NBSIR 77-1273

Directions to Improve Application of Systems Approach to Fire Protection Requirements for Buildings

Harold E. Nelson

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Institute for Applied Technology
National Bureau of Standards
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Interim Report
(Sept. 1975 to Dec. 1976)

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U. S. DEPARTMENT OF COMMERCE

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U.S. DEPARTMENT OF COMMERCE, Juanita M. Kreps, *Secretary*
Dr. Sidney Harman, *Under Secretary*
Jordan J. Baruch, *Assistant Secretary for Science and Technology*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Acting Director*

FOREWORD

This report is an interim product of a joint effort of the Department of Health, Education, and Welfare (HEW) and the National Bureau of Standards (NBS) Center for Fire Research. The Program is a five-year activity initiated in 1975 consisting of projects in the areas of decision analysis studies, fire and smoke detection systems, smoke movement and control, automatic extinguishment, and behavior of institutionalized populations in fire situations.

This report is part of the decision analysis study. In addition to giving a history of recent developments in this area the report looks toward the future and proposes a model of fire impact based on a states transition concept leading to a plan for the derivation of a viable fire protection engineering technology. Work in developing these concepts further is a part of the Program and the other efforts of the Center for Fire Research.

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Harold E. Nelson

Abstract

This paper covers an examination of the recent and ongoing work in the development of systems' approaches for design of fire protection in buildings, as carried out in the United States. The scope of coverage includes:

(1) a brief review of the development of fire safety systems' approaches in the United States, to the degree felt important to understanding the current situation;

(2) an overview of the more extensive and pertinent fire growth systems' analysis approaches;

(3) a discussion of systems for the analysis of building fire safety design directed at establishing building requirements;

(4) a review of the directions and activities now underway to integrate the fire growth models and the total building performance models into a combined approach.

This paper proposes a model of fire and its impact based on a "states-transition" concept. The fire is viewed as two separate sequences (Fire Behavior and Human Behavior). Each sequence consisting of connected realms of consistent behavior. The concept views these sequences as interrelating, with a distinct rate consistent for each realm. The concept of "states-conditions" is also evaluated. A matrix relating the factors, conditions, and development phase of fire is presented. Finally, a plan for the derivation of a viable fire protection engineering technology is presented.

Key words: "And" gate; behavior; critical events; decision; decision tree; dominant factors; episode; event; fire; fire behavior; fire growth; fire safety; human behavior; models; phase; probability; rate constant; realm; sequence; state; states-transition; system's approach.

1. RECENT HISTORY OF THE DEVELOPMENT OF SYSTEM'S APPROACH TO FIRE SAFETY IN THE UNITED STATES

It is worthwhile to briefly view the history of system's development in fire safety in the United States. Of particular interest is that portion of the history that relates to the use of event trees as a principal instrument in total building fire safety performance analysis. The "success" or decision type of event is a candidate alternative to the current approaches used in building codes.

The event tree methodology has its technical antecedents in reliability analysis and fault tree analysis. Both of these approaches have been extensively examined in the United States. An excellent review of the state-of-the-art at varying levels of sophistication in reliability and fault tree analysis is contained in the recent Society for Industrial and Applied Mathematics publication, "Reliability and Fault Tree Analysis" [1][1].

The recent history of milestones in the application of such systems' concepts to the determination of fire protection requirements for buildings can be chronicled approximately as follows:

A. <u>International Conference on Firesafety in High-Rise Buildings - Airlie, Virginia, April 12-16, 1971</u>.

   The report of this conference [2] strongly emphasized the need for a total system's design and management approach in transferring new design and use concepts to the creation and operation of modern high-rise buildings. The conference report made a number of proposals listing the general elements for such a system.

B. <u>Seattle Federal Building</u>. The Seattle Federal Building was chosen by the General Services Administration (GSA) to be used as an example of potentials for engineered fire safety for

[1] Numbers in brackets refer to the literature references listed at the end of this paper.

high-rise buildings. The author, then Director of Accident and Fire Prevention for the General Services Administration, reviewed the proposed design of the Seattle Building in consultation with the design team and unilaterally selected the fire safety requirements for that building. This occurred in June 1971. While the items selected were the best judgement of the writer in terms of systematic approaches to fire safety there was no system technique developed at that time. The Seattle Federal Building can best be considered as the father rather than the child of system's approach techniques.

C. Reconvened International Conference on Fire Safety in High-Rise Buildings, Washington, D.C., October 5, 1971.

This conference was primarily important in two aspects:

1. A presentation entitled "A Method of Analysis for Control of Building Fire" was delivered by Mr. Irwin A. Benjamin, National Bureau of Standards. Included in this presentation was a fault tree event logic diagram considering the elements or events essential to the control of the building fire. This fault tree is reproduced as figure 1 attached to this paper.

2. The author presented a review of the fire safety systems for the Seattle Federal Building. Fire Protection elements were summarized in a fire safety systems guide sheet which is included as figure 2. Figures 1 and 2 constitute the first attempts to make logical analysis of the total fire safety systems in buildings.

D. GSA Decision Tree. A joint effort by NBS and GSA (General Services Administration) developed a success tree aimed at determining the various approaches available to achieving fire safety objectives in buildings. This was then taken by GSA through several revisions and generations. The current version is attached as figure 3. This is the basic reference document in the GSA goal-oriented system's approach.

E. National Fire Protection Association (NFPA) System's Committee. In 1972 the NFPA formed the Committee on System's Concepts for Fire Protection in Structures. This Committee using the background for all the preceding items developed a success tree. The current version of that success tree is available from the NFPA. The principle difference between the GSA and the NFPA tree is in manner of expression. The GSA tree generally uses a quasi-Algebraic approach that attempts to express the subdivision of each event as functional elements of that event. The NFPA tree expresses itself in terms of cause and effect. At each gate in the NFPA tree, an attempt has been made to assure the events below the gate represent all causal elements of the event above the gate.

F. GSA System's Approach. The General Services Administration produced the "Interim Guide to Goal Oriented Systems Approach to Building Fire Safety" [3]. This was initially produced in 1972 and published as a GSA internal criteria. As of this time this is the only completely described analytical system for probabilistic evaluation of the expected success in total performance of fire safety in buildings.

G. Application of the GSA Goal-Oriented System to Building Design. GSA has applied the goal-oriented system's approach to several buildings and has used the results to acquire the data base of information as essential elements in making design determinations. The level of confidence in the system at this time, however, is such that the system output can be considered an important input but not a sole determiner of major design decisions. Where the system's approach indicates a solution in conflict with traditional (i.e., code type) approaches, it is important that the conflict be resolved on its technical merits rather than any assumption of corrections inherent in either approach. The largest single structure and most extensive application of this has been to the Atlanta Federal Building. This building has currently been designed though not yet built. In 1974 GSA published a report of the application of the goal-oriented system to the Richard B. Russell Court House and Federal Building now under construction in Atlanta, Georgia [4].

H. <u>NFPA/Department of Housing and Urban Development Study.</u> In 1975 the U.S. Department of Housing and Urban Development awarded a contract to the National Fire Protection Association to undertake a study of the application of system's analysis and the success tree approach to residential types of structures. This project is now underway. The most significant potential of this project to date is the work done by its subcontractor, Mr. Ed Connelly, OMNEMII Incorporated, in the modeling support for the study.

I. <u>Recent Developments in System's Dynamics/States Transition.</u> The interplay of the participants in all of the above activities has resulted in new concepts. These generally relate to the conditions that govern or dominate any state of fire development, the transition from state to state and the interplay between the states and transition and the actions of humans or the impact of fire protection measures. These are discussed in more detail later in Section 4.

2. SYSTEMS TO DESCRIBE FIRE GROWTH — PHYSICAL MODELS/COMPUTER MODELS

At this time most of the inputs used by those working with system's approach are the same as used in code application and fire insurance consideration. These consist primarily of experience, data from individual tests, separate research results, personal experience, and collected consensus opinion. This imposes important constraint on the use of current systems approach techniques due to the limited degree of confidence that can be placed on the inputs into the system related to fire growth factors. Several different deterministic types of fire growth concepts and fire growth models, however, are currently being developed. One or more of these may make a major contribution towards raising the confidence level in total systems' approaches to the point where it would be reasonable to use system's analysis as the unilateral determinant of fire safety requirements.

A conceptual approach to evaluative fire growth has been published under the title "Systems Analysis of Energy Environment in Buildings" [5]. This study conceived fire in a step-by-step growth process. Its principal value at this time is in evaluating the various <u>states</u> and <u>transitions</u> involved in fire growth.

Efforts have also been directed towards development of empirical models to describe fire growth in more quantitative terms. All of the major efforts in this area involve incremental finite analysis as the basis of the empirical approach. Each of the three major contributions in this area has, however, approached the problem of modeling a fire from a different perspective.

(1) Dr. John A. Rockett in 1968 [6] proposed a model based on subdividing the entire volume of the building or space into cubicle elements and undertaking an analysis of interactions between and within the cubes. In an article discussing the proposed model Dr. Rockett expressed the significant problem as the volume of data necessary to be handled. He expressed confidence in the ability of such a system to handle gross action. However, he expected that fine details about the course of a fire or the movement of smoke will not be susceptible to such analysis for some time. Dr. Rockett is not personally continuing to work in this area but others are using the programs he developed and other aspects of his initial studies.

(2) A University of Dayton Research Institute team with Mr. Jerry Reeves as principal investigator has developed a computerized program for description of fire development (unpublished). In the UDRI approach the positions of all elements in a space are described and the finite fire growth analysis described as incremental spaces on the surfaces of the combustible materials. This program was designed to predict fire development in aircraft interiors and is predicated on spread along contiguous surfaces and transfer across spaces separating such surfaces. The program input is taken from rate of heat release of the exposed materials with the test values measuring speed of flame propagation horizontally, upward, and downward at varying levels of incident flux. To date, the model has not been proof-tested and has not yet been released for public view. Full-scale tests of the system are to be made using aircraft cabin burn-out tests in the near future.

(3) Messers Tom Waterman and Ronald Pape at the Illinois Institute of Technology Research Institute working on a grant from the Center for Fire Research at NBS have proposed a system which they refer to as semistochastic. In their approach, the space is described in terms of its constituents with all fuels identified as boxes located in this space. The input required is basically the rate of heat release of the individual boxes as would occur in a free burning test situation. Using empirical energy input data from numerous tests of furniture and fuel loads in

rooms and spaces, they have developed a computerized system. This system interfaces this data with the impact of the enclosing space, the separation of fuels, and other factors to determine the time, intensity, and form of fire spread, energy development, and combustion product development in the room of fire origin. This program has been completed and is now being reviewed by members of the staff of the Center for Fire Research. Full-scale testing will be conducted at the NBS and the results will be correlated with the model.

3. SYSTEMS FOR THE ANALYSIS OF BUILDING FIRE SAFETY DESIGN

Current approaches to system's analysis for determining building fire safety requirements are primarily based on the decision-tree approach presented in the GSA document entitled "Interim Guide to Goal Oriented Systems Approach to Building Fire Safety" [3].

The use of a decision tree approach of this type provides the user with a unique capability to:

1. study and determine the organization of the various "events"[2] that control or determine fire and the response to fire;

2. establish the interrelationships between these events, and the sequence in which the impact of events must be considered; and

3. state the level of success or other measurements of performance in a given situation.

All systems' approaches are (1) limited by the validity of the data used and (2) require understanding of the meaning of the statements of success or performance produced.

With these capabilities and limitations in mind, the objective of the system's approach is to achieve a better and more exact understanding of the degree of safety provided

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[2] The term "event" is used to describe any physical conditions, use factors, activity, or action that can cause or control fire, its effects, or the response to fire.

along with the ability to determine the impact of individual events or the sensitivity of the system to change during that event. In addition the system's approach will give:

1. a mechanism to allow design innovations and options that best combine the necessary degree of safety with all of the other building design features;

2. a basis to evaluate cost effectiveness where the safety worth can be related to the cost, not simply in terms of monetary differences, but in relation to the actual safety impact per dollar invested; and

3. a system whereby the responsible authorities, be they code officials, underwriters, owners or others can evaluate whether safety goals are being met without having to review each specific design requirement or variation.

The tree network is a diagrammatic means of showing a complete event/logic system that progressively subdivides the problem into smaller and smaller elements to the level at which the user wishes to make input into the system. The tree arrangement assists in: (a) pointing out events which must occur simultaneously or independently, (b) showing which events can contribute most effectively to reaching a goal, and (c) expressing the choices or tradeoffs to insure a satisfactory goal or objective level. The tree does not within itself show the extent of conditionality or exclusivity. It does however provide a visual arrangement which can assist the user in identifying where questions regarding exclusivity or conditionality must be resolved.

In a decision tree, the levels of events are connected by gates. There are two types of gates: the "and" gate and the "or" gate. The type of gate used indicates the relationship of the events below the gate to the success of the events above the gate in the decision tree.

The location of an "and" gate between two levels of events signifies that all of the events in the level immediately below the gate are necessary for achievement of the success of the event above the gate. Exclusion of any element directly connected to the lower side of an "and" gate precludes success of the event above the gate. Therefore, the maximum probability of success of an event above the "and" gate is limited to the lowest probability of success of any event connected to it. Formula for determining the probability of success of achieving the goal objective of an event above an "and" gate is shown in figure 4.

The location of an "or" gate between two levels of events signifies an "and/or" relationship. In this case, total inclusion of all of the events below the gate is desirable, but not necessary, to achieve the goal of the event above it. Exclusion of any event connected to the lower side of an "or" gate does not preclude success of the event above that gate. The probability of success of an event above an "or" gate is always equal to or greater than the highest probability of success of any of the events connected to it.

Figure 5 provides graphic examples and formula for determining the probability of success of achieving a goal objective through an "or" gate.

Both the GSA and the NFPA decision trees are amenable to the probabilistic approach upon which the GSA goal-oriented system is based. These decision trees have been extensively examined by groups interested in fire safety and are felt to represent sound representations of the elements that determine the course of fire development and growth and its impact on people and the course of fire development and growth and its impact on people and property. Other trees could be developed that would be as effective. The actual events in the tree are not individually important. It is necessary however that any alternative tree seeking to produce the same results follow the protocol of starting from the same top event "Fire Safety Objective" and at each step divide the entire universe of events as either an "and" or an "or" function. At each gate the subordinate events must sum to be the total universe of events that constituently add up to the event above the gate. If this is not followed at an "and" gate the result will be failure to protect against a potential system's failure. If an element is omitted at an "or" gate the result will not reduce the potential safety but would reduce the flexibility of choice in the system by eliminating one or more alternatives.

4. DIRECTIONS

The goal-oriented systems' approaches have been valuable in giving indications of the extent of the impact of fire. They are currently limited in their ability to include rate or time factors and in the lack of an adequate store of fire protection engineering data. This lack of data forces the system to use either engineering opinion or concensus committee-type of decision for many of the most important inputs. To overcome these limitations it is necessary to find better linkages between applied fire protection and scientific and/or empirical engineering data and to develop a procedure which relates to fire growth. In addition, a better methodology is needed for interrelating human action as it impacts either on the fire and its development or on the safety of persons exposed to fire.

Recently, a combined concept has emerged. This resulted from examinations of the various concepts on energy development, the system's approach, and data that is being developed by current research. In this concept, both fire growth modeling (part 2, above) and building fire safety design systems' approaches (part 3, above) are combined into an integrated system. The purpose of this new approach is to provide a more complete base of knowledge by which rational inputs can be made into a decision tree analysis.

This concept is based on the premises that:

1. Fire behavior and the behavior of persons involved can be expressed as series of realms connected together to form sequences.

2. The fire behavior and people behavior sequences are separate, but can be (and often are) interacting with each other. (A typical interaction is the opening or closing of the door to a room that is on fire.)

3. A sequence consists of individual periods of consistent behavior pattern, varying in length, and beginning and ending with a critical event. These periods of consistent behavior are called "realm" when discussing fire behavior and "episodes" when discussing human behavior. (The burning of a chair might be a typical realm; if a second item becomes involved or the room flashes over the rate of burning will significantly change and a new realm will exist.)

4. For each realm there is a "rate constant" which, if identified, can describe the rate of change during that realm. A change in the rate constant constitutes a change in realm. (The chair described above either burns, releases energy, or produces smoke at a consistent acceleration; if the realm changes this rate of acceleration changes.)

5. At any instant in the combined fire behavior/human behavior sequences there is one and only one value for each behavioral property. These properties are called "states conditions" and are identifiable and potentially quantifiable (e.g., the size of the flame or rate of smoke production).

6. There are potentially identifiable factors in the decision tree events that control both the rate constant within a realm, and the level of events that determine the start and termination of a realm. These factors are described by both the GSA and NFPA trees; but, the individual dominance or proportional impact of a single factor is not directly identifiable from the decision tree approach. In terms of the sequence, a significant change in a dominant factor, its degree of dominance, or the entry of new "dominant factors" will result in a change in the rate constant, and thereby a change in realm. (A prime example of this occurs in the transition through flashover. Prior to flashover the fuel properties such as ignitability and fuel arrangement dominate the fire development and energy levels. After flashover the dominant factors are the ventilation and the total amount of available fuel.)

Fire Behavior Sequence. Figure 6 is a modification of the overview design presented in reference [3]. This figure presents the major sequences (or "phases") in fire development. The input arrowheads at the left of the figure indicate the necessity for the combination of energy in an environment to have a fire start.

> Energy as shown means the input or potential ignition energy to start the fire sequence. Environment describes the physical situation consisting of fuel, geometry, construction, ventilation, and general layout and arrangement as exists at the moment of introduction of the energy source.

The development and spread of fire and fire energy through a facility is then divided into five basic phases each of which will consist of one or more realms. The division of phases is based on the expected types of dominant factors. These are:

1. The Ignition-Initiation Phase covers the period from the entry of the potential ignition energy to the point of self-sustained burning of one or more items. In this phase, the development is almost entirely dominated by: (1) the transfer of energy from the ignition source to the target, (2) the reaction to this energy by the target,

and (3) the critical ignition parameters of the target material. The shape of the target and the arrangement or geometry of the environment have little to do with ignition or development realms in this phase.

2. The Initial Item Development Phase is the second phase and covers the development of fire from the initiation of a self-sustained flame to the point where the fire either terminates or extends to one or more additional items. In this phase, not only the basic physical properties of the material, but also its shape and form, the spacing and arrangement of other materials (second targets), and the space configuration and ventilation begin to play parts.

3. The Intra-Room Development Phase concentrates on the spread of fire between items within a room or space up to a point of fire termination of flashover in a room. In this phase the additional elements of radiation from the burning item or its flame, the degree of separation between items, and other space factors come into more important play.

4. The Interspatial Propagation Phase covers the spread of fire from space to space through unprotected openings. In this phase, important factors related to ventilation, transfer of combustion products, convected energy, and radiated energy dominate the basic fuel considerations more important prior to flashover.

5. The Intercompartmental Spread Phase considers the factors related to spread fire when a physical barrier exists. Here the impact of total fire severity on structural elements leading to building collapse or ignition due to conduction of energy are the most important and dominating considerations.

The arched lines in figure 6 going from phase to phase are a schematic representation of the fact that it is not necessary to totally progress through any phase before passing through the next phase. In fact, the development conditions necessary for a critical event may cause a jump to a next phase or even skip an entire phase.

States Conditions — Fire Sequence. The "states conditions" describe the state of the fire behavior at any instance in the sequence. The fire development subsequent to any instant is dependent upon the states conditions and the realm at that instant; but is not dependent on the history of how that set of conditions came to be.

The "states conditions" necessary to describe the fire state at a given time are:

1. Fire Bed Location - Described in terms of the size and location of the energy generator. It includes both the basic burning area and the area away from basic burning area where gaseous combustion is taking place.

2. Energy Release - Expressed both in terms of the rate of energy release at a given instant and the total energy released in the course of the fire accumulated to that instant.

3. Pyrolysis Products - States in terms of concentrations and rate of change in concentrations. Covers the non-energy releasing aspects of fire products such as particulates, gases, vapors, be they toxic or non-toxic, visible or non-visible. In the case of chemical products it also includes the rate of subsequent change in the chemical products.

Rate Constant of Realm. Various research projects and tests where rates of energy production or other reasonable measurements indicative of rates of energy or products production have been taken indicate that under fire conditions the energy release rate in a given realm varies at a constant rate of acceleration. This rate constant is determined by the reaction of the total fuel and environment conditions to the fire energy input. The formula for each realm is the same but there is a different factor (k) for each realm. The definition of a realm is the period of fire development with a constant k. In terms of a single realm, the formula for the energy release states conditions, is believed to be:

$$\dot{q}_n = \dot{q}_i e^{kt}$$

$$K = \frac{1}{t} \ln \left(\frac{\dot{q}_n}{\dot{q}_i} \right)$$

$\dot{q}$ = rate of energy release

$\dot{q}_n$ = $\dot{q}$ at any instant <u>with a realm</u>

$\dot{q}_i$ = $\dot{q}$ at another prior instant <u>with the same realm</u>

t = time between i and n

k = rate constant <u>for the realm</u>

As one test of this concept the data from the 1974 full room burn conducted as part of the Harvard/Factory Mutuals home fire tests was calculated using this formula. Figure 7 is a plot of the values of k. This plot shows a marked consistency between the value of k and the observed realms in the fire. The plot is superimposed with labels of the observable realms.

<u>Realms, Dominant Factors and Critical Events</u>. Figures 8 through 12 have been developed covering the five phases shown in figure 6. In each of these phases, the figure shows likely realms, the expected dominant factors, and the critical events expected within that phase. In no case is it expected that all of the realms depicted will occur. In each case the first critical event is the most likely entry into the realm and the last critical event is the definition of an event that would result in passing from the final realm in the phase into the first realm of the next phase.

<u>Human Behavior Sequence</u>. The basic criterion for the protection of humans during fire is the avoidance of occupancy of the same space at the same time by people and conditions intolerable to people. In fire situations the fire effects may be moving, or of consequence in only a very limited area. The humans involved may or may not be mobile and their safety may or may not be dependent on their actions.

Studies of the types of actions (episodes) involved in human behavior in fire are relatively few and rudimentary in nature. To date, however, they would indicate that the types of actions can be classified as: investigate, flight, attack, alarm, rescue, and no action. These are not in sequence and the probability of any action is unknown. At this time the state-of-the-art is simply one of recognizing the types of episodes and searching for any indication of which factors are dominant.

<u>States Conditions — Human Behavior Sequence</u>. Looking ahead towards the time when more rational predictions on human actions can be made, the only states condition necessary to describe person or persons involved is:

Position - Expressed in terms of a vector that defines not only the location of the person(s) but the rate and direction of movement.

With this it is possible to visualize the expression of the rate constant in terms of the formula:

$$d_n = d_i + jt$$

d_n = position at any instant within an episode

d_i = position at another prior instant within the same episode

t = time between i and n

j = rate constant for the episode

This can be seen as a linear formula versus the exponential formula used for energy development. In addition, the non-physical factor of human decision is visualized as an efficiency factor. Physically, no human can react faster than his personal maximum speeds and cannot occupy less space than that required by his body. In practice, however, these capabilities can be reduced by the types of decision made.

General Model. Figure 13 is a general model of the human behavior and fire behavior sequences. As indicated by this model, fire behavior is looked upon as a series of independent realms connected by critical events while human behavior is a series of independent episodes connected by decisions. The two sequences influence each other with stimuli that flow from the fire behavior sequence to the human behavior sequence causing action or impacting on the well being of the humans. The flow of stimuli is caused by the fire behavior sequence and is proportional to it, but entirely separate from it. The flow from the human behavior sequence to the fire sequence is in the form of impacting actions. The type of impacting action can be one countering the development of fire such as fire attack activities or the closing of doors or other activities aimed at confining the fire or relieving its effects. Impacting actions can also be detrimental to the restraint of fire due to activities such as evacuees leaving doors open or ineffective attempts at fire control activities that result in further spread and development. Human behavior can also progress through part or all of its sequence without impacting in any way on the fire, such as where evacuation takes place without any action that causes the fire to grow or be confined.

Figure 14 is a three-dimensional matrix interfacing States Conditions, Phases (Realms), and Dominant Factors (Decision Tree Events). The purpose of the matrix is to direct and organize the knowledge base in fire science and technology in a manner focused on specific realms, conditions, or determinants. As the matrix inputs are developed, the knowledge derivable from the fire science and technology can be fed into a decision analysis system for determining building fire safety requirements, giving a significantly increased level of confidence in the product.

A proposed program for this transition is:

1. the assembly and organization of the existing knowledge base to identify the relationship of the knowledge to each of the intersections in the matrix, and to identify apparent knowledge voids;

2. the identification of the significant phenomenon controlling the k factor or comparable constant in each matrix block (realm) and the phenomenon that can cause critical events resulting in a transition to another realm;

3. develop models for predicting the fire phenomena and for the response of the facility, its contents, and its occupants;

4. improve these models towards a complete system of deterministic models covering all realms, and critical events to complete all the connections and interfaces possible through the expansion of the general model, figure 14;

5. for each realm, episode, and critical event, identify the impact (sensitivity) of each event or group of events (branch) of the decision tree;

6. conduct parametric analyses of the models to develop possible scenarios and their resulting impact. Relate the probability of each scenario to accident loss data. Enter these values into the building fire safety design system.

Relevance to Decision Tree. In an analysis of the fire behavior sequence the k factor provides a mechanism for the understanding of fire development which provides an input to the tree. The specific impact on each individual decision tree event will be consistent through the course of a realm. Some events on the tree will have major impact on the course of fire in that realm, others lesser or no influence. For example the specific fuel ignition characteristics in combination with the ignition source dominate the course of fire on the initial surface ignited and establish the realm. The fire resistance of the structure plays no part in this realm. Conversely in a fully involved room fire the structural fire resistance along with the ventilation and total fuel mass are the principle control factors. In this realm the ignitability or flame spread characteristics are of insignificant impact. The decision tree, therefore, is a mechanism for describing all of the events that can influence the achievement of the top event "Fire Safety Objectives" during all possible realms of the fire. In an individual realm it is normal for some of the events to have no significance.

This potential relationship between the k factor and the decision tree provides new mechanisms for understanding and application of system's analysis. Since the k factor accounts for fire growth in terms of time, it will be possible to interlock the life-safety aspect of the protection branch of the decision tree to the control branch.

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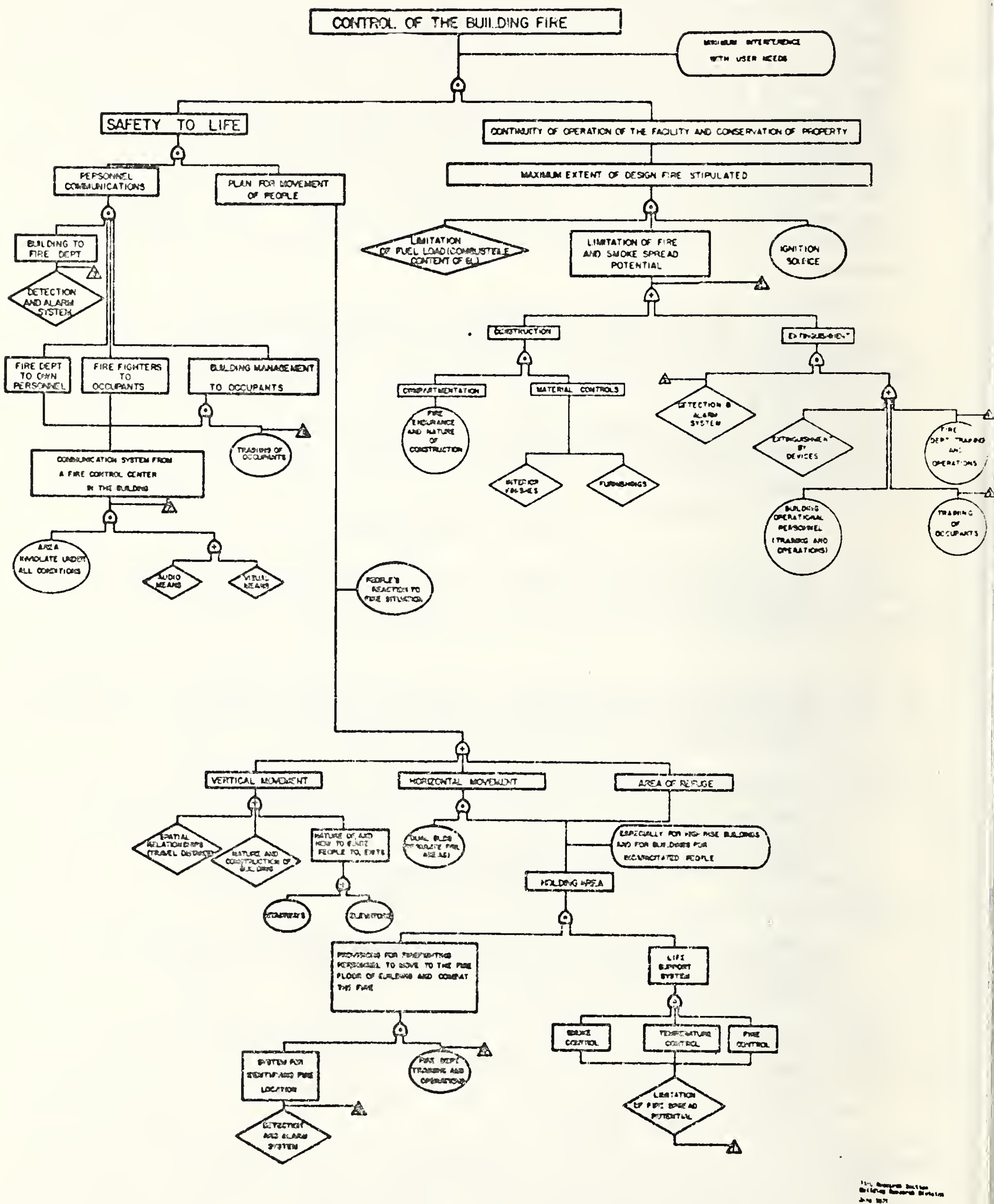
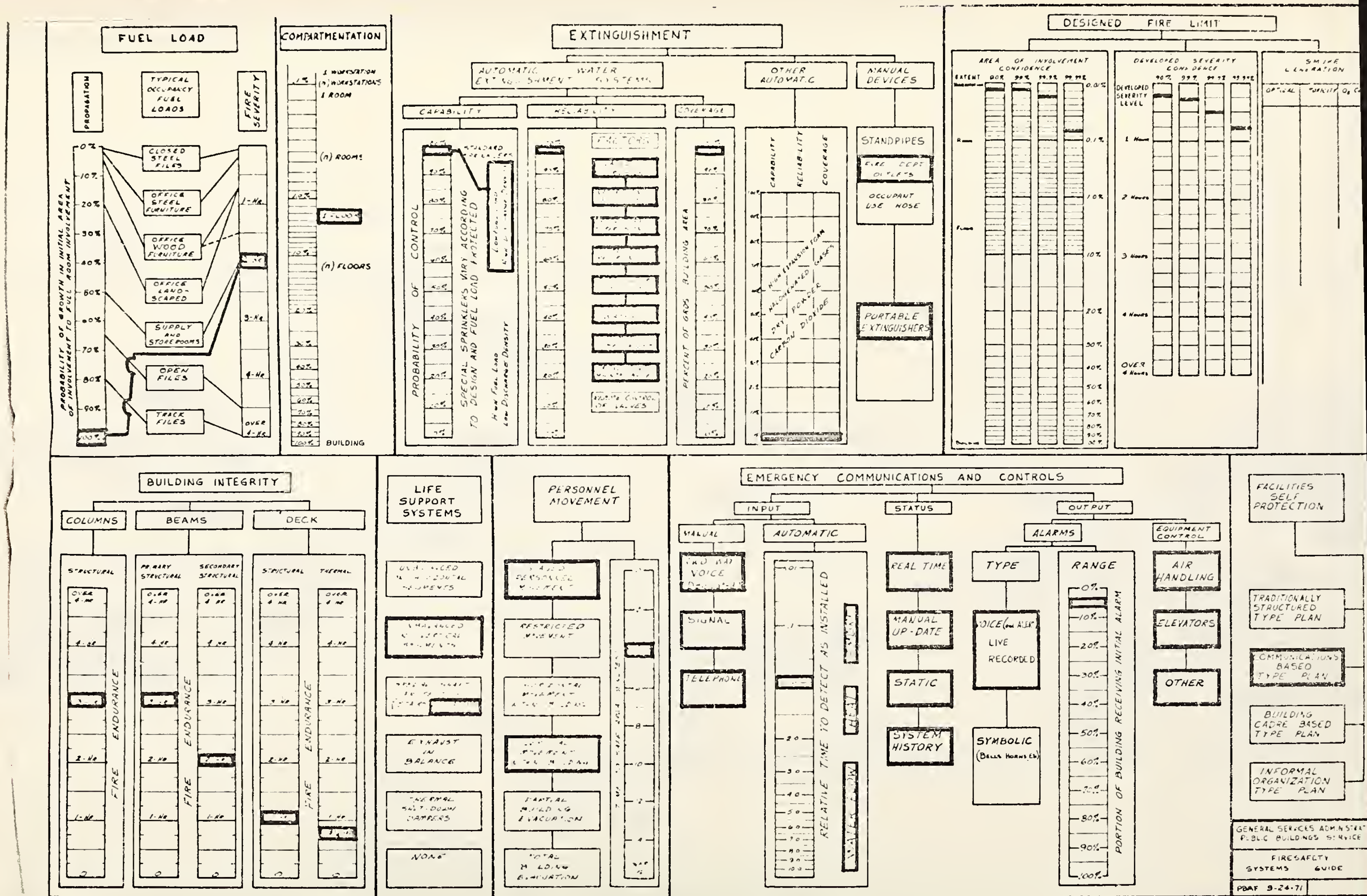
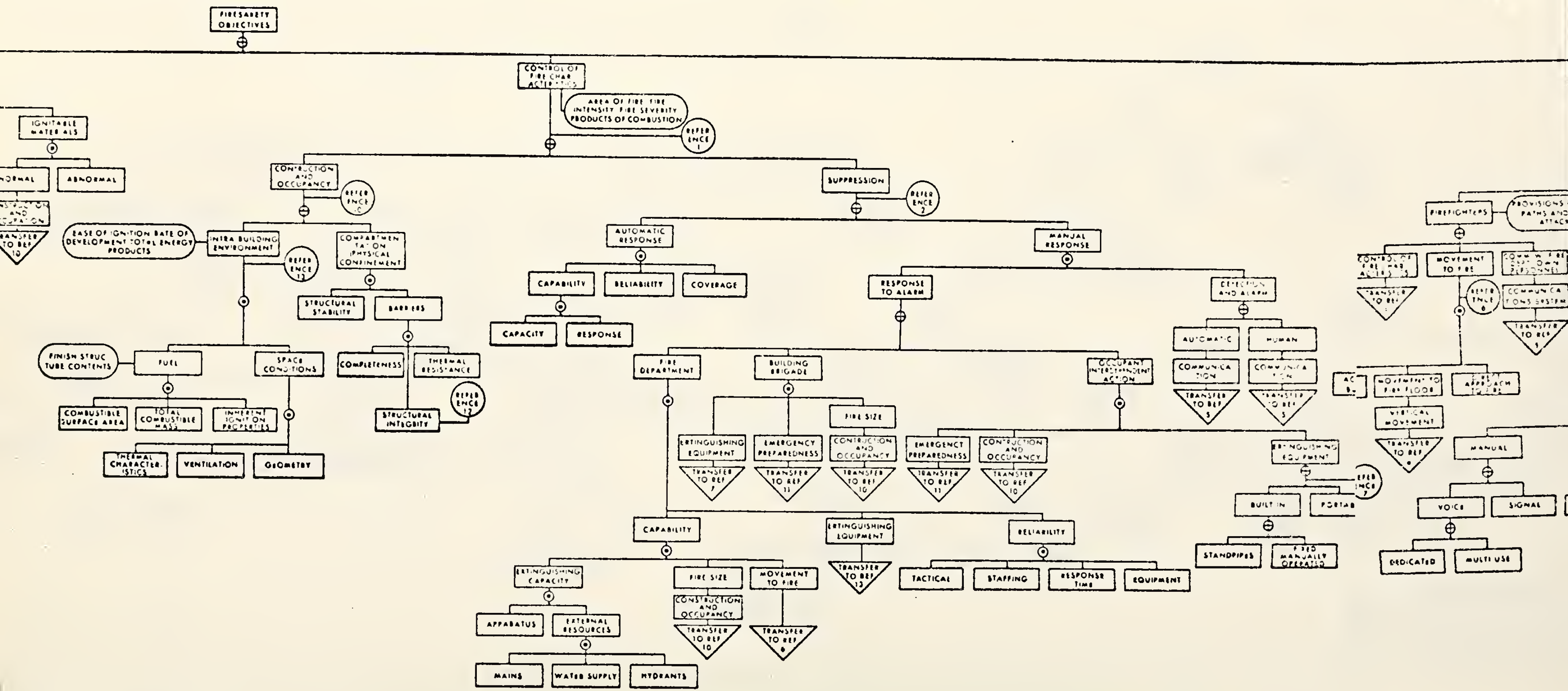
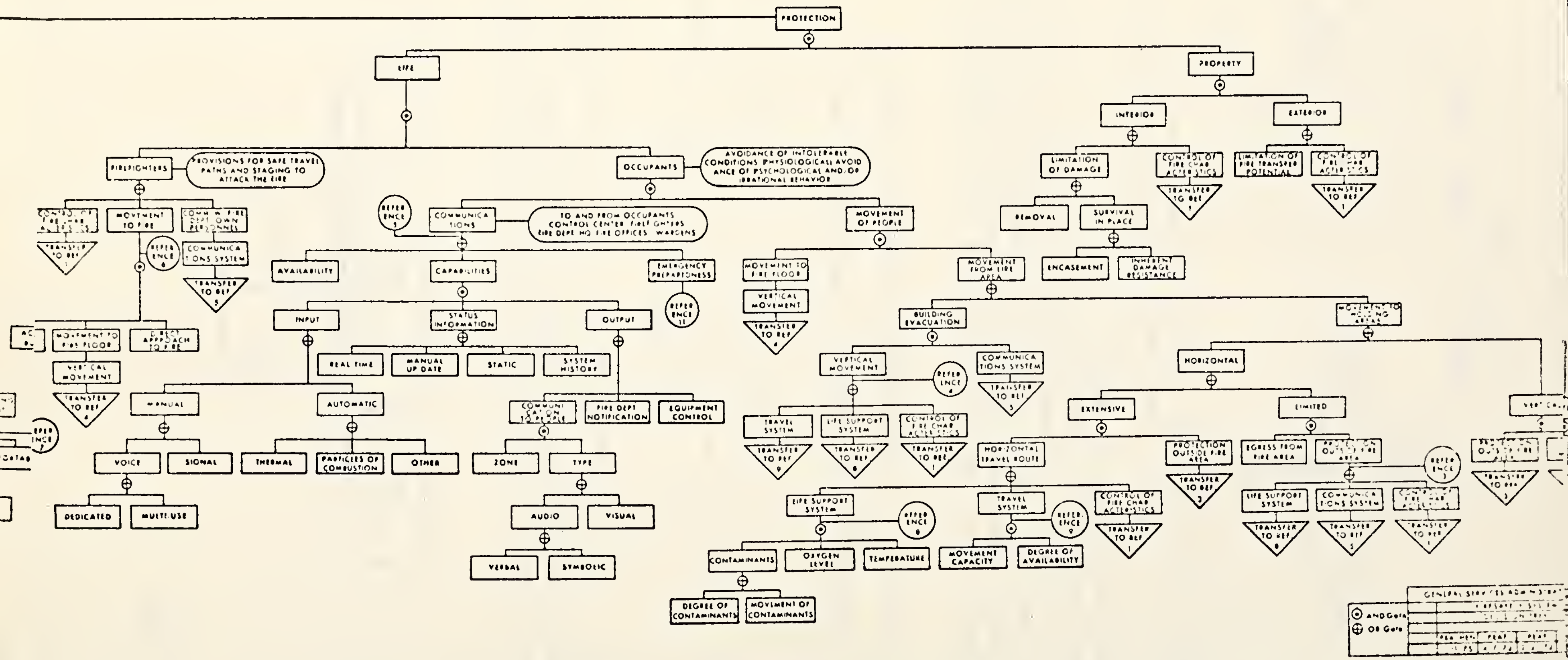


Figure 1. NBS Fault Tree - Control of the Building Fire

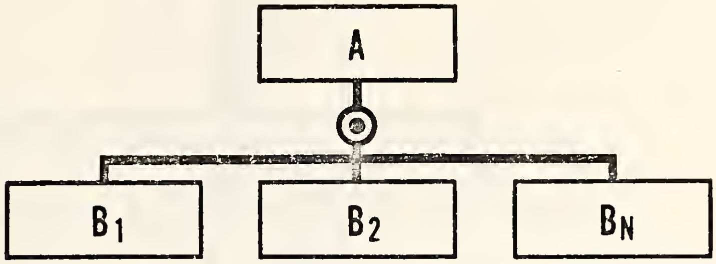

FUEL LOAD
PROPAGATION
TYPICAL OCCUPANCY FUEL LOADS
FIRE SEVERITY
PROBABILITY OF GROWTH IN INITIAL AREA OF INVOLVEMENT TO FULL ROOM INVOLVEMENT
CLOSED STEEL FILES
OFFICE STEEL FURNITURE
OFFICE WOOD FURNITURE
OFFICE LANDSCAPED
SUPPLY AND STORE ROOMS
OPEN FILES
TRACK FILES
COMPARTMENTATION
1 WORKSTATION
(n) WORKSTATIONS
1 ROOM
(n) ROOMS
(n) FLOORS
BUILDING
EXTINGUISHMENT
AUTOMATIC WATER EXTINGUISHMENT SYSTEMS
CAPABILITY
RELIABILITY
COVERAGE
PROBABILITY OF CONTROL
SPECIAL SPRINKLERS VARY ACCORDING TO DESIGN AND FUEL LOAD PROTECTED
STANDARD SPRINKLERS
High Fuel Load
Low Discharge Density
PERCENT OF GROSS BUILDING AREA
OTHER AUTOMATIC
HIGH EXPANSION FOAM
HALOGENATED GASES
DRY POWDER
CARBON DIOXIDE
MANUAL DEVICES
STANDPIPES
FIRE DEPT OUTLETS
OCCUPANT USE HOSE
PORTABLE EXTINGUISHERS
DESIGNED FIRE LIMIT
AREA OF INVOLVEMENT CONFIDENCE
EXTENT
DEVELOPED SEVERITY CONFIDENCE
DEVELOPED SEVERITY LEVEL
1 Hour
2 Hours
3 Hours
4 Hours
OVER 4 Hours
SMOKE GENERATION
OPTICAL
BUILDING INTEGRITY
COLUMNS
BEAMS
DECK
STRUCTURAL
PRIMARY STRUCTURAL
SECONDARY STRUCTURAL
THERMAL
FIRE ENDURANCE
LIFE SUPPORT SYSTEMS
EXHAUST IN BALANCE
THERMAL SHUT-DOWN DAMPERS
NONE
PERSONNEL MOVEMENT
RESTRICTED MOVEMENT
PARTIAL BUILDING EVACUATION
TOTAL BUILDING EVACUATION
EMERGENCY COMMUNICATIONS AND CONTROLS
INPUT
MANUAL
TWO WAY VOICE
SIGNAL
TELEPHONE
AUTOMATIC
RELATIVE TIME TO DETECT AS INSTALLED
SMOKE
HEAT
WATER FLOW
STATUS
REAL TIME
MANUAL UP-DATE
STATIC
SYSTEM HISTORY
OUTPUT
ALARMS
TYPE
VOICE (and ALERT)
LIVE
RECORDED
SYMBOLIC (Bells Horns Etc)
RANGE
PORTION OF BUILDING RECEIVING INITIAL ALARM
EQUIPMENT CONTROL
AIR HANDLING
ELEVATORS
OTHER
FACILITIES SELF PROTECTION
TRADITIONALLY STRUCTURED TYPE PLAN
COMMUNICATIONS BASED TYPE PLAN
BUILDING CADRE BASED TYPE PLAN
INFORMAL ORGANIZATION TYPE PLAN
GENERAL SERVICES ADMINISTRATION
PUBLIC BUILDINGS SERVICE
FIRESAFETY SYSTEMS GUIDE
PBAF 9-24-71



FIRESAFETY OBJECTIVES
CONTROL OF FIRE CHARACTERISTICS
AREA OF FIRE FIRE INTENSITY FIRE SEVERITY PRODUCTS OF COMBUSTION
REFERENCE 1
IGNITABLE MATERIALS
NORMAL
ABNORMAL
CONSTRUCTION AND OCCUPANCY
REFERENCE 10
SUPPRESSION
REFERENCE 2
EASE OF IGNITION RATE OF DEVELOPMENT TOTAL ENERGY PRODUCTS
INTRA BUILDING ENVIRONMENT
REFERENCE 12
COMPARTMENTATION PHYSICAL CONFINEMENT
AUTOMATIC RESPONSE
MANUAL RESPONSE
STRUCTURAL STABILITY
BARRIERS
CAPABILITY
RELIABILITY
COVERAGE
RESPONSE TO ALARM
DETECTION AND ALARM
CAPACITY
RESPONSE
FINISH STRUCTURE CONTENTS
FUEL
SPACE CONDITIONS
COMPLETENESS
THERMAL RESISTANCE
STRUCTURAL INTEGRITY
REFERENCE 12
FIRE DEPARTMENT
BUILDING BRIGADE
OCCUPANT INTERVENTION ACTION
AUTOMATIC
HUMAN
COMMUNICATION
TRANSFER TO REF 5
COMBUSTIBLE SURFACE AREA
TOTAL COMBUSTIBLE MASS
INHERENT IGNITION PROPERTIES
THERMAL CHARACTERISTICS
VENTILATION
GEOMETRY
FIRE SIZE
EXTINGUISHING EQUIPMENT
EMERGENCY PREPAREDNESS
CONSTRUCTION AND OCCUPANCY
TRANSFER TO REF 7
TRANSFER TO REF 11
TRANSFER TO REF 10
BUILT IN
PORTABLE
STANDPIPES
FIXED MANUALLY OPERATED
CAPABILITY
EXTINGUISHING CAPACITY
MOVEMENT TO FIRE
TRANSFER TO REF 13
TRANSFER TO REF 6
TACTICAL
STAFFING
RESPONSE TIME
EQUIPMENT
APPARATUS
EXTERNAL RESOURCES
MAINS
WATER SUPPLY
HYDRANTS
FIREFIGHTERS
PROVISIONS PATHS AND ATTACK
MOVEMENT TO FIRE
REFERENCE 6
MOVEMENT TO FIRE FLOOR
VERTICAL MOVEMENT
MANUAL
VOICE
SIGNAL
DEDICATED
MULTI USE


PROTECTION
LIFE
PROPERTY
INTERIOR
EXTERIOR
LIMITATION OF DAMAGE
REMOVAL
SURVIVAL IN PLACE
ENCASEMENT
INHERENT DAMAGE RESISTANCE
FIREFIGHTERS
PROVISIONS FOR SAFE TRAVEL PATHS AND STAGING TO ATTACK THE FIRE
MOVEMENT TO FIRE
DIRECT APPROACH TO FIRE
MOVEMENT TO FIRE FLOOR
VERTICAL MOVEMENT
COMMUNICATIONS SYSTEM
OCCUPANTS
AVOIDANCE OF INTOLERABLE CONDITIONS PHYSIOLOGICAL AVOIDANCE OF PSYCHOLOGICAL AND/OR IRRATIONAL BEHAVIOR
COMMUNICATIONS
TO AND FROM OCCUPANTS CONTROL CENTER FIRE DEPT HQ FIRE OFFICES WARDENS
AVAILABILITY
CAPABILITIES
EMERGENCY PREPAREDNESS
INPUT
STATUS INFORMATION
OUTPUT
REAL TIME
MANUAL UP DATE
STATIC
SYSTEM HISTORY
MANUAL
AUTOMATIC
VOICE
SIGNAL
DEDICATED
MULTI-USE
THERMAL
PARTICLES OF COMBUSTION
OTHER
FIRE DEPT NOTIFICATION
EQUIPMENT CONTROL
ZONE
TYPE
AUDIO
VISUAL
VERBAL
SYMBOLIC
MOVEMENT OF PEOPLE
MOVEMENT TO FIRE FLOOR
MOVEMENT FROM FIRE AREA
BUILDING EVACUATION
VERTICAL MOVEMENT
COMMUNICATIONS SYSTEM
TRAVEL SYSTEM
LIFE SUPPORT SYSTEM
CONTROL OF FIRE CHARACTERISTICS
HORIZONTAL
HORIZONTAL TRAVEL ROUTE
EXTENSIVE
LIMITED
PROTECTION OUTSIDE FIRE AREA
EGRESS FROM FIRE AREA
CONTAMINANTS
OXYGEN LEVEL
TEMPERATURE
MOVEMENT CAPACITY
DEGREE OF AVAILABILITY
DEGREE OF CONTAMINANTS
MOVEMENT OF CONTAMINANTS
TRANSFER TO REF
REFERENCE
AND Gate
OR Gate
GENERAL SERVICES ADMINISTRATION

"AND" GATE



In the success type of decision tree the "and" gate probability of success in achieving the goal objective of element A is:

a. Where the events at the B level are independent.

$$P_A = (P_{B_1})\ (P_{B_2})\ \ldots\ldots\ (P_{B_N})$$

b. Where the events at the B level are interdependent.

$$P_A = (P_{B_1})\ (P_{B_2}/P_{B_1})\ \ldots\ldots\ (P_{B_N}/P_{B_1}\ \&\ P_{B_2})$$

P = Probability of success of subscripted element

/ = Probability conditional on preceding element(s) ... read as "given.

An example of an "and" gate extracted from the GSA tree is shown on the left below. Here the success of a barrier is dependent on the barrier being complete. It is also equally dependent on maintaining its structural integrity if exposed to fire. And finally, it is dependent upon thermal resistance in preventing the passage of ignition temperatures to the unexposed of the wall.

On the right below an "and" gate is depicted in the form of a venn diagram. The degree of success is equal to the degree of intersection of all of the elements.

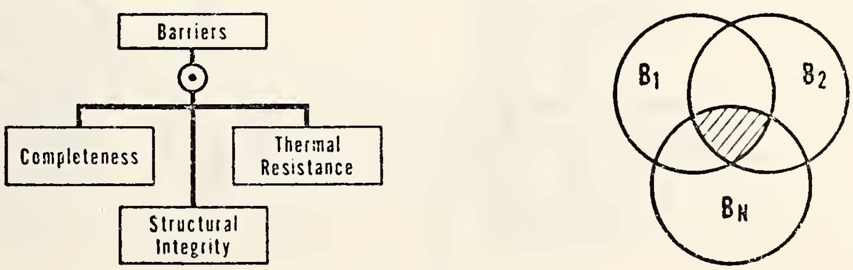
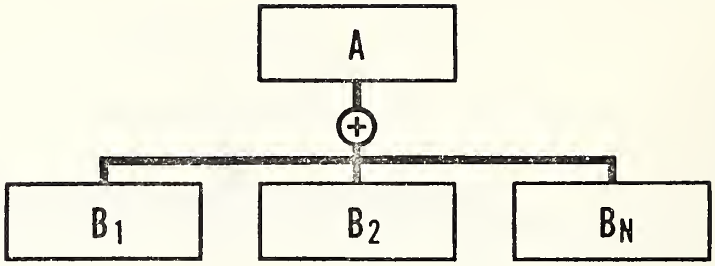


Figure 4. "AND" GATE

"OR GATE"



In the success type of decision tree the "or" gate probability of success in achieving the goal objective of element A is:

a. Where the events at the B level are mutually exclusive.

$$P_A = (P_{B_1}) + (P_{B_2}) \ldots + (P_{B_N})$$

b. Where the events are not mutually exclusive but are independent.

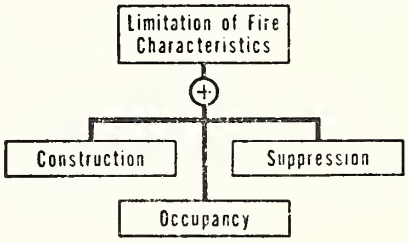
$$P_A = 1.00 - (1-P_{B_1})(1-P_{B_2}) \ldots (1-P_{B_N})$$

c. Where the events are not mutually exclusive and are interdependent.

$$P_A = 1.00 - (1-P_{B_1})(1-P_{B_2}/P_{B_1}) \ldots (1-P_{B_N}/P_{B_1} \& P_{B_2})$$

An "or" gate is a point of potential design trade-off. An example of an "or" gate from the GSA tree is shown on the left, below. This indicates the supportive interplay between suppression systems; the built-in construction features; and the fire potential of the occupancy.

On the right below the "or" gate is depicted in the form of a venn diagram. The degree of success is equal to the union of success provided by any of the elements.



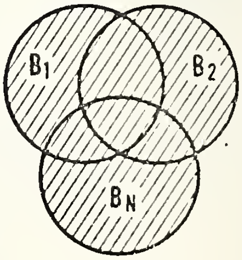


Figure 5. "OR" GATE

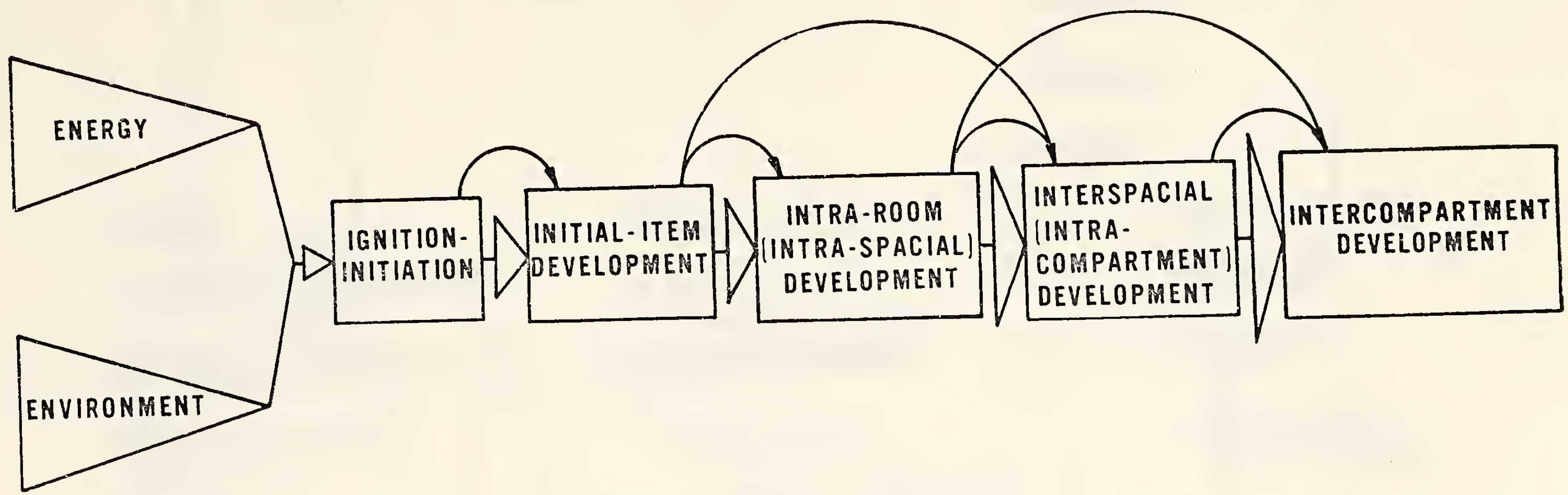


Figure 6. Overview Diagram - Fire Behavior Sequence

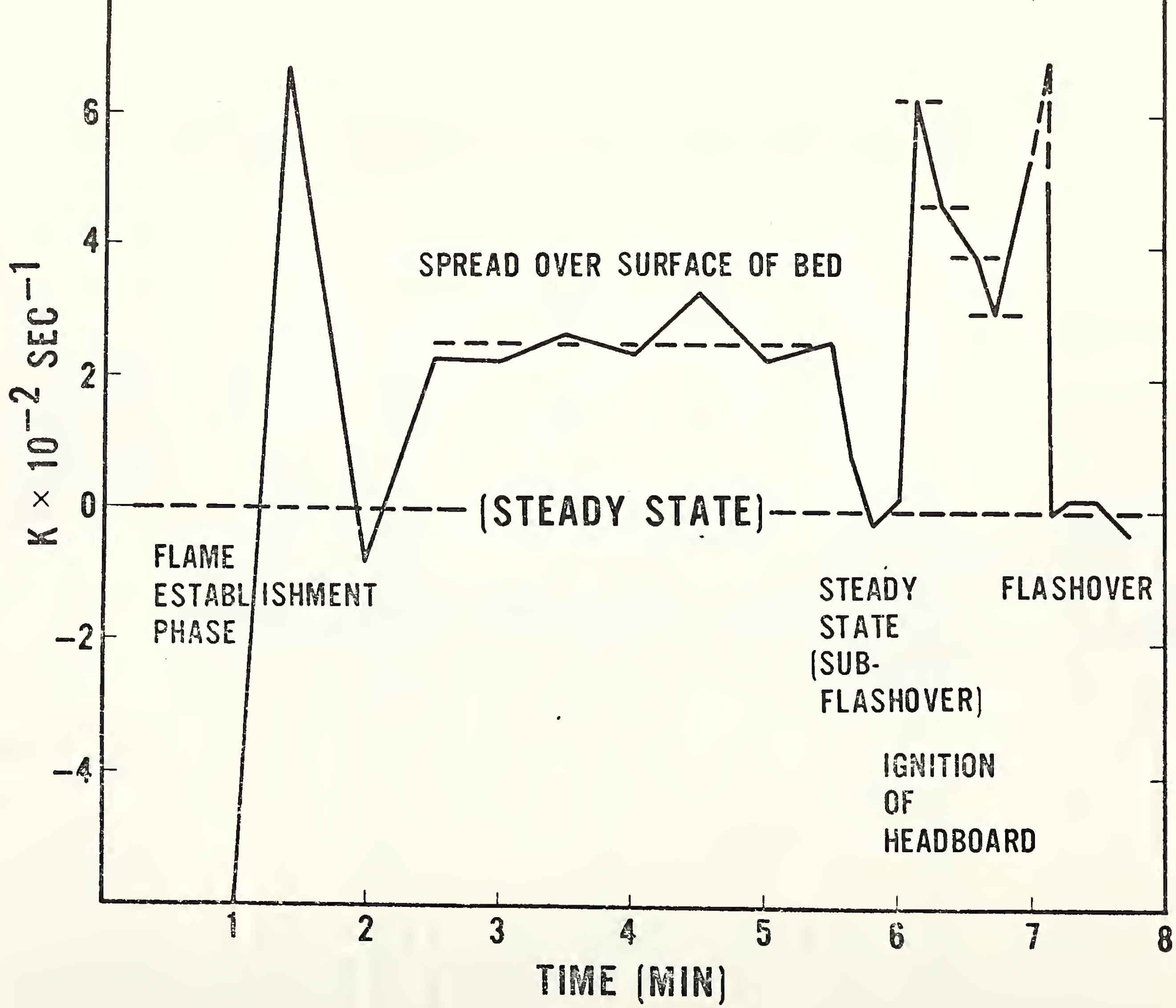


Figure 7. K Values - 1974 Harvard/Factory Mutuals Test

REALMS

- PREHEAT
- GLOWING COMBUSTION
- SUPPORT FLAMING COMBUSTION

DOMINANT FACTORS

- ENERGY INPUT
  - -INCIDENT ENERGY
  - -FLAME CONTACT
- FUEL RESPONSE
  - -THERMAL INERTIA
  - -IGNITION TEMPERATURE
  - -FUEL GEOMETRY

CRITICAL EVENTS

- IGNITION
- FLAME
- TERMINATION OF IGNITION SOURCE
- STEADY FLAME

Figure 8. Ignition-Initiation Phase

REALMS

- SPREADING ON A SURFACE
- MULTI-SURFACES
- STEADY STATE

DOMINANT FACTORS

- ORIENTATION OF BURNING SURFACE(S)
- ORIENTATION OF EXPOSED SURFACE(S)
- ENERGY RELEASE RATE
- ENERGY REQUIRED TO SUSTAIN COMBUSTION
- SPACE GEOMETRY
- VENTILATION

CRITICAL EVENTS

- STEADY FLAME
- IGNITION OF NEW SURFACE
- IGNITION OF NEW FUEL
- EXTENSION OF BURNING THE FUEL PERIMETER
- INVOLVEMENT OF SECOND ITEM

Figure 9. Initial-Item Development Phase

REALMS

- INVOLVEMENT OF SECOND ITEM
- INVOLVEMENT OF ADDITIONAL ITEM(S)
- FULL ROOM INVOLVEMENT
- STEADY-STATE

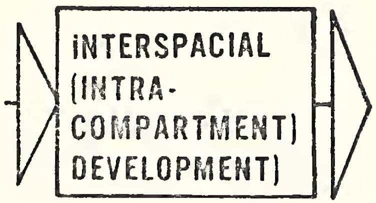
DOMINANT FACTORS

- ITEM BURNING RATE
- ENERGY RELEASE RATE
- ITEM SPACING
- ITEM IGNITION SUSCEPTIBILITY
- SMOKE CLOUD
- SPACE GEOMETRY
- SPACE VENTILATION

CRITICAL EVENTS

- IGNITION OF SECOND ITEM
- IGNITION OF NEW ITEMS (OR SURFACES)
- FLASHOVER
- FIRE DECAY
  - POST FLASHOVER
  - NO FLASHOVER
- IGNITION EXTERNAL TO SPACE OF ORIGIN

Figure 10. Intra-Room (Intra-Spacial) Development Phase.



REALMS

- DECELERATING PROPAGATION
- ACCELERATING PROPAGATION
- STEADY-STATE
  - WITHOUT FLASHOVER
  - POST FLASHOVER

DOMINANT FACTORS

- INCIDENT ENERGY
  - POSITION
  - LEVEL
  - FORM
- FLAME EXTENSION
- COMBUSTIBLE EFFLUENT
- EXPOSED FUEL
- SPACE GEOMETRY
- VENTILATION

CRITICAL EVENTS

- IGNITION EXTERNAL TO SPACE OF ORIGIN
- ESTABLISHMENT OF DECELERATING TREND
- ESTABLISHMENT OF ACCELERATING TREND
- ENTRY OF NEW FUEL
- FLASHOVER

Figure 11. Interspacial (Intra-Compartment) Development Phase.

INTER-COMPARTMENT DEVELOPMENT

REALMS

- DEVELOPMENT FROM DISCRETE IGNITIONS
- SUPPORTED DEVELOPMENT (EXPOSURE FROM RADIATING SURFACES)
- MASSIVE ENERGY TRANSFER (MAJOR STRUCTURAL FAILURE OF BARRIER)

DOMINANT FACTORS

- EXPOSING SEVERITY
  - TOTAL ENERGY
  - ENERGY LEVEL
  - DURATION OF EXPOSURE
  - HEAD PRESSURE OF EXPOSING FIRE
- INCIDENT ENERGY ON MEMBER
  - BARRIER
  - CLOSURE (DOOR, ETC.)
  - BEARING ELEMENT
- GRAVITY LOADING
- ELEMENT CAPABILITIES
  - STRUCTURAL
  - THERMAL
  - COMPLETENESS

CRITICAL EVENTS

- FLASHOVER IN EXPOSING SPACE
- DISCRETE IGNITION
- MASSIVE IGNITION
- GEOMETRY CHANGE

Figure 12. Inter-Compartment Development Phase

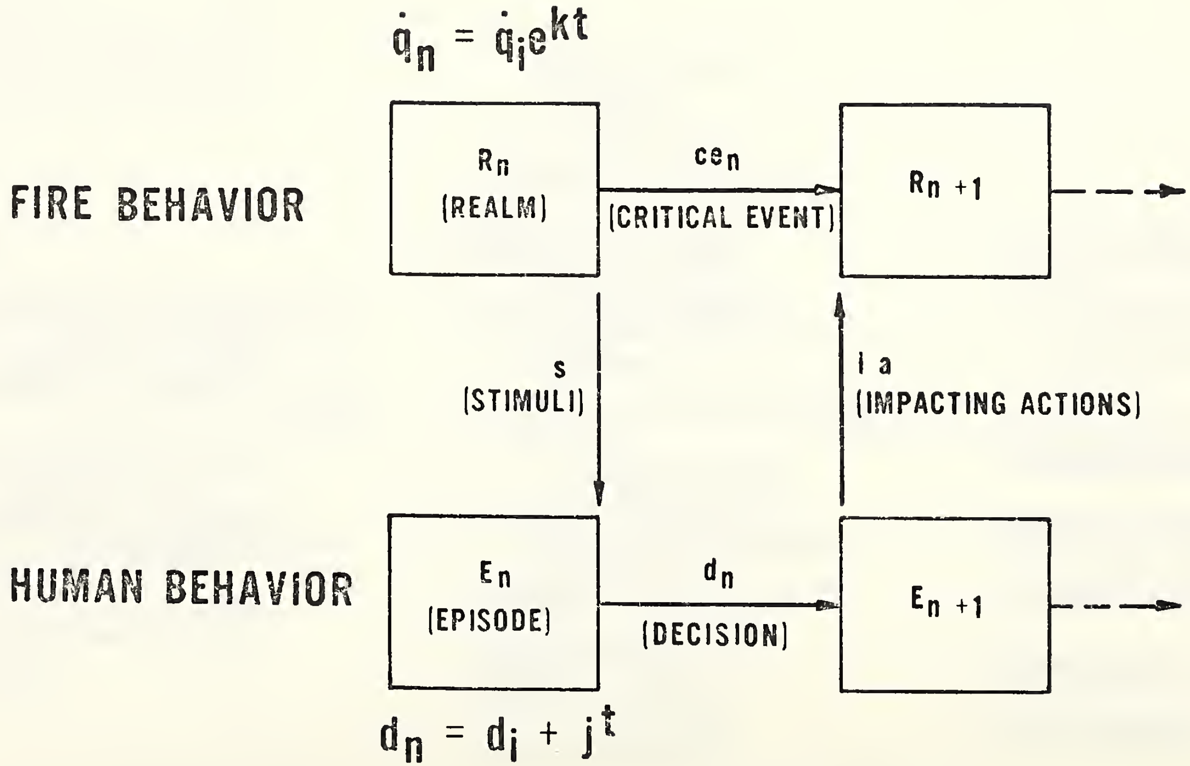


Figure 13. General Model

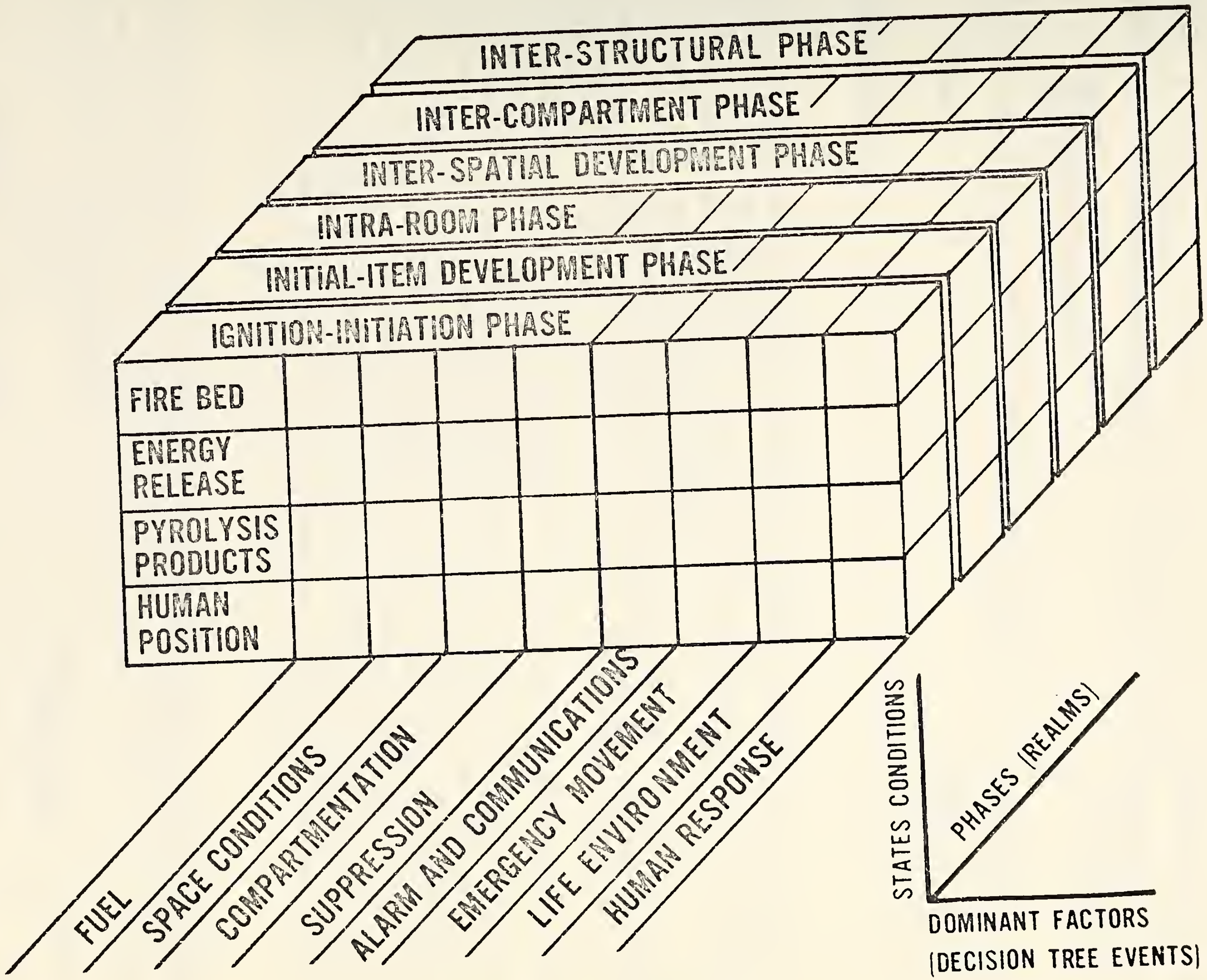


Figure 14. Matrix

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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

This paper covers an examination of the recent and ongoing work in the development c systems' approaches for design of fire protection in buildings, as carried out in the United States. The scope of coverage includes:

(1) a brief review of the development of fire safety systems' approaches in the Unit States, to the degree felt important to understanding the current situation;
(2) an overview of the more extensive and pertinent fire growth systems' analysis approaches;
(3) a discussion of systems for the analysis of building fire safety design directec at establishing building requirements;
(4) a review of the directions and activities now underway to integrate the fire grc models and the total building performance models into a combined approach.

This paper proposes a model of fire and its impact based on a "states-transition" concept. The fire is viewed as two separate sequences (Fire Behavior and Human Behavic Each sequence consisting of connected realms of consistent behavior. The concept viev these sequences as interrelating, with a distinct rate consistent for each realm. The concept of "states-conditions" is also evaluated. A matrix relating the factors, conditions, and development phase of fire is presented. Finally, a plan for the derivati of a viable fire protection engineering technology is presented.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)* "And" gate; behavior; critical events; decision; decision tr dominant factors; episode; event; fire; fire behavior; fire growth; fire safety; human behavior; models; phase; probability; rate constant; realm; sequence; state; states-transition; system's approach.

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