by heat, smoke, toxic gases, etc. (This probability clearly depends on detection time and on the degree of mobility of the occupants, as well as on the rate of fire growth. Accordingly, some people will fail to escape even from a very slowly growing fire)."

Friedman does not develop the probability of ignition although he notes that it may be developed in a "straight forward manner". He represents the fire growth with an exponential equation which yields a range of "fire doubling times" for a variety of fuel materials. He then develops a ratio of critical threat variables that relate to the manner in which the fire is detected and to the manner in which it reaches the critical condition.

One of the essential steps in establishing a quantitative assessment of fire risk is to separate the diverse and complex issues of unwanted fire so that they can be treated individually. Williamson[3] has suggested that every serious fire has two essential characteristics: one, it can be considered as a causal chain-of-events, and two, the element of time is of ultimate importance. "But for the rapid growth of the fire in a particular location" is a typical phrase that almost always marks the difference between a serious fire with a tragic ending and an incidental fire which was easily controlled. This "sine qua non" (but for the presence) logic and the element of time are important components of a universal fire model. Therefore, in the following section a State Transition Model (STM) of fires will be introduced which represents the growth of the fire in the room-of-fire-origin and its subsequent spread beyond.

The fire resistance tests of walls and floor/ceiling assmeblies, as well as of the elements interrupting the integrity of those assemblies, such as doors, windows, pipes and cable penetrations, are introduced in the risk assessment as quantitative data concerning the ability of those components to contain fire. The fire tests for flame spread and the full scale fire growth experiments are used to quantify the growth of fire in the room-of-origin, and then, once the containment elements are breached, its spread to other spaces. The quantitative assessment of fire risk is strongly dependent on the quality and completeness of the information provided by the fire tests.

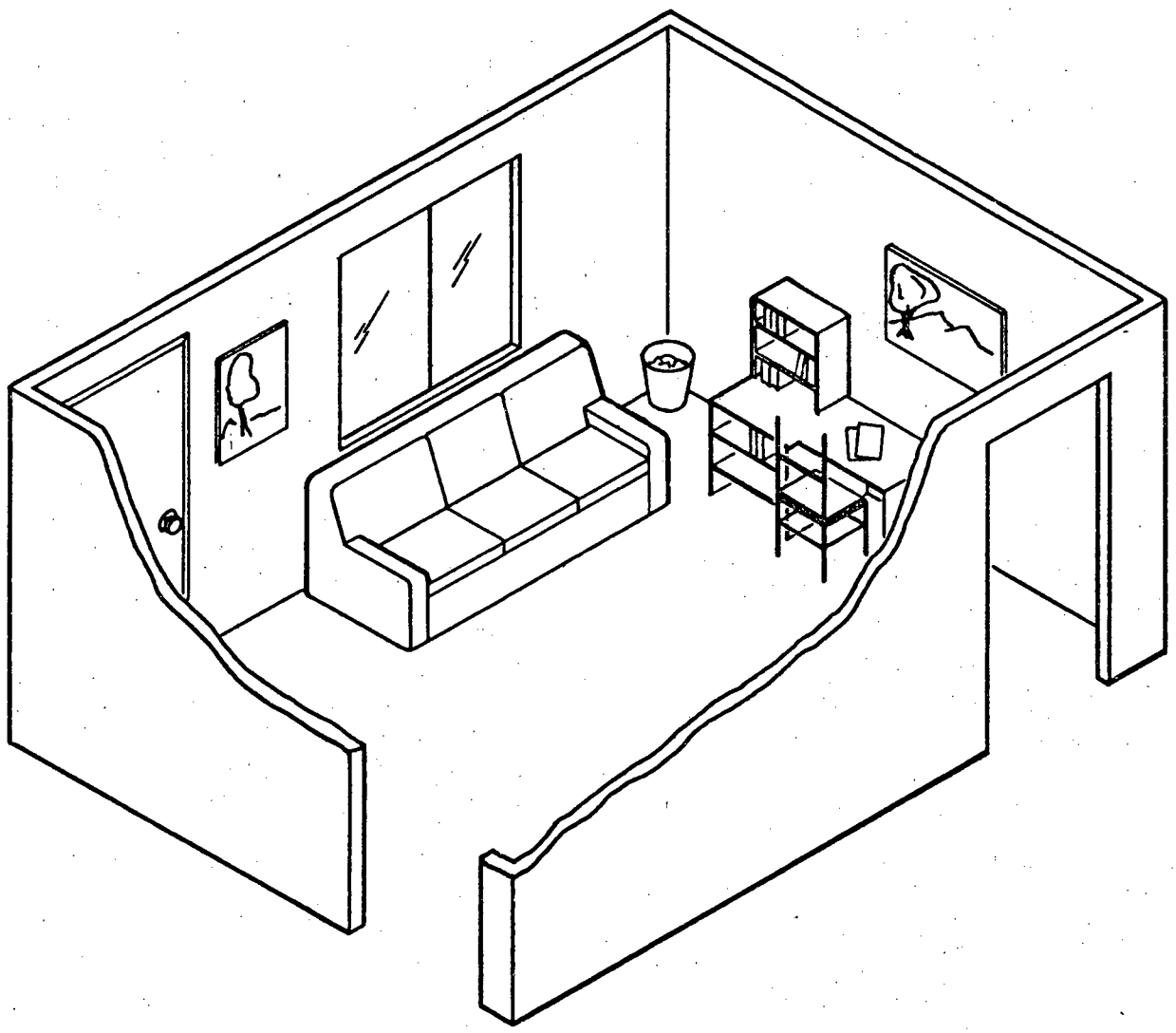
STATE TRANSITION MODEL

Williamson[3] presents a method for combining both deterministic and stochastic modelling techniques for unwanted fire which is based on a State Transition Model (STM). This STM is flexible enough to accept theoretical, experimental as well as subjective information. Williamson's formulation of the problem is based on the fact that though there are a number of distinct aspects to any serious fire, they all have a common time coordinate, and certain events can be identified as being particularly significant. Any complete model of unwanted fire development must be able to answer the following four questions:

1. What is the extent of fire growth with time?
2. What is the extent of spread of combustion products (smoke) from the fire as a function of time?
3. What are the roles of people with the fire in causing its ignition, in fighting it and possibly in becoming its victims?
4. What fire protection techniques can be expected to prevent the spread of fire and smoke?

Each one of these questions can be looked upon as a separate issue and can be utilized as a subsection of a complete model. One way to visualize this process is to compare it to the "separation of variables" common to solving many deterministic problems utilizing differential equations. The complete model thus consists of submodels which are defined in terms of answering the four questions above.

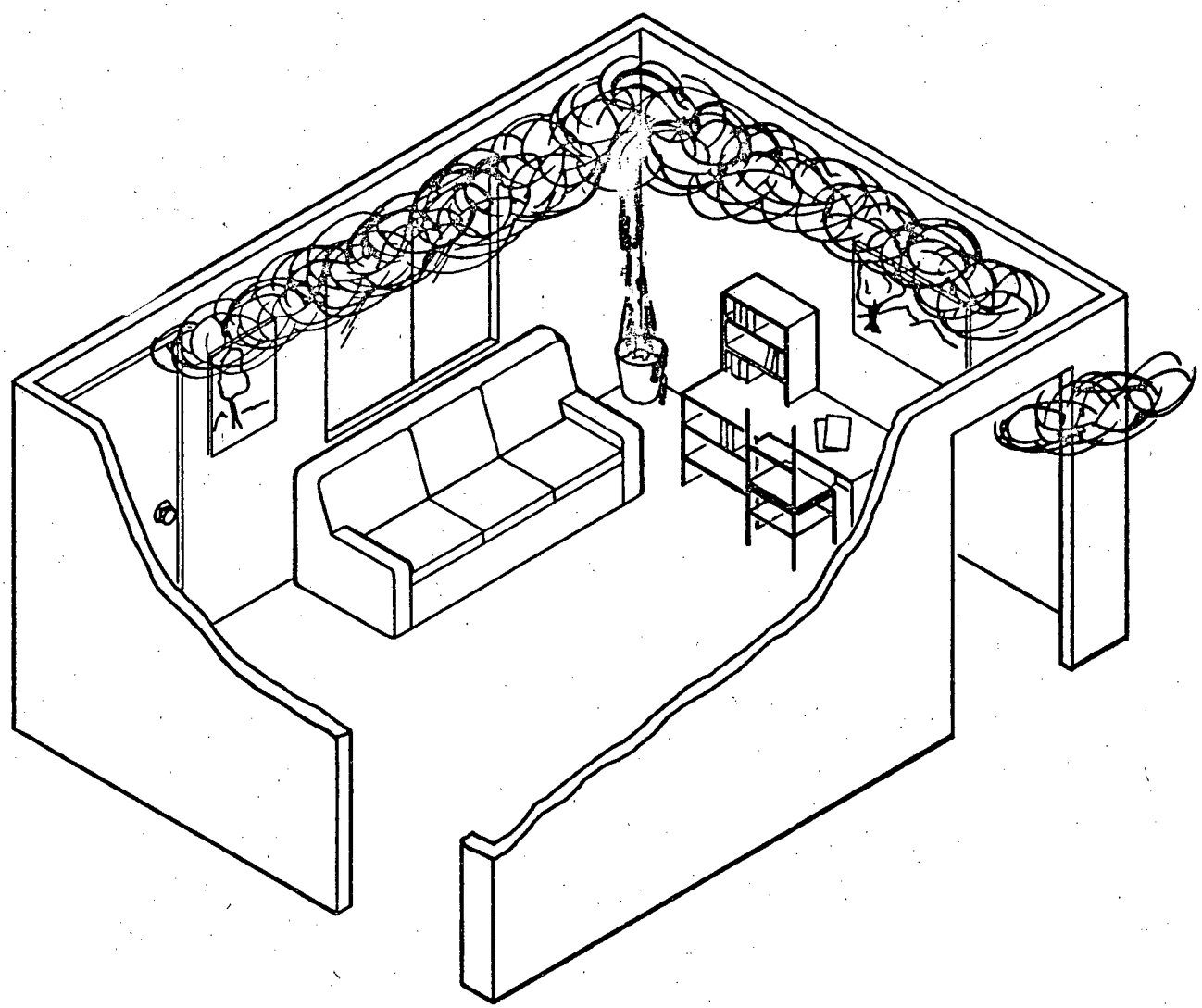
This first question can be answered by a Fire Growth Model (FGM), the second by a Smoke Spread Model (SSM), the third by a Human Response Model (HRM), and, finally, the fourth by a Fire Protection Model (FPM). Each of these subsections of the overall model can be formulated as state transition models which are divided into separate states or realms that represent the



(a)

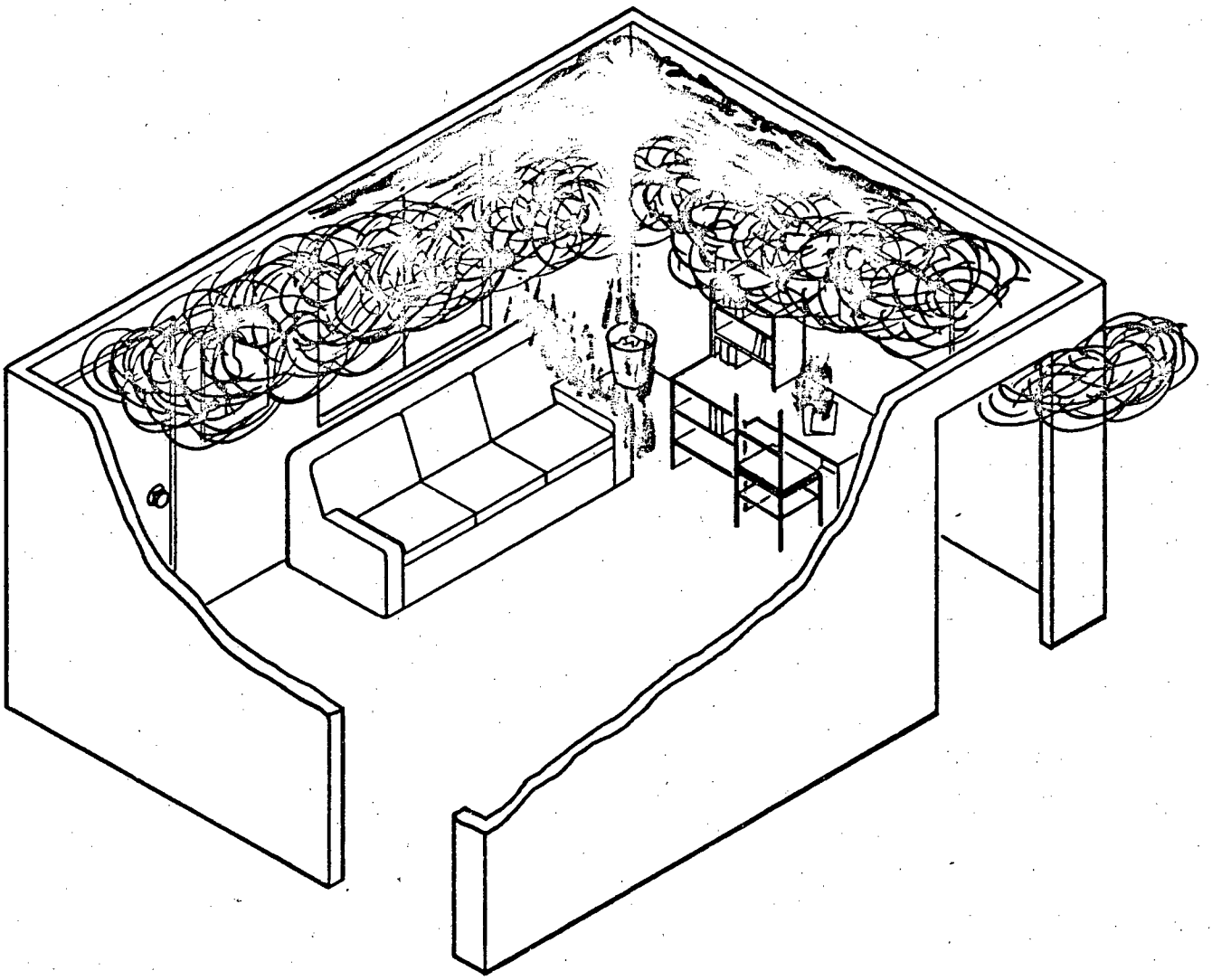
Basic Living Room

FIGURE 1: Schematic Disgram of Flame Spread in Room-of-Origin from Ignition to Flashover.



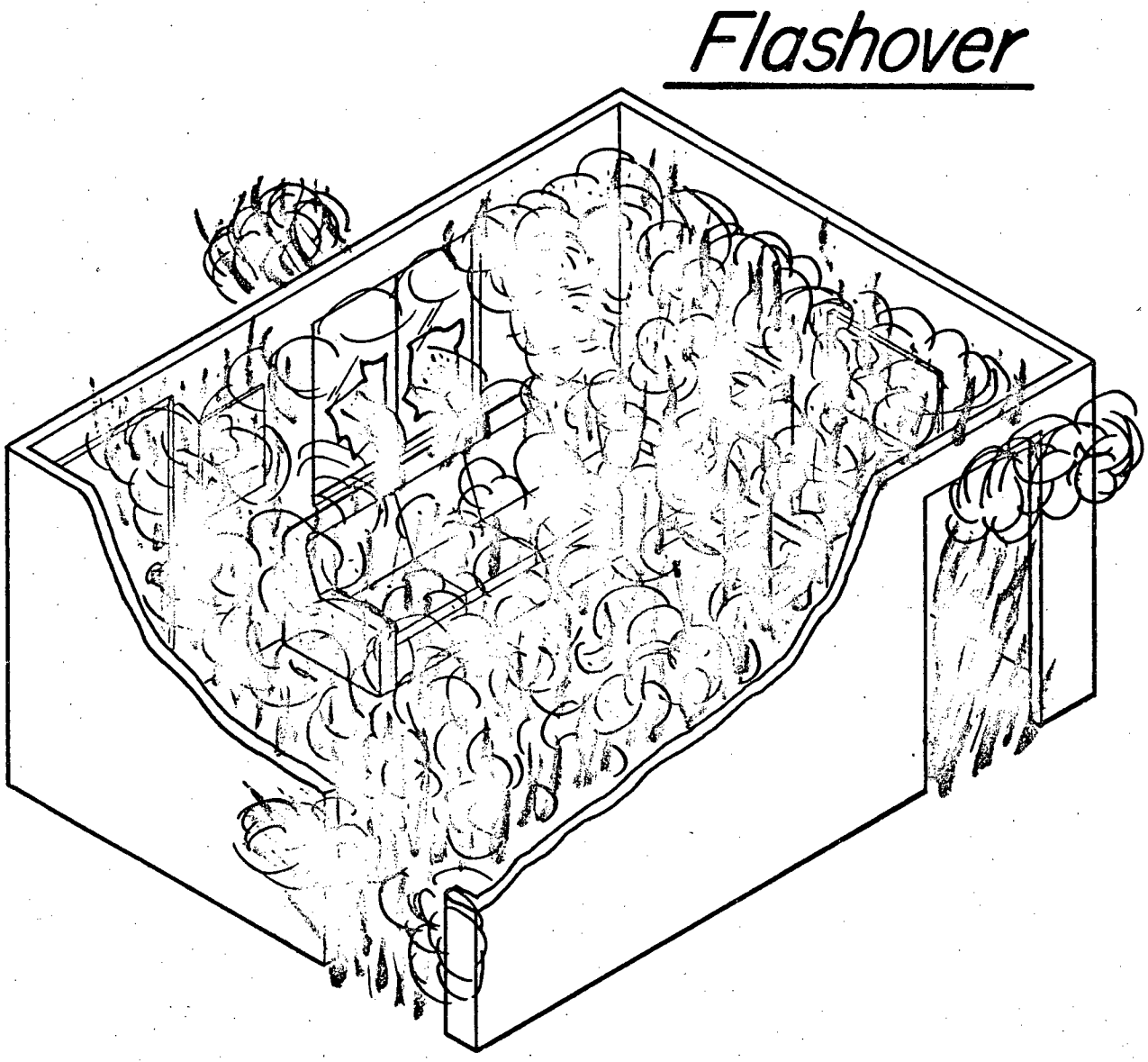
(b)

Basic Living Room



(c)

Basic Living Room



(d)

Basic Living Room

conditions of the fire appropriate to each subsection of the complete model.

The FGM can be considered to give a running account of the fire until it is contained by barriers or it has been extinguished by manual or automatic suppression. Williamson[4] presents a FGM that is based on dividing the fire growth process as if it were a full-scale experiment in which a given product is exposed to an ignition source, and the growth of the fire is recorded as a function of time.

If the initial state before the fire is called "I", the subsequent states can bear the letters that follow in the alphabet, J, K, L, M and N. If the unwanted fire is inside a building or similar structure, it will proceed in a manner similar to that shown schematically in Figure 1 for a living room fire. Figure 1(a) shows the room before the ignition events which start the fire scenario. A fire could have started in a number of locations, but we have chosen the waste paper basket and Figure 1(b) shows a plume of flame and smoke rising out of that location. This depicts state J since only the waste container, and no other object has been ignited. It is important to note that the flame does not reach the ceiling although there must be convective heat transfer to the ceiling since heated air and combustion products rise to the ceiling. The black "smoke-cloud" above the waste basket can be considered to schematically represent the buoyant heat plume as well as the smoke per se, and this heat and smoke will "pool" in the upper portion of the room. This pool of hot gases and smoke will be at least as deep as the soffits of the highest door or other opening in the room.

In his full scale experiment which would correspond in a more general household fire scenario to the ignition of the wall or furniture, Williamson[4]

defined the end of state J and the beginning of state K as the ignition of the specimen. There may be multiple ignitions in the vicinity of the original ignition source, but if a fire is to become serious, the actual number of burning objects is not as important as the conditions in the zone of hot gases filling the upper portion of the room. At this state of the fire growth, the instance the flames reach the ceiling constitutes one of the most important events since combustible gases, or the ceiling itself, if it is combustible, can ignite and contribute to the burning in the room. The flames shown in Figure 1(c) have reached the ceiling and are spreading along its surface. These flames add to the heated zone at the ceiling and reinforce the radiation which is bathing the room. One of the important consequences of this radiation is that other combustible materials can be ignited, as schematically shown in Figure 1(c) by the papers on the desk and the couch near the windows. Following ignition of the wall or furniture, the moment when the flames first reach the ceiling thus stands out as the next most critical occurence in the chain-of-events of fire growth. Williamson chose it to denote the end of state K and the beginning of state L.

As more and more heat builds up in the room, there is a point in time, known as flashover, when all of the combustible materials in the room can ignite and begin to contribute to the fire. From that moment, the fire in such a room is considered "fully involved". The flashover state is schematically shown in Figure 1(d) where the windows are broken due to the thermal shock and flames are shown spreading out through both the windows and the doorways. Fires will rarely cause injury to very many people or cause large property damage unless they reach flashover in at least the room-of-origin, and, in general, such fires are also characterized by rapid fire spread beyond the room-of-origin. Williamson shows the flashover event as the end

of state L and the beginning of state M which is the initial state of the fully involved room fire. State M is characterized by an air supply which is insufficient to completely burn all of the contents within the boundaries of the room. This ventilation controlled portion of the fire has ended when enough fuel has been expended or more openings have been supplied to allow most of the burning to take place in the room. That event ends state M and begins state N which, unless new fuel is supplied, or the air supply is diminished, will be the final state of the fire.

The definition of these states of fire growth in a room are as follows:

I - the initial pre-fire period of time which ends with the ignition of the "source".

J - the period of time from the ignition of the source until the ignition of the wall and/or furniture.

K - the period of time from ignition of the wall and/or furniture until flames touch the ceiling.

L - the period of time from when the flames first touch the ceiling until full involvement (flashover) occurs.

M - the period of time from flashover until there is enough air available to burn the fuel in the compartment, and

N - the period of time from when there is enough air available to burn the fuel in the compartment until the fire has burned out.

An event diagram, such as the one in Figure 2, can be constructed to represent this fire growth model. The fire can terminate in any state, and generally, until flashover, the fire can be considered confined to the original compartment. It is during state M that the fire is most likely to spread through openings in the walls or ceiling. In the adjacent space, the fire growth process then starts from a new state J in which the flames emerging from the room-of-origin can be considered the ignition source. This is schematically represented by the symbol (R') in Figure 2.

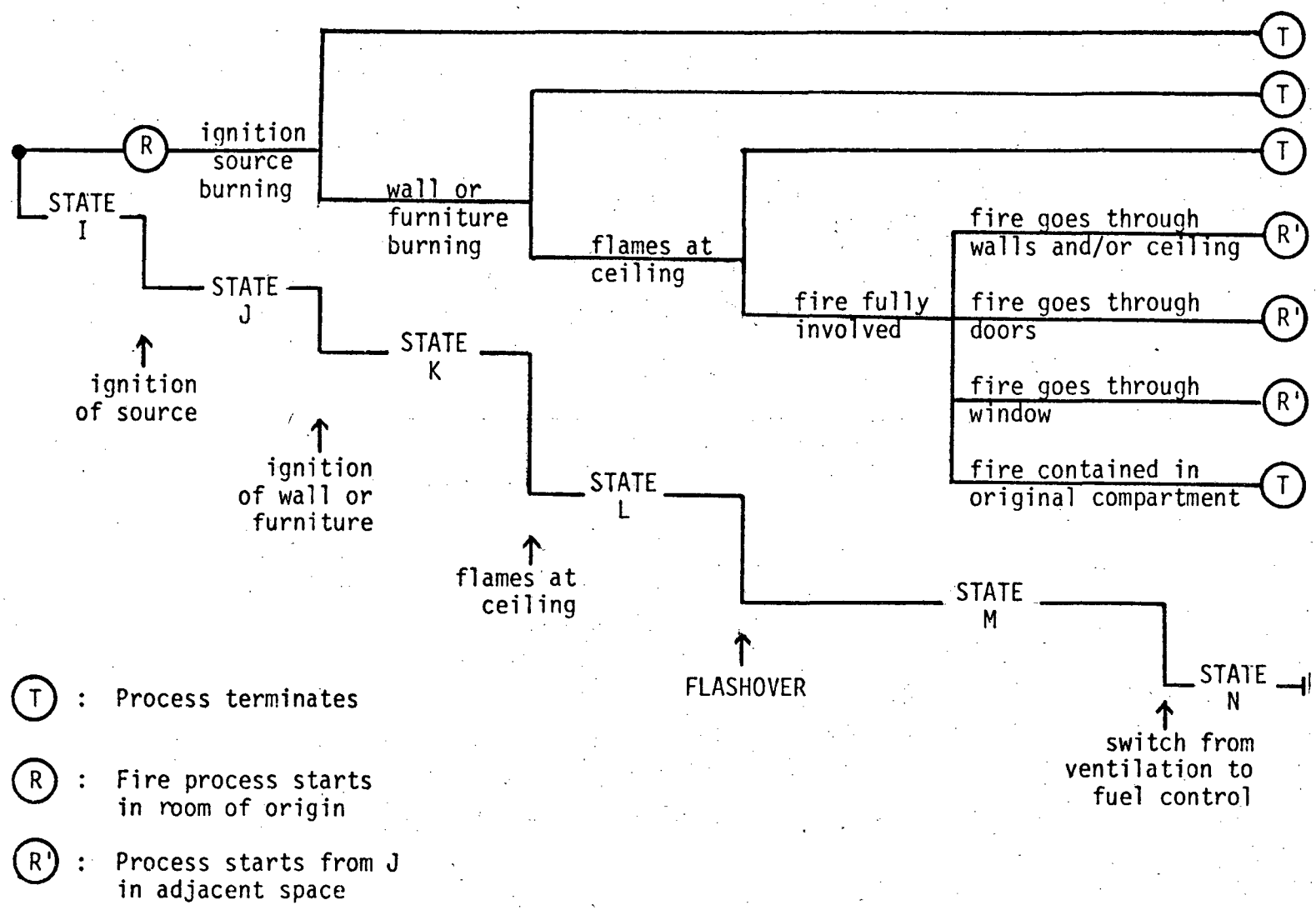


FIGURE 2: Fire Growth Model for Fire in a Room

This paper will concentrate on the Fire Growth Model (FGM) and the Fire Protection Model (FPM) and it will not explicitly develop the Smoke Spread Model (SSM) or the Human Response Model (HRM). The Fire Protection Model (FPM) consists of three distinct elements: "Control Combustion Process"; "Suppress Fire"; and "Control Construction" as described in the well-known National Fire Protection Association's Decision Tree under the heading, "MANAGE THE FIRE"[5]. That portion of the NFPA Decision Tree is shown in Figure 3 for illustrative purposes. This decision tree is a success tree with the top event denoting the satisfactory management of the fire to prevent injury or loss of property. This type of success tree is the dual of a fault tree in which the top event would be the loss of fire control leading to fire injury or property loss. The FPM is more appropriately described by a success tree since it is designed to manage the fire rather than to allow its uncontrolled growth. While the FGM focuses on fire growth, the FPM essentially opposes it.

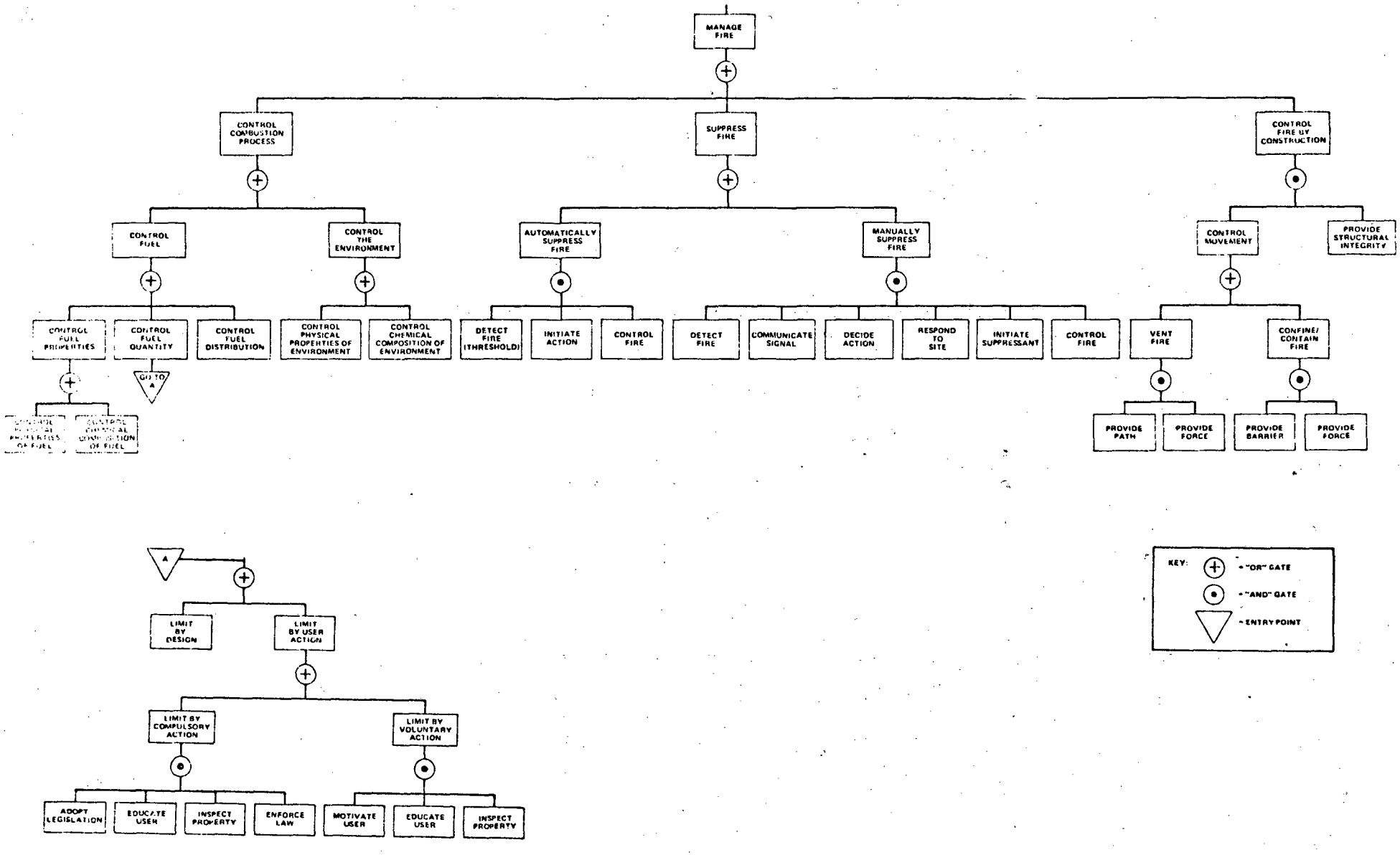


FIGURE 3: Excerpt from the NFPA Decision Tree

APPLYING FIRE TESTS TO QUANTIFY THE STM

Both the FGM and FPM can be quantified by the use of fire test information. The FGM can be quantified by the use of full scale fire growth tests[3,4] and by the use of tunnel test information[6] One of these branches, "Control by Construction," is quantifiable by using fire resistance test results. It is assumed here that flashover has occurred in the room-of-origin. It should also be remembered that the containment of a fire depends on the walls, the doors, the ceiling and perhaps other building elements such as windows or cable and pipe penetrations.

The quantitative development of both the FGM and FPM will be presented through the use of an example. Let us suppose that a certain building is being considered for rehabilitation. Figure 4 shows the floor plan of a high rise office building constructed in the late 1930's. The arrows point to the only stairways which provide escape from each floor. The many offices on both sides of the dead-end corridor labelled A-B could be isolated if a fire started in an office such as No. 1, and then blocked the corridor between No. 1 and 3. Moreover, the corridor doors and transoms in the actual building are 90% plain glass (as opposed to wire glass), and once a fire has fully involved an office, such as No. 1 in Figure 4, it would break the glass in the door and transom and spread smoke and fire into the corridor. Not only would this prevent the escape of everybody in other offices served by this corridor, but it would also cause the plain glass in the door and transom of the opposite office, Office No. 3 to shatter and allow the fire to spread within that space. The fire would then proceed down the corridor from A to B entering the remaining offices by way of the plain glass doors and transoms. More than thirty floors of the building have the same basic floor plan.

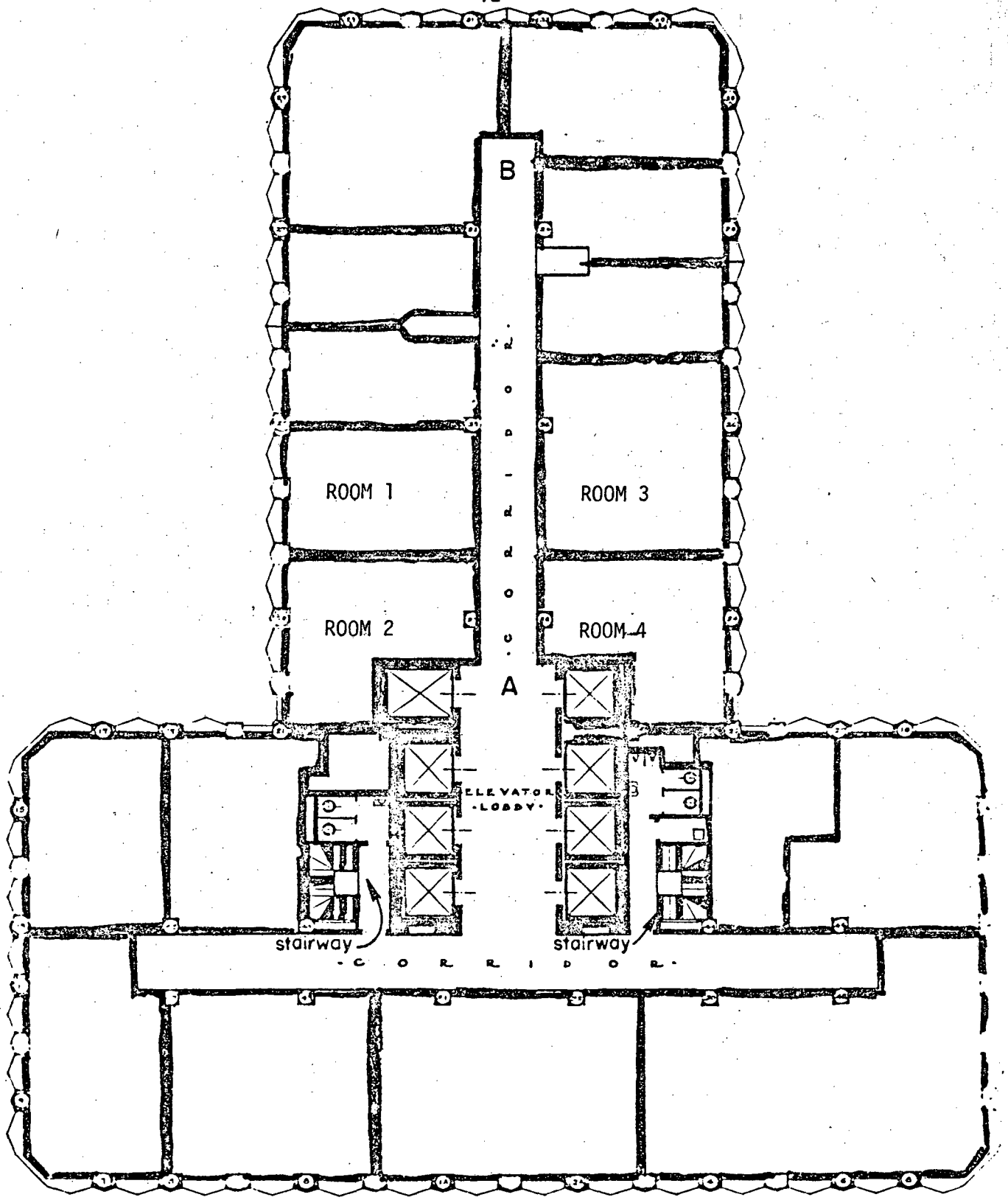
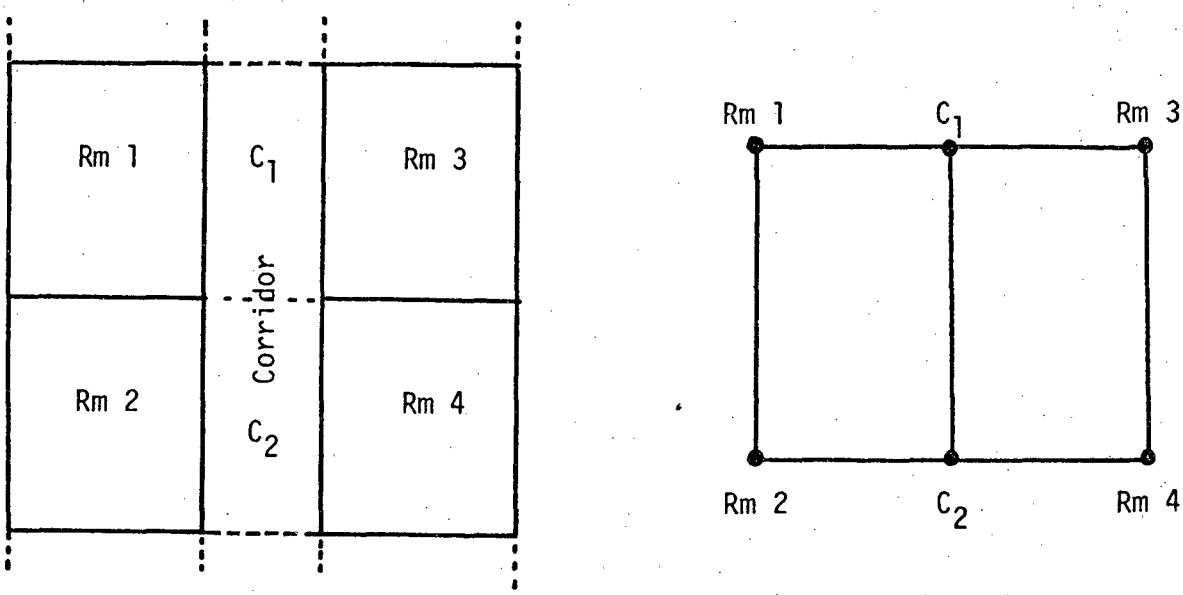


FIGURE 4: 23rd Floor of a High-Rise Office Building Built in the 1930's. Entrance doors to all offices have plain glass covering approximately 90% of their area. There are also plain glass transoms.

At the start of our fire risk assessment we can see that the configuration of Rooms 1 through 4 shown in Figure 4 can be schematically represented by the elementary floor plan in Figure 5(a). The rooms are simplified to squares and the corridor is represented by the segments C_1 and C_2 which are opposite Rooms 1 and 2, respectively. Then in order to enable us to consider the spread of fire beyond the room-of-origin, the floor plan is transformed into a graph as shown in Figure 5(b). This is similar to the process described by Dusing et al[7]. Each link in the network represents a possible route of fire spread for the FGM and some of the links are exit paths for the HRM.



(a) Floor Plan

(b) Corresponding Graph

FIGURE 5: Illustration of Transforming a Floor Plan into a Graph.

The method[8] to be used in this paper for calculating the expected shortest time for the fire to spread from one compartment to another is based on the premise that the duration of fire resistance of each barrier

element, and the duration of the fire to fully develop in each compartment have a given independent discrete probability distribution. We shall begin by showing how to construct a discrete probability distribution from fire test data. First, partition the time axis into equal spacing intervals. Then, construct a histogram for the duration of the fire resistance of a particular material and element. From this histogram, a discrete distribution can be made by collapsing everything within each interval into the midpoint of that interval. For example, the fire resistance of various 10.16 cm (4") clay tile masonry walls is reported to vary between 10 and 35 minutes[9]. There are eleven different fire tests on exposed clay tile assemblies which can be used to produce the histogram shown in Figure 6(a). This histogram can then be replaced by the discrete distribution shown in Figure 6(b).

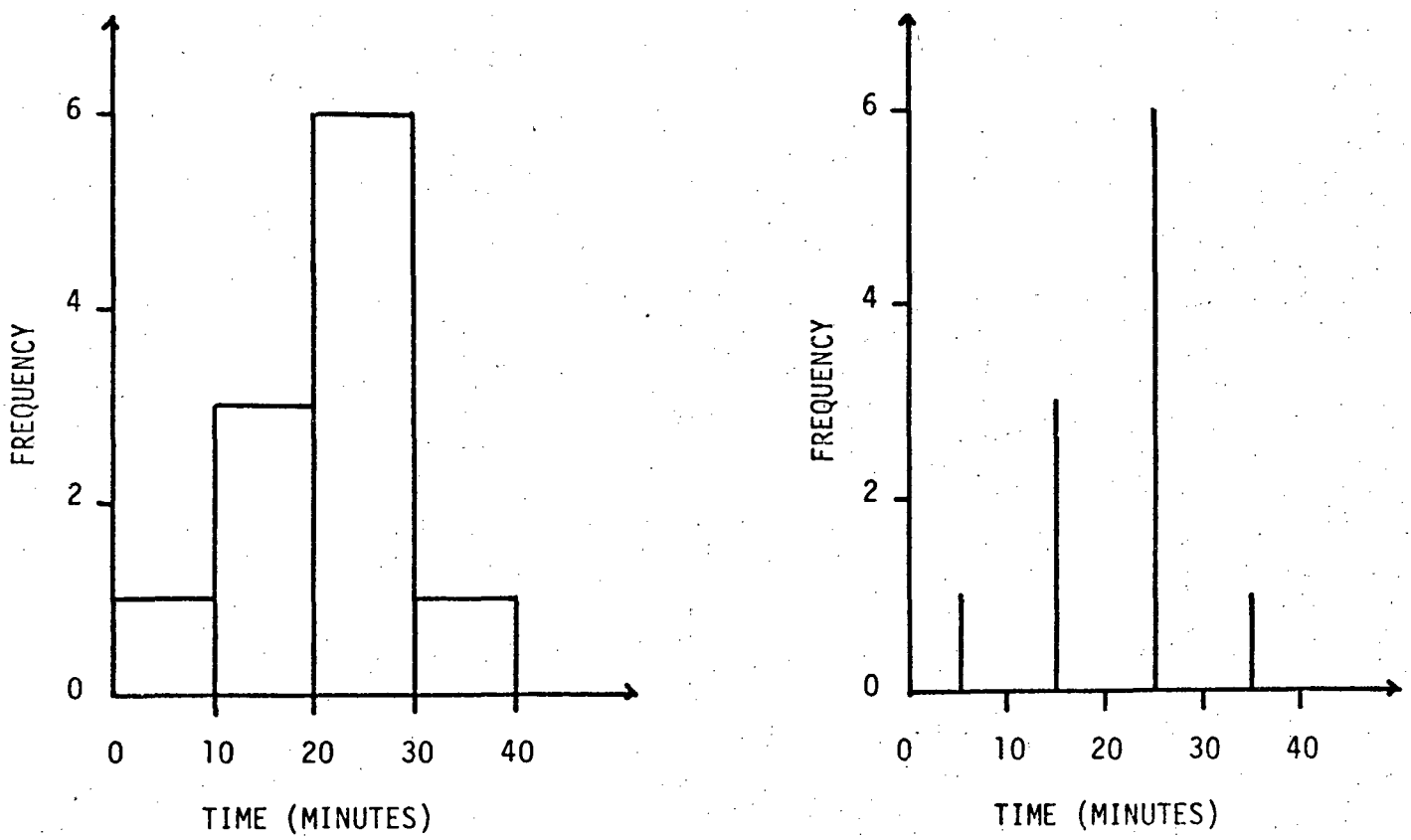


FIGURE 6: Histogram of Discrete Distribution of 10.16 cm (4") Clay Tile Walls.

The discrete distribution for this 10.16 cm (4") clay tile wall is:

$$\rho(t) = \begin{cases} \rho_1 = 0.091\ (1/11) & \text{at} \quad t = 5 \\ \rho_2 = 0.273\ (3/11) & \text{at} \quad t = 15 \\ \rho_3 = 0.545\ (6/11) & \text{at} \quad t = 25 \\ \rho_4 = 0.091\ (1/11) & \text{at} \quad t = 35 \end{cases}$$

If we assume that Room 1 is the room-of-origin, and that once a compartment has been burned out, fire cannot return to that compartment, then the graph shown in Figure 5 can be modified to represent the spread of fire and the passage of time. It now becomes the FGM network, and is schematically arranged in Figure 7 to show a flow of time to the right. The nodes denoted by a prime represent a fully developed fire in the compartment. Three different types of links are identified. The first corresponds to the fire growth in a compartment, the second to the fire breaching a barrier element, and the third to the fire spread along the corridors. To each link i, a pair of numbers (p_i, t_i) is assigned. In this paper p_i represents the probability that a fire will go through link i, and t_i represents the time that is will take for such a fire to go through link i.

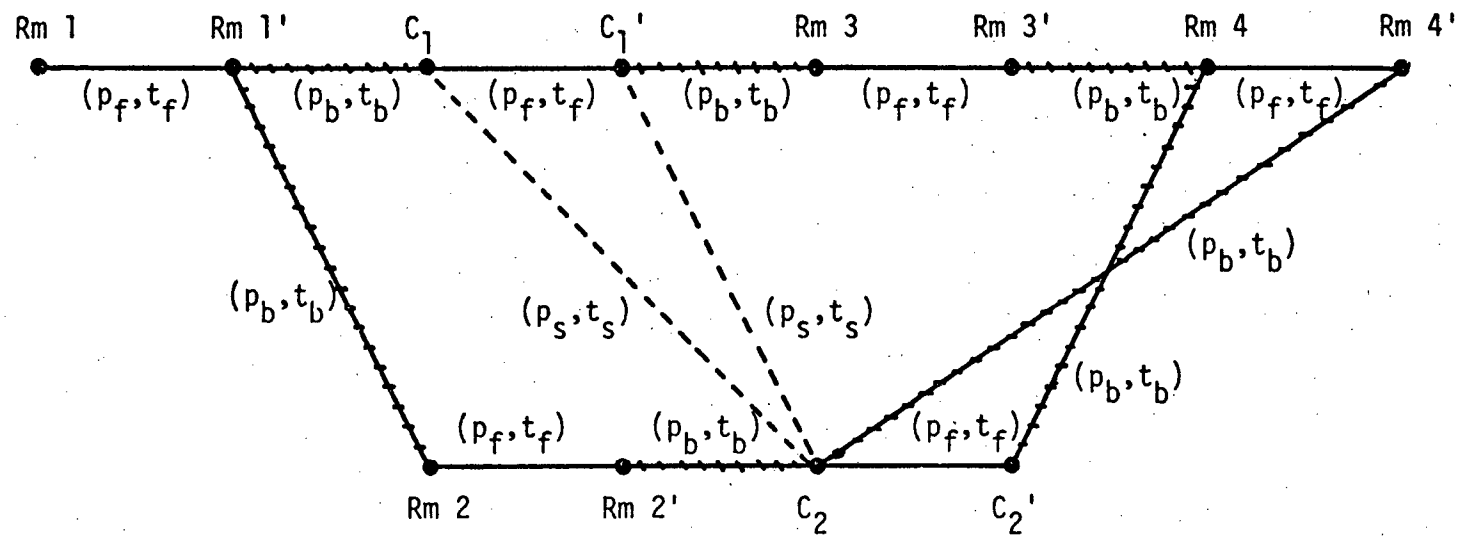


FIGURE 7: Probabilistic Network of Fire Spread of Room 1 to C_2

———— : Fire growth within compartment

———— : Fire breaches barrier elements

- - - - - : Fire spread along corridor

The number pair (p_f, t_f) represents the probability and time for the fire in the room to progress from state J through state L, i.e., to become fully involved. The flashover time, t_f, in a room varies according to the type of wall and ceiling lining material used, as well as the room's contents. For this example the FGM in each space is simplified by taking the approach of Lie and giving a probability distribution based on flame spread or reaction to fire tests[6]. Figure 8 shows Lie's estimates for time-to-flashover of three levels of performance represented by a flame spread classification of 25, 75, and 150 as measured by the Tunnel Test, ASTM E-84, or the Dutch "flashover" test. It should be noted that the authors doubt the validity of this behavior for plastic lining materials, but consider it to be realistic for cellulosic materials[10].

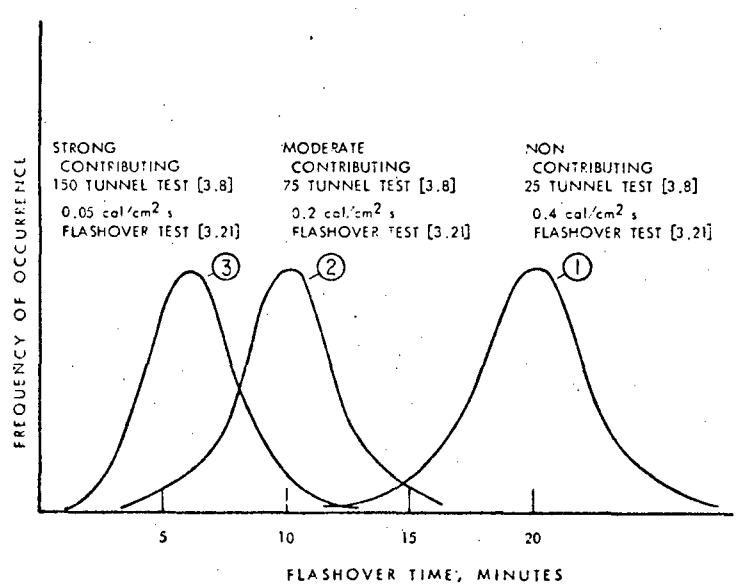


FIGURE 8: Frequency of Fires with a Certain Flashover Time for Rooms Lined with Materials which are Strong Contributing, Moderately contributing and Non-Contributing to the Fire Growth.[6]

The section of the corridor. C_1, opposite Room 1 is treated as a separate fire compartment and is assigned a (p_f,t_f) for the link from C_1 to C_1' . The number pair (p_s,t_s) represents the probability and time for the pre-flashover spread of fire along the corridor from C_1 to C_2. As a first approximation, one could consider the probability of pre-flashover spread of fire in the corridor from C_1 to C_2 to be governed by the flame spread classification of the corridor's finish materials on the walls and ceiling, as measured by a test method such as the ASTM E-84, Tunnel Test. This again would be limited to cellulosic materials, although a detailed review of the test results could yield information for plastic lining materials.

Once full involvement occurs in C (i.e., the node C_1' is reached) the fire spread in the corridor is influenced more by the ventilation in the corridor and by the contribution of Room 1 than by the material properties of the corridor itself[11]. Thus, there is a separate link, C_1' to C_2 which has its own (p_s,t_s).

The number pair (p_b,t_b) represents the probability of failure of the barrier element with t_b representing the endurance of the barrier element as measured by a standard fire resistance test such as ASTM E-119. Barriers may consists of such components as walls, ceilings and doors. Penetrations, such as piping or cables through walls, will affect the fire resistance of barrier elements. If not properly protected, the penetration tends to increase p_b, and decrease t_b. With regards to doors, an open door would offer no resistance to fire spread, and t_b would equal zero. On the other hand, if the door is closed, t_b would depend on the type of materials that the door is made of. Figure 9 on the next page shows some distribution of t_b for doors based on the authors' subjective judgement. The probability

of doors being open would depend on the presence of self-closing devices and the absence of door stops.

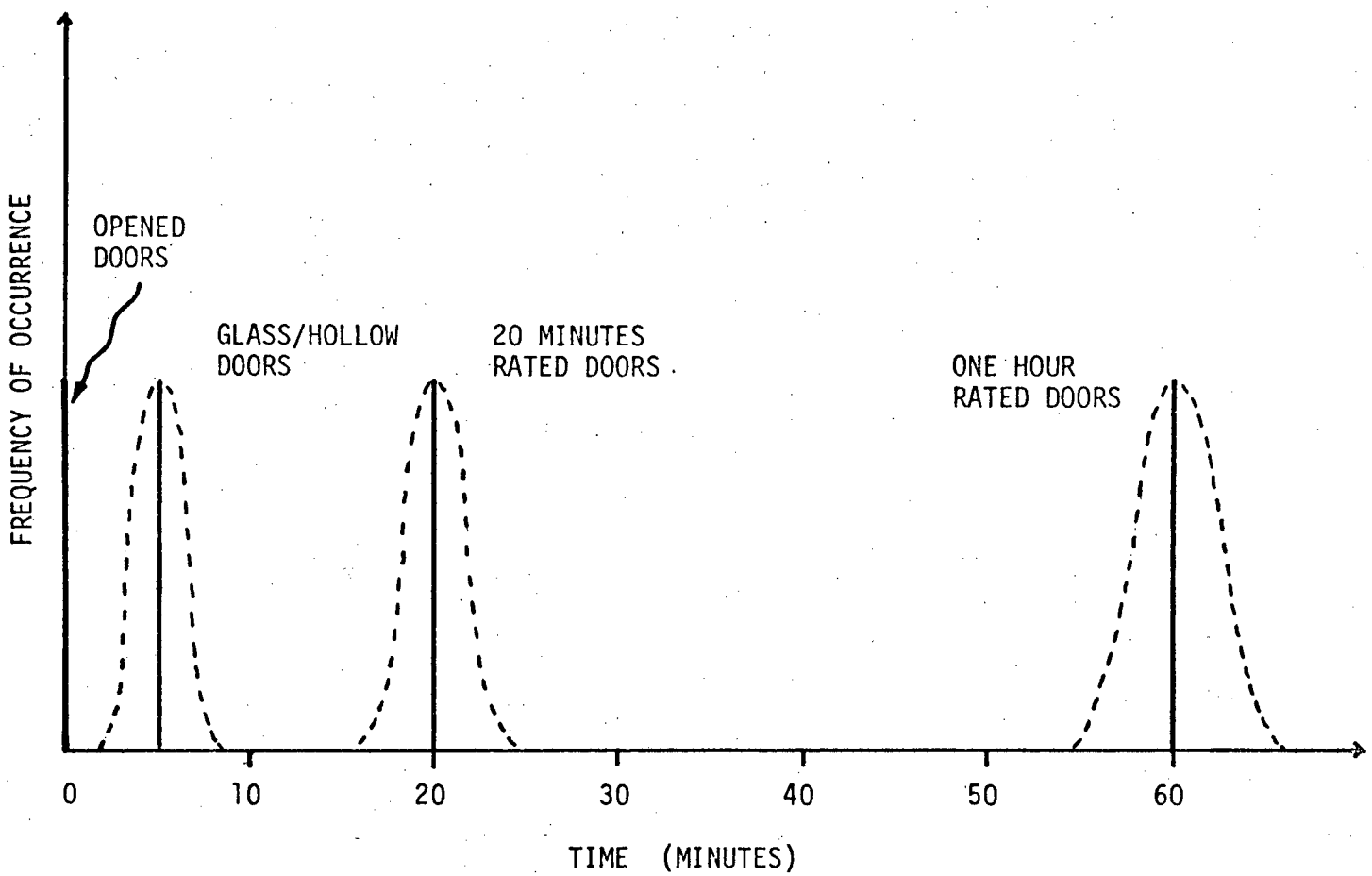


FIGURE 9: Frequency Distributions for Fire Containment by 3 Types of Doors. These are based on subjective experience. NOTE: Open door has a zero rating.

COUPLING THE FGM and FPM

As shown above, the FGM and FPM can be quantified by the use of fire test data, but to solve the problem of determining the risk of fire spread it is necessary to couple them together. We have chosen the use of an emergency equivalent network. This is an abstraction of the given network in which (a) each link has a Bernoulli probability of success, (b) the link delay time is deterministic, and (c) the expected shortest time between two points in the emergency equivalent network is equal to the expected shortest time in the original network. If in the original network one link, say the link between nodes j and k, has discrete probability distribution:

$$\rho_{j,k}(t) = \begin{cases} \rho_m & \text{for } t = t_m, \quad m = 1,2,\ldots r, \\ \rho_\infty = 1 - \sum_{i=1}^{r} \rho_i & \text{for } t = \infty \end{cases}$$

then the transformation into an emergency equivalent network can be accomplished by replacing the (j,k) link by r parallel links (j,m,k), m = 1,2,...4, where each link (j,m,k) has an independent probability of success p_m and associated time t_m where:

$$p_1 = \rho_1$$

$$p_m = \rho_m \left(1 - \sum_{i=1}^{m-1} \rho_i\right)^{-1}, \quad m = 2,3,\ldots r \qquad (1)$$

If we are interested in the expected shortest time for the fire spread between two nodes in the network, call it the source node and the sink node, we have to list all the possible paths between these two given nodes.

Many different algorithms are available to find all the paths[12]. Let $P_1, P_2, \ldots, P_n$ be all the paths going from the source to the sink node. For each path P_i, $i = 1, 2, \ldots, n$, find the travel time T_i and the probability P_i where:

$$T_i = \sum_{\text{link } j \in P_i} t_j \qquad P_i = \prod_{\text{link } j \in P_i} p_j \tag{2}$$

Number the n paths such that $T_1 < T_2 < \ldots < T_n$. Let E_i denote the event that path P_i is connected. That is, with probability greater than zero, fire will spread through each node in P_i. Let Q_m denote the probability that the fire will spread from the source to the sink node via one or more of the paths $P_1, P_2, \ldots, P_m$. That is mathematically:

$$Q_m = \text{Prob}\,[E_1 \cup E_2 \cup \ldots \cup E_m] \tag{3}$$

Let the conditional probability that paths P_1 or P_2 or ... or P_{m-1} are connected, given that path P_m is connected, be denoted by $P_{U|m}$. That is

$$P_{U|m} = \text{Prob}\,[E_1 \cup E_2 \cup \ldots \cup E_{m-1} \mid E_m]$$

Let us define $P_{U|0} = P_{U|1} = Q_0 = 0$. We then obtain $P_{U|m}$ from Q_{m-1} using

$$P_{U|m} = [Q_{m-1}]_{P_{m \leftarrow 1}} \tag{4}$$

where subscript $P_{m \leftarrow 1}$ indicates that all the link probability associated with P_m are set equal to unity in the subscript expression. Using basic probabi-

lity theory we can then show that:

$$Q_m = Q_{m-1} + P_m [1 - P_{U|m}] \tag{5}$$

where P_m is the probability that path P_m is connected. Equations (4) and (5) can be used recursively to determine expressions for $P_{U|1}, P_{U|2}, \ldots, P_{U|n}$. The probability of connectivity R is then given by:

$$R = P_1 + P_2 (1 - P_{U|2}) + \ldots + P_n (1 - P_{U|n}) \tag{6}$$

and the expected shortest time for the fire to spread from the source node to the sink node, given that the two nodes are connects, $\overline{T}$, is given by:

$$\overline{T} = [T_1 P_1 + T_2 P_2 (1 - P_{U|2}) + \ldots + T_n P_n (1 - P_{U|n})]/R \tag{7}$$

NUMERICAL SAMPLE SOLUTION

Let us go back to the example stated above involving unrated doors on the corridor. Take the floor plan shown in Figure 5(a) and suppose we want to find the expected shortest time for a fire to spread from Room 1 to corridor C_2, given that Room 1 has ignited. This would indicate fire growth is such as to make the corridor unavailable for either an exitway or for access for fire suppression in the rooms along the corridor. The following assumptions are made for this illustration:

1) All the paths involving Rooms 3 and 4 are ignored.

2) The room-of-origin (Room 1) as well as the other rooms are to have contents and lining materials that are characterized by Lie[6] to be moderately contributing to fire growth and thus, according to Figure 8, has a t_f of 10 minutes.

3) The probability of a fire in the room-of-origin to grow to flashover is 0.50 (1/2), and in the other rooms it is 1.

4) The initial assumption will be that all rooms have plain glass doors without self-closing devices leading to the corridor. This will be modified later to illustrate a shift to self-closing 20 minute doors. It will be assumed that the probability of a door being closed is 0.50 (1/2). This gives:

$$\rho_1 = 0.50\ (1/2) \quad \text{at} \quad t = 0 \text{ minutes}$$

$$\rho_2 \quad 0.50\ (1/2) \quad \text{at} \quad t = 5 \text{ minutes}$$

Using formula (1) results in having two links between rooms and corridors with (p_i, t_i) being equal to (0.50, 0) and (1, 5).

5) The walls between the rooms are 10.16 cm (4") clay tile masonry walls. Using the discrete distribution shown earlier and equation (1), we have four links between rooms with (p_i, t_i) being equal to (0.091, 5), (0.30, 15), (0.86, 25), and (1, 35), respectively. Notice that the application of equation (1) results in the fire having a probability of 1 of eventually breaching the wall in 35 minutes.

6) The differentiation of C_1 and C_1' will be dropped for this example. An open door or a plain glass door will cause a very severe fire in the corridor, and transition to flashover in the corridor will be very rapid. To estimate the fire propagation from C_1 to C_2 we will rely on NBS Corridor Test data reported by Fung[13]. Neglecting the inclusion of the initial fire growth, this data gives the following distrubtion:

$$\rho_1 = 0.50\ (1/2) \text{ at } t = 7.5 \text{ minutes}$$
$$\rho_2 = 0.125\ (1/8) \text{ at } t = 12.5 \text{ minutes}$$

This results into having two links between C_1 and C_2 with (p_i, t_i) becoming equal to (0.50, 7.5) and (0.25, 12.5), respectively.

An emergency equivalent network to represent the fire growth and the various barriers to its spread can now be constructed for this example, and it is shown in Figure 10 on the next page.

There are a total of twelve links in the network labeled $\ell_1, \ell_2, \ell_3, \ldots \ell_{12}$ from which twelve different paths from Room 1 to C_2 can be established. These paths are listed in Table I and the corresponding P_i and T_i's [as calculated from equation (2)] are given. The paths are enumerated so that

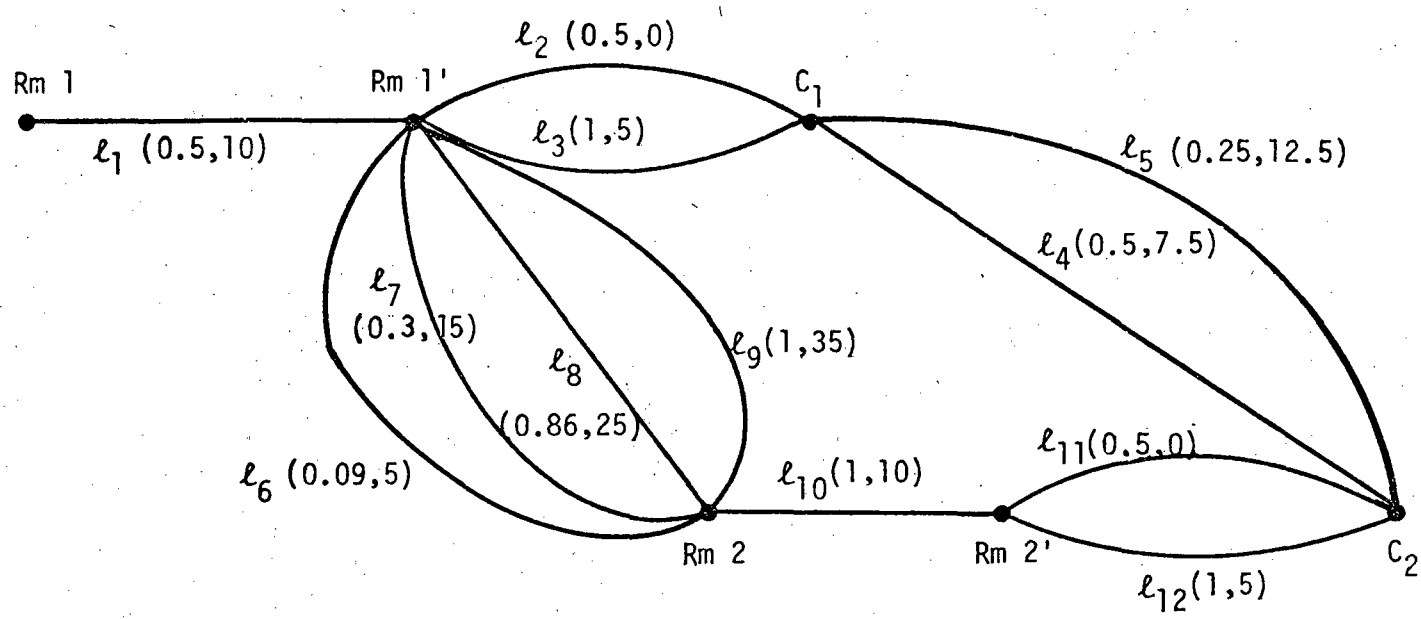


FIGURE 10: Emergency Equivalent Network with 5-Minute Unrated Doors

Paths	Component Links	Probability P_i	Time T_i (minutes)
1	1-2-4	0.13 (1/8)	17.5
2	1-2-5	0.06 (1/16)	22.5
3	1-3-4	0.25 (1/4)	22.5
4	1-6-10-11	0.02 (1/44)	25.0
5	1-3-5	0.13 (1/8)	27.5
7	1-6-10-12	0.05 (1/22)	30.0
8	1-7-10-12	0.08 (3/40)	35.0
9	1-8-10-11	0.21 (3/14)	40.0
10	1-8-10-12	0.43 (3/7)	50.0
11	1-9-10-11	0.25 (1/4)	55.0
12	1-9-10-12	0.50 (1/4)	60.0

TABLE I: Pathways Through the Example Emergency Equivalent Network Assuming 5-Minute Unrated Corridor Doors

$T_1 < T_2 < \ldots < T_{12}$, and the component links are identified in Table I thereby enabling the reader to identify the path of the fire. Each of these paths can be described by a fire scenario in words; for instance, path 1 consisting of links ℓ_1, ℓ_2 and ℓ_4 would be:

> "The fire flashes over, escapes from Room 1 through an open door into the corridor C_1 and then spreads along the corridor to C_2".

The probability of that scenario is 0.13 (1/8); it is strongly dependent on the original subjective assignment of the probability being 0.50 (1/2) that flashover will occur in Room 1, and of the probability being 0.50 (1/2) that the door will be open. The time, T, of 17.5 minutes is composed of the assigned times of 10 minutes for Room 1 to flashover and 7.5 minutes for the fire to spread in the corridor from C_1 to C_2. If more sophisticated models were incorporated for these links the final P_i and T_i would be different, but the reader can see the origin of each value in Table I. One can also see that as the paths begin to include the higher fire rated wall between Room 1 and 2 the probability increases. For instance, path 12 consists of links ℓ_1, ℓ_9, ℓ_{10}, and ℓ_{12}, which could be described:

> "The fire in Room 1 breaches the clay tile wall and spreads to Room 2. After having reached flashover, the fire breaches the closed door into the corridor C_2".

The probability for this scenario is 0.50 (1/2) with a time of 60 minutes.

The emergency equivalent network can be examined further by finding all the $P_{U|m}$, m = 2,3, ... 12, from equations (4) and (5) and then the connectivity, R can be found from equation (6) to be 0.50 (1/2) and the

expected shortest time, $\bar{T}$, from equation (7) to be 29.6 minutes. The origin of the connectivity of 0.50 (1/2) is a direct result of the assumed probability of 0.50 (1/2) for flashover in the room-of-origin and the occurrence of unity probabilities in the remaining links which make-up certain paths through the network.

Let us change the starting assumptions slightly and explore how the network changes. Suppose self-closing 20-minute fire-rated doors had been installed in the corridor of our example. We will assume that the reliability of the self-closures is perfect and that door stops had not been allowed. This changes assumption (4) (above), but all other conditions remain the same. The emergency equivalent network is shown in Figure 11 and the P_i and T_i for the paths are given in Table II. Note that the links have been renumbered for this example. For instance, ℓ_9 from Figure 10 has become ℓ_8 in Figure 11.

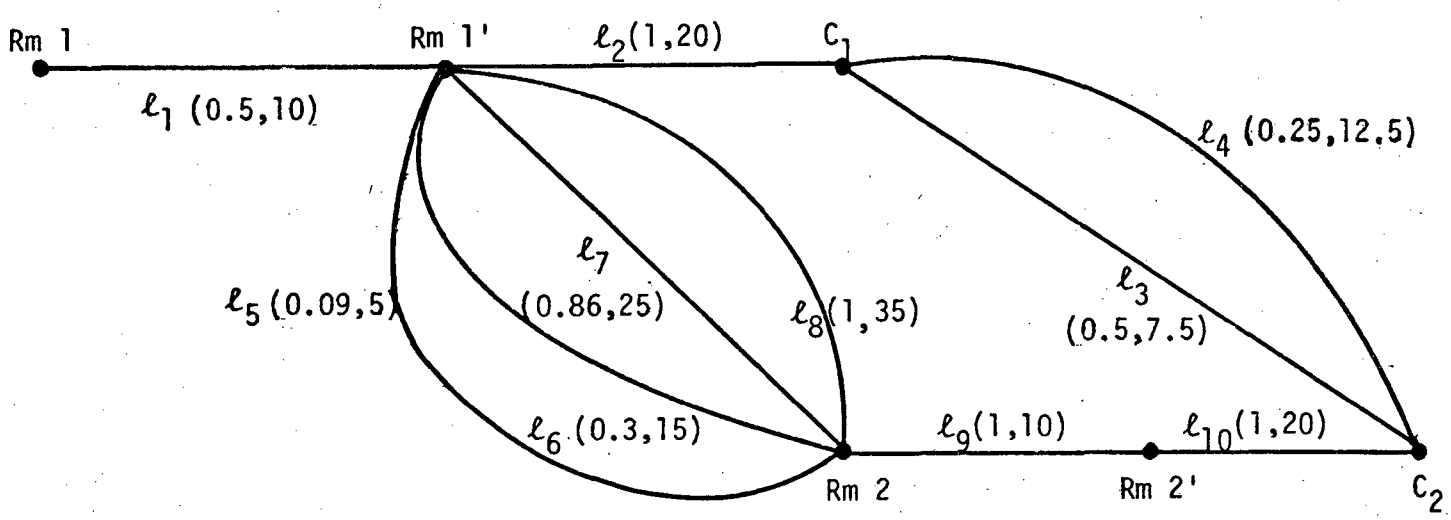


FIGURE 11: Emergency Equivalent Network with Self-Closing 20-Minute Rated Doors.

Paths	Component Links	Probability P_i	Time T_i (minutes)
1	1-2-3	0.25 (1/4)	37.5
2	1-2-4	0.13 (1/8)	42.5
3	1-5-9-10	0.05 (1/22)	45
4	1-6-9-10	0.15 (3/20)	55
5	1-7-9-10	0.43 (3/7)	65
6	1-8-9-10	0.50 (1/2)	75

TABLE II: Pathways Through the Example Emergency Equivalent Network Assuming Self-Closing 20-Minute Rated Corridor Doors

The connectivity remains 0.50 (1/2) in this case but the expected shortest time becomes $\overline{T}$ = 47.1 minutes. All of the T_i's have been increased by the presence of the fire rated door reflecting the rational of model building codes to require self-closing 20-minute doors on corridors.

CONCLUSIONS

The interplay of fire growth and fire protection has been modelled in the emergency equivalent network. This model facilitates an evaluation of design changes and affords ready comparison of the different strategies under consideration to effect such changes. The numerical example was necessarily simplistic, but it illustrated how the original assumptions could be clearly traced. The individual fire tests on clay tile, for instance, could be seen in the final pathways of the network. If the original fire in Room 1 had been modelled more completely, the ventilation controlled phase of the fire (state M) would have ended before the 35 minute wall had been breached. This more sophisticated step could easily be added and this would make the connectivity, R , more meaningful.

Looking at this model in detail, we realize that more information is required from the fire tests performed on building elements than we now obtain from standard tests. At this time, the furnace fire conditions do not necessarily represent the positive pressure and excess fuel conditions of the ventilation controlled phase of a fire thereby decreasing the meaningfulness of the test results. The end point criteria are features of the standard test which are not rationally based and many of the tests terminate before these criteria are reached. It is our recommendation that new test standards be established which are rationally based with regards to the fire exposure and the criteria, and which at the same time, ensure that passing the new standard would be equivalent to the passing of the old standard. Such new test standards are essential to the development of more sophisticated techniques for risk analysis.

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