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A Theoretical Rationalization of a Goal-Oriented Systems Approach to Building Fire Safety

February 28, 1979

Sponsored by

U.S. Department of Commerce
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A THEORETICAL RATIONALIZATION OF A GOAL-ORIENTED SYSTEMS APPROACH TO BUILDING FIRE SAFETY

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by

Jack Watts

February 28, 1978

Department of Fire Protection Engineering

University of Maryland

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Notice

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PREFACE

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.

Many people have contributed to this document in the form of guidance, encouragement and direct assistance. Operational support was provided by the Program for Design Concepts, Center for Fire Research, National Bureau of Standards. Significant contributions were made by Harold Nelson, Jeff Shibe, Dr. Howard Hung and Laura Kauffman of NBS; Dr. John Bryan, Craig Beyler, Phil DiNenno, Ron Lee, Betsy Weaver, Eloise McBrier, Jeanne Decker, Donna Fitzpatrick and Cindy Silberman of the Department of Fire Protection Engineering, University of Maryland; John M. Watts, Sr. of Cazenovia, New York; and Dr. Richard J. Giglio and Dr. Hugh J. Miser of the Department of Industrial Engineering and Operations Research, University of Massachusetts.

Judy Watts was a direct contributor and also provided the moral and financial sustenance.

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Figure

Dogmatism has no place in science, and dogmatism about the unknown is especially reprehensible. We live by faith, faith in the order of nature, faith in ourselves, and faith in our fellow men. This faith is our most prevalent motivation, and it is a reliable guide for behavior just in so far as it is founded on knowledge. Where knowledge is lacking we may extrapolate with due regard for the uncertainties arising from the incompleteness of our knowledge. The mystics too often neglect this caution. The naturalists must not.

-- Charles Judson Herrick
Evolution of Human Nature, 1956

ABSTRACT

The Goal Oriented Systems Approach to Building Fire Safety developed by the U.S. General Services Administration is presently the only probabilistic methodology for fire protection evaluation in use in the United States. This paper describes and analyzes the GSA approach and formulates a more scientific procedure by synthesizing GSA concepts with additional probability theory. Discussion of systems analysis and modeling concepts emphasizes the need for probabilistic considerations of fire safety. The revised model, identified by the hyphenated expression: Goal-Oriented, simplifies data requirements through parameter estimation techniques. The new approach is consistant with the GSA model for several example cases. A demonstrated advantage of the new methodology is the facility for sensitivity analysis of alternative fire protection strategies.

Key Words: building, fire protection engineering, fire safety, probability, systems analysis.

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CHAPTER I

THE GOAL ORIENTED SYSTEMS APPROACH

The state-of-the-art of building fire safety evaluation is nascent. In the seventy years since this country's first model building code was written there has been some evolution from detailed specifications to more flexible component performance criteria. This change has not improved the prevailing situation whereby most structures are either over protected or under protected with respect to safety from fire. It is only within the last few years that the General Services Administration has synthesized the agglomeration of component requirements into a systems approach to fire safety in buildings. This "Goal Oriented Systems Approach" [1][1] is presently employed in the design process by both federal and non-federal agencies and represents the first step toward a new technology for fire protection design and evaluation.

1.1 Approaches to Fire Protection Design and Evaluation

At present there is no universally accepted methodology for the evaluation, analysis or design of fire protection in structures. There are basically three approaches to the formulation of fire protection requirements: the historic or traditional approach, the deterministic approach, and the probabilistic approach.

[1]The numbers in brackets refer to the list of references at the end of this paper.

1.1.1 The Traditional Approach

The prevailing method of fire safety evaluation in the United States is by code compliance. Building codes are legal documents which set minimum requirements to protect public health, safety and welfare in structures. The traditional code approach is to categorize structures by occupancy, construction and sprinkler protection and then apply specific provisions within each category.

Problems with Code Classifications

A typical model building code [2] labels structures by one of ten occupancy classes and by one of seven construction classes. This approach to classification by present-day codes reflects a less technically complex society of a bygone era. Occupancy classification attempts to describe in one or two words the totality of the function of a structure. Modern buildings, however, often cannot be categorized by a single function. Chicago's original McCormick Place dramatically illustrates this point: Exhibition halls are generally classified by codes as places of assembly and as such are not considered to contain large amounts of combustible contents. The quantity of combustibles accumulated for the 1967 National Housewares Manufacturers Association Show was completely contradictory to this concept. As a result of this and other significant factors, the building was destroyed by fire January 16, 1967, an estimated forty million dollar loss [3].

Consider the Broadway Plaza, a $75 million multi-purpose structure occupying a city block in Los Angeles. This project consists of four basic occupancies as described in Engineering News Record:

"A 32-story office building containing 764,000 square feet.
A 23-story, 500-room hotel topped by a circular revolving restaurant.
A department store containing 25,000 square feet on three floors.
A garage for 2000 cars" [4, p. 31].

The parking garage occupies six floors above the department store and one floor underground. The entire complex is interconnected by a two level mall, by the underground parking area, and by a sub-basement service level. The extent of the code variances required for this structure emphasizes the limitation of the traditional approach.

Similar problems occur with respect to mixed construction. The result in this case, however, is that the codes force designers to use identifiable classes.

Problems also exist with code recognition of active protection systems such as automatic sprinklers. As indicated by the American Iron and Steel Institute, the building codes do not, in general, encourage active protection due to reliability:

"Because any mechanical system is subject to failure or improper function, relaxation of minimum building code requirements must be carefully weighed and kept within reasonable bounds" [5, p.83].

Yet the codes fail to acknowledge that there may be an even higher uncertainty of reliability for passive (structural) protection due to improper installation, penetrations for utility services, or physical abuse. One New York Plaza was a modern fire-resistive building when it experienced a fire in 1970. One hundred ninety-one "protected" steel beams had to either be replaced or strengthened and approximately twenty-one thousand square feet of "fire-resistive" concrete flooring had to be replaced on two stories [6].

The basic problem with the code-generated classifications is that they break into a small number of classes what in the real world is a continuum of levels of protection.

Limitations of Code Provisions

Specific code requirements prescribe the materials and assemblies used to construct buildings with respect to their composition (specification requirements) or their ability to withstand (as determined by testing) the impact of hostile fire (performance requirements). Development of code provisions has largely been a response to specific fires and the desire to prevent the recurrence of undesirable events. For example, many of the present requirements for life safety were implemented as a result of the Cocoanut Grove Night Club fire in Boston in 1942 in which 492 lives were lost [7,8]. The outcome of this process of stimulus and response is that new provisions are added to existing ones without evaluation of the net resultant impact on the efficiency of fire safety. This layering of requirements provides the potential for expensive redundancy in building design. Thus the justification for code requirements is more sociological than scientific.

Other Problems with the Traditional Approach

Beyond the lack in the technical validity of the traditional approach, there are at least three other adverse situations which codes perpetuate: no defined level of fire safety, lack of understanding of the fire problem by designers, and non-cost-effective fire protection.

Building codes identify as the minimal level of fire safety that which results from conformance to their provisions. A survey by the National Commission on Fire Prevention and Control in 1973 indicated there were thirty-eight different building codes among forty-eight of the nation's largest cities [9]. The Commission further asserted that "differences among these local codes are not inconsequential." The implication is that there are thirty-eight different minimum levels of fire safety among these cities and that the traditional approach is not consistent with respect to identifying the objective.

Caravaty and Winslow have identified a problem area of the traditional approach which may have far-reaching ramifications:

> "A building code, once adopted, becomes the designer's substitute for understanding. The architect who follows all the applicable code requirements feels he has provided complete fire protection for his project and safety for its occupants. This is not always true" [10, p. 22].

As illustrated by the fire protection problems at the Broadway Plaza in Los Angeles: As the built environment becomes more and more complex, building codes are less and less capable of covering all situations, thus the designer is faced with more and more decisions. This problem also applies to the agencies which must enforce the codes. Many legal authorities also substitute a code for understanding of the fire phenomenon and its effects. A further confounding of this problem is that code adherence is relied on to absolve liability for negligence. In 1970, the National Commission on Product Safety recommended a doctrine of strict liability by which a party need only prove injury due to an unreasonably hazardous defect [11]. That is, negligence of the consumer is not accepted as defense of the manufacturer. As the application of this doctrine makes the probable extension from consumer products to more complex risks such as large structures, the legal shelter of the code will disappear and designers will be forced to understand the hazards of their products.

Although building codes are tending toward performance, rather than specification criteria, little variation is permitted within code requirements. This prescriptive nature of the codes cumulates with aforementioned problems to constrain innovation in fire protection design. Thus cost-benefit analysis is a seldom used tool in fire protection, there being effectively no alternatives to compare. Yet, the inconsistencies among the codes raises the question as to whether the fire safety dollar is being wisely spent [12].

Roux succinctly summarizes the present limitations of the traditional code approach to building fire safety:

> "In the history of building codes and regulations, one finds a nearly universal use of the singular approach to answer a given problem, in most cases exclusive of the other singular approaches to answer other problems. Granted, many of these singular approaches were dictated by the need for immediate action after a particularly devastating and/or publicized fire. The urgency of the then-political situation probably did not permit any overall analysis of the problem that had resulted in the subject fire. Of more importance to our consideration is that the singular approach is rarely, if ever, subject to a critical analysis of its cost effectiveness, either when first adopted or in later years. In looking at any modern building code, the end result is a book of redundancies that are gross and unfitting to today's task of constructing needed, safe buildings of reasonable cost" [13].

1.1.2 The Deterministic Approach

One alternative to the traditional codes and standards is a deterministic approach. This approach presumes an ability to determine the precise behavior of any fire at any time in the future, given exact contemporary conditions and the antecedent state of the building and its contents. Although great strides have been made in recent years to identify the physico-chemical nature of fire, relatively little is yet known.

The deterministic approach is, therefore, the most idealistic and beyond immediate capabilities.

Emmons, in a review [14], identifies specific difficulties in the areas of ignition, pyrolysis, fire retardants, smoke and toxic gas, detection and convection; and describes what has been learned so far toward a quantitative understanding of fire. Interested researchers have recently formed the Ad Hoc Working Group on Mathematical Fire Modeling and foresee deterministic fire modeling as a comprehensive design concept in about seven years time [15]. Because of the large number of variables and the seemingly random behavior of many of them, it is unlikely that any valid design techniques in the near future will be devoid of probabilistic concepts.

1.1.3 The Goal Oriented Systems Approach - A Probabilistic Approach[2]

Building codes have significant limitations in providing satisfactory means to define fire safety while determinism is not yet a broad enough tool. The probabilistic Goal Oriented Systems Approach developed by the U.S. General Services Administration Provides an alternative to the traditional and deterministic approaches.

Rational for the Development of a Goal-Oriented Approach

Unlike the vast majority of structures in the U.S., the property of the Federal Government does not fall under the jurisdiction of commonly

[2] See Appendix A1; Availability of the Interim Guide for Goal Oriented Systems Approach to Building Fire Safety.

used building codes. In this light, Harold E. Nelson of GSA was able to deviate from the accepted practice of code compliance and formulate the Goal Oriented Systems Approach [16]. Nelson's concept of fire safety negated the lexical definition of safety as total absence of risk. He, and more recently Lowrance of the National Academy of Sciences, reason that absence of risk is unattainable and contend that a certain amount of hazard is unavoidably present in all human activity [17]. Nelson, therefore, hypothesized that a fire safety goal, such as maintaining the continuity of an organizational mission, could be expressed in terms of a probability of limiting fire extent.

Any system to be effective must be responsive to management objectives. In the development of the Goal Oriented Systems Approach, the GSA policy statement on safety was reformulated and a probabilistic criterion was developed for mission focused goals [18]. This goal criterion is expressed in terms of the probability of limiting fire involvement in each of successive spatial or structural modules within a building. Figure 1.1 represents the GSA mission continuity goals for general level and critical operations.

Quantitative application of the Goal Oriented Systems Approach involves a probability calculation for each work station, room and floor of a specific building. Where calculated probabilities fall within the area under the goal curve of Figure 1.1, the required objectives have been met. The methodology for these probabilistic determinations is the principal focus of this paper.

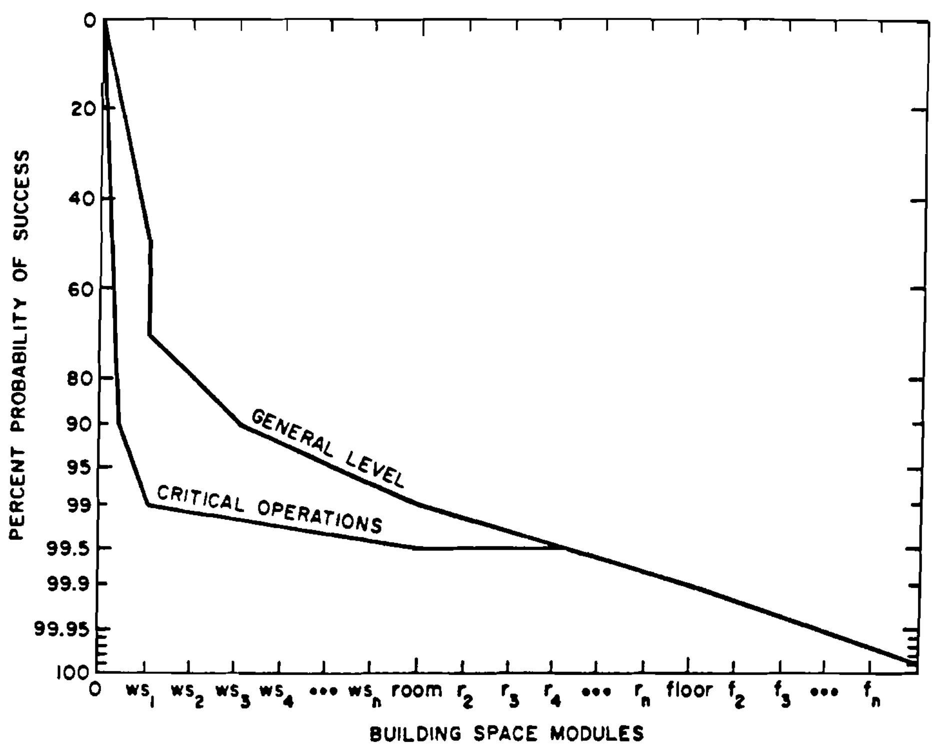

Figure 1.1

GSA Mission Focused Goals
ws = work station, r = room, f = floor

(This Figure is explained in
section 1.3.1 on page 21.)

Components of the Goal Oriented Systems Approach

There are two basic components of the Goal Oriented Systems Approach as it is presently practiced. The qualitative component covers all aspects of fire protection, while the quantitative component addresses itself to that aspect of fire protection about which we have the most specific knowledge.

Qualitative component. The underlying structure of the Goal Oriented Systems Approach is that of a logic tree. The nature of this tree evolved from the fault trees developed in the field of systems safety as primarily practiced in the aerospace industry. The "Fire Safety" tree is intended to represent every conceivable means of providing fire safety. Thus the elements of the tree represent a collectively exhaustive set of fire protection measures and the tree provides a qualitative tool for examining all of the possibilities for fire safety design.

Quantitative component. Fault trees are often used as a framework for the quantitative analysis of system safety. A branch of the "Fire Safety" tree which is particularly amenable to this type of analysis is concerned with the management of fire, as opposed to the prevention of fire or the management of persons or property exposed to the effects of fire (Figure 1.2). For this branch knowledge and data appear adequate to support a probabilistic measure of the level of fire safety.

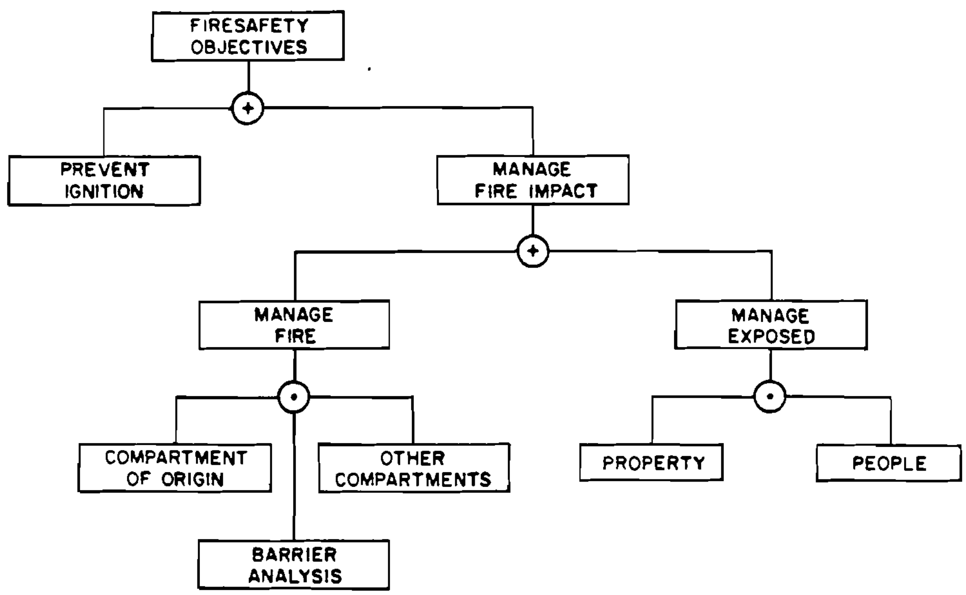

Figure 1.2

Major Branches of Fire Safety Tree

Present Limitations of the Goal Oriented Systems Approach

Codification or extensive application of a fire protection evaluative technique such as the Goal Oriented Systems Approach is presently restricted in three areas: the development of input parameters, the expertise for implementation, and the documentation of theoretical concepts.

The inputs to the Goal Oriented Systems Approach are of two types: inputs similar to those of the presently used code approach and inputs which are unique to the systems approach.

There are implicit inputs to the traditional code approach such as fire load and fire severity which are recognized as incorrect characterizations of fire phenomena [19]. However, these invalid concepts are vehemently adhered to out of the acute inconvenience of any alternative. Some of the concepts which these parameters ascribe to measure are also inherent in the Goal Oriented Systems Approach as currently utilized. Basically, however, this approach has the potential to accommodate the convenience parameters of the traditional codes and yet be amenable to the inevitable forthcoming changes in criteria.

Inputs unique to the Goal Oriented Systems Approach are of a probabilistic nature. Adequate data on features such as the reliability of fire suppression systems and the probability of wall penetrations have been unavailable. Until such time as statistical verification becomes possible, it is necessary to synthesize professional judgement with available knowledge to produce the required input.

Perhaps the most significant limitation to application of the Goal Oriented Systems Approach is expressed by the natural reluctance of acceptance by those entrenched in the traditional code approach. Individuals prominent in their field have identified this problem. John G. Degenkolb, a code consultant states:

> "The typical Building Department does not have the financing nor the staff to develop the level of expertise that the GSA has available. I doubt that the Headquarters Staff for each of the model codes organization can feasibly employ the qualified manpower needed nor use the time necessary to work its way through the details connected with the systems approach used" [20].

and Norman A. Koplon of the Atlanta, Georgia, Building Department says:

> "The GSA concept, as I view it is based upon advance theories - some probabilistic and difficult for the average building official to be responsible for" [21].

Thus implementation of the Goal Oriented Systems Approach mandates an expanded level of expertise of those responsible for building fire safety evaluation.

Vytenis Babrauskas, in his doctoral dissertation [22], examined and evaluated fire protection design methodologies, primarily with respect to their treatment of fire endurance. He identified the GSA approach as ". . . the most inclusive and well developed systematic approach to building fire safety ever issued in the U.S. . . ." [22, p. 92]. In his evaluation of the Goal Oriented Systems Approach, Babrauskas identified three valid limitations. The first area of concern is that there is no generalized procedure for identifying and quantifying goals in the manner utilized by the approach. Beyond the GSA goals shown in Figure 1.1, the only other published example of a goal "curve" is for the Children's Hospital National Medical Center in Washington, D.C. The fire safety design objectives for Children's Hospital were:

"1. That in-patients be protected in their beds, without evacuation of more than one room.

2. That damage be limited and the area affected be restored to normal use within three days of the incident" [23, p. 1139].

These objectives were translated into an "L-Curve" similar to the general level GSA mission focused goal of Figure 1.1, but there is no indication of the nature of the translation process.

The second significant limitation that Babrauskas points out is the absence of substantiated numbers for the calculations. The unavailability of probability data has been discussed and will be further addressed in later chapters of this paper.

In summarizing the comparative merits of the design methodologies which he evaluated, Babrauskas says:

> "The GSA method has the same drawbacks as the traditional methods insofar as it is based on the (Ingberg) equal-area hypothesis. But it is much more consistant, treats fuel load in a better way, and recognizes the stochastic nature of fire" [22, p. 309].

Babrauskas also notes that the method is flexible enough to accommodate a better fire endurance procedure and he suggests introducing component evaluation utilizing critical temperature.

1.1.4 Other Probabilistic Approaches

It is axiomatic that fire is a stochastic phenomenon. The dearth of probabilistic treatment of fire is therefore surprising. There are, however, three other significant probabilistic approaches to fire in structures which have been published in the literature.

The most theoretically rigorous approach is Magnusson's safety analysis, using probabilistic methods, of fire exposed structural steel [24]. His paper presents several alternative approaches to the evaluation of uncertainty measures in the design of structural fire protection. The focus is on the stochastic response of protected steel building components to fire.

The work of Lie [25] which has been modified by Burros [26] represents a more generalized approach. Lie develops a scheme for economic optimization of the level of structural fire protection. By varying a number of design parameters, he illustrates their effect on the total cost plus loss over the life of a building.

Baldwin and Thomas [27] take a more simplified approach. They consider, however, both active and passive methods of fire protection. Their optimization considers only three possible outcomes but represents a qualitative basis for further effort.

These papers are important in their treatment of the probabilistic nature of fire. Yet the Goal Oriented Systems Approach is unique in that it has been employed in actual building design.

1.2 The Development of the Goal Oriented Systems Approach

A chronology of the systems approach to fire protection requirements for buildings has recently been compiled by Nelson [28]. This section will address the traceable points in the development of the Goal Oriented Systems Approach which are significant to this study.

1.2.1 System Safety and Fault Tree Analysis

The intense demand for reliability in the aerospace industry in the 1950's generated a new discipline: System Safety Analysis. The fault tree technique was developed by the Bell Telephone Laboratories in 1961 for the Minuteman ICBM system [29]. The Fault Tree process is basically an application of Boolean algebra, utilizing logic diagrams to portray and analyze potentially hazardous events. A commendable introduction to Fault Tree Analysis is given by Lambert [30].

In 1970 an effort was made to apply the techniques of system safety to the fire protection in hospitals of the Veteran's Administration [31].

The work was not well received when presented to the fire protection profession [32] and thus was not widely disseminated.

1.2.2 International Conferences on Fire Safety in High Rise Buildings

The United States General Services Administration sponsored a special workshop and a follow-up conference of a selected group of experts to undertake a systematic effort in developing new or revised approaches to fire safety in high-rise buildings.

The conference in Warrenton, Virginia, April 12-16, 1971, was a brainstorming session. The impetus for the conference was a series of fires in modern, well-built, code conforming high rise structures, which illustrated the vulnerability of these buildings to rapid fire development; entrapment of occupants; vertical and horizontal spread of fire, smoke and toxic fumes; and difficult and dangerous firefighting problems. The objective was to develop a logical framework as a basis for action to provide adequate fire safety in high-rise structures [33].

The conference reconvened on October 5, 1971 [34]. At this meeting Irwin A. Benjamin of the National Bureau of Standards delivered a presentation entitled: "A Method of Analysis for Control of Building Fires" [35,36]. Benjamin described the application of Fault Tree Analysis to the generalized problem of fire safety in buildings and illustrated the potential level of detail available. His utilization was of a qualitative rather than a quantitative nature. This presentation was the stimulus for the development of two comprehensive fire safety logic trees.

Also at the reconvened conference, Harold E. Nelson (the coordinator of the conferences) of the General Services Administration, presented a review of how he had synthesized the concepts of the first meeting into a fire safety system for the Seattle Federal Building. In this presentation the concept of a "designed fire limit" was introduced. This concept implies a design for fire safety in structures which limits fire spread to a specified probability. GSA believed the occurrence of a serious ignition during the life of a building was very nearly certain and that this fire should be controlled within identified probabilistic limits [37].

1.2.3 Fire Safety Decision Trees

The reconvened conference led to the development of two fire safety logic trees. The trees were identified as "decision trees" rather than fault trees for several reasons: They dealt with success rather than failures or faults, their elements were concepts rather than events, and they were intended as an assistance to fire protection decision making. The fire safety decision trees are distinct from the more common decision tree concept inherent to the discipline of decision analysis.

The GSA Decision Tree

Subsequent to the meeting of October 5, 1971, the General Services Administration and the National Bureau of Standards joined forces to develop a comprehensive generalized logic tree of the various approaches available to achieve fire safety objectives in buildings. After several revisions this tree formed the basic reference document in the GSA Goal Oriented Systems Approach [16].

The NFPA Decision Tree

In 1972 the National Fire Protection Association formed the Committee on Systems Concepts for Fire Protection in Structures with the charge to develop systems concepts and criteria for fire protection in buildings. This committee promulgated a logic tree similar to that of GSA but slightly more generalized [38,39].

1.2.4 The GSA Goal Oriented Systems Approach

The General Services Administration maintains a handbook, Building Firesafety Criteria, as an internal document intended for use by GSA staff in reference to properties for which GSA is responsible (most general service federal buildings). In the 1972 change order to this handbook, Appendix D ("Interim Guide to Goal Oriented Systems Approach to Building Fire Safety") was added. Revised in 1975, Appendix D is the cumulation of five years of concerted effort toward the development of a systems approach to fire protection in buildings. At this time it ". . . is the only completely described analytical system for probabilistic evaluation of the expected success in total performance of fire safety in buildings" [28, p.4].

1.3 Quantitative Aspects of the Goal Oriented Systems Approach

The focus of this study is on that portion of the Goal Oriented Systems Approach which is quantitative in nature. This is the aspect of the approach which derives probabilities of success of limiting fire spread.

1.3.1 Probability Curves

Presentation of derived probabilities is made in the form of "curves" such as the GSA objectives curve portrayed in Figure 1.1. Most of the present applications of the Goal Oriented Systems Approach consist of a defined sequence of such curves.

The common abscissa of these curves represents spatial models of increasing size within a building. The initial modules represent work stations or fuel packages which are semi-contiguous combustible materials in which a fire may originate or among which a fire may spread. An example would be a desk, chair and waste basket in close proximity to one another. Thus a fire starting in the waste basket would ignite the desk and chair by direct flame impingement, whereas spread to an adjacent work station would most likely be by radiative heat transfer from the first work station. Total room involvement is defined as fire spread among n work stations where $n \geq 1$. In most compartments n will take a value of 3 or 4, i.e., the entire room will be involved simultaneously with the involvement of the third or fourth fuel package. The sequence of fire spread is then considered from room to room where n rooms represent an entire floor. Similarly, the building is considered to be composed of n floors. Thus n is an arbitrary variable used to indicate a terminal number of work stations, rooms or floors.

The ordinate of the curves is the cumulative probability of success of limiting fire spread. The scale used is basically a linearized cumulative normal probability distribution, selected, apparently, for convenience and availability. The extreme portions have been altered or adapted in various ways by GSA and other users of the approach. Since the abscissa is not continuous, there can be no significance of the normal distribution to the curves. Thus, the curves of the Goal Oriented Systems Approach are in fact discrete points which are not truly related in a continuous manner, however, they are connected to facilitate the effectiveness of their graphical presentation.

1.3.2 The Compartment of Origin

The first probabilistic evaluations are made for the work stations or fuel packages within the compartment of origin. These evaluations are based on the relevant portion of the logic tree (Figure 1.3) which dictates that the limitation of fire spread to a work space is achieved by self-termination of the fire (i.e., it just goes out) by manual suppression (e.g., fire department) or by automatic suppression (e.g., automatic sprinkler system). GSA has developed from staff experience and available technical data [1, p. A18] a series of plots of the probability of self-termination for various types of office occupancies

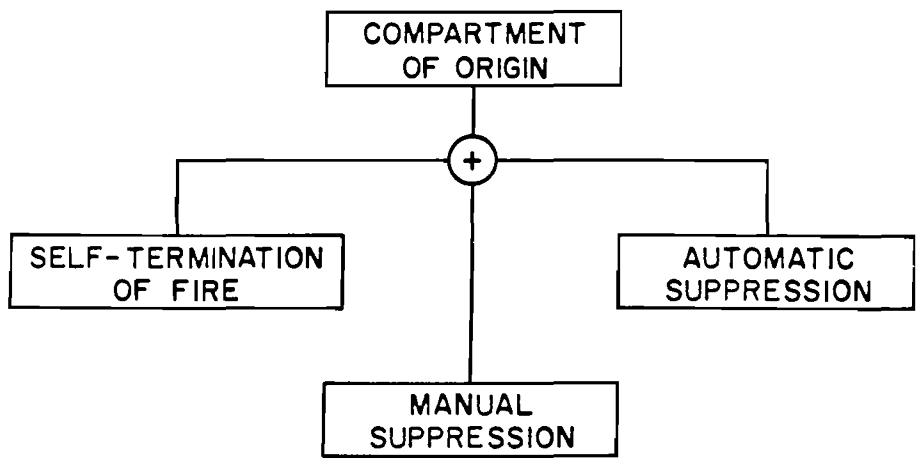

Figure 1.3

Compartment of Origin Branch of Fire Safety Tree which are referred to as "I-curves" (Figure 1.4)[3]. The designer or fire protection engineer must make similar judgement decisions as to the suppression probabilities ("M-curves" and "A-curves"). Then, following the indicated logic of the tree, the probability of limiting the spread of fire to work station i is given by:

$$P\{L_i\} = P\{I_i + M_i + A_i\}$$

which by Boolean algebra is readily calculable from:

$$P\{L_i\} = 1.0 - P\{\tilde{I}_i\}\ P\{\tilde{M}_i\}\ P\{\tilde{A}_i\}$$

where $\sim$ indicates the complement of the respective event. The probabilities of limitation of fire spread for work stations 1, ..., n, when connected together are referred to as the "L-curve" for the compartment of origin.

The Illinois Institute of Technology Research Institute (IITRI) has developed an alternative approach to identifying the probability of limiting fire development within a room [40]. This effort, which utilizes deterministic principles of heat transfer and thermodynamics,

[3]There is an important caveat on the applicability of these graphs:

"The user of this appendix is cautioned that these curves represent the best judgement at the time of writing of the GSA Accident and Fire Prevention Division staff for the conditions labeled on the graphs and envisioned by the staff. They should be considered useful in field application to other situations but should not be taken as universally applicable to all buildings ..." [1, p. A11].

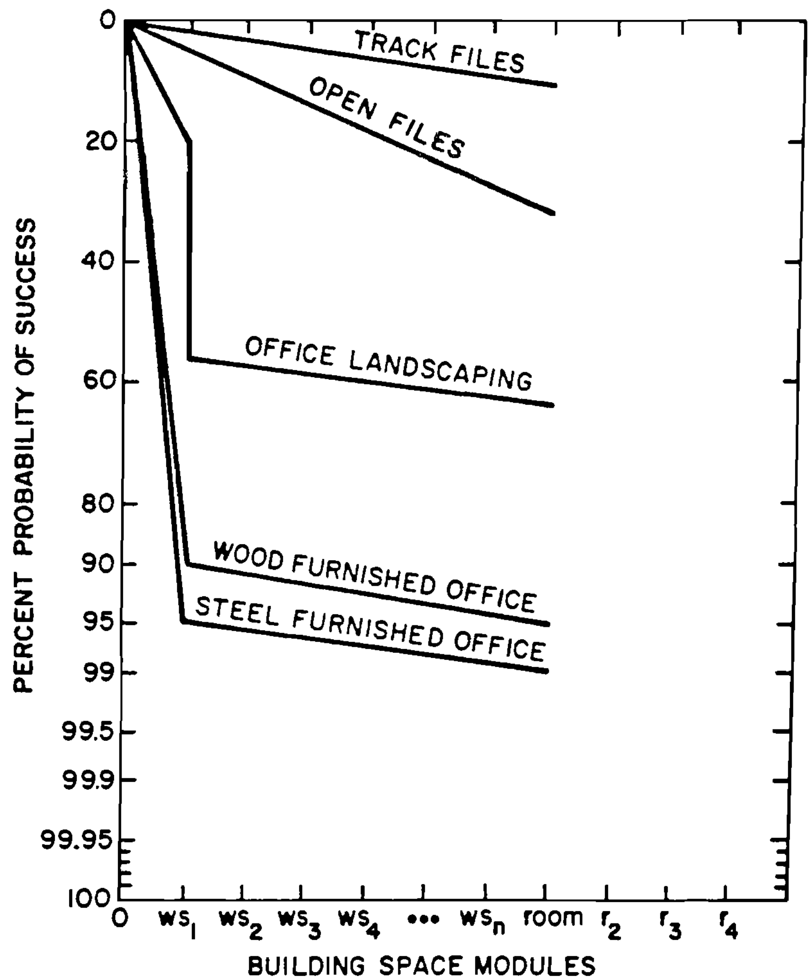

Figure 1.4

GSA I - Curves
ws = work station, r = room

and the objectives of the Ad Hoc Working Group on Mathematical Fire Modeling indicate that less subjective determination of probabilities for the compartment of origin may soon be available.

1.3.3 Barrier Analysis

When a fire reaches the physical boundaries of the compartment, it encounters its first material barrier to further spread. Determination of the capability of a structural barrier to retard fire spread is the most sophisticated aspect of the Goal Oriented Systems Approach.

Three failure modes of fire barriers are considered in the traditional fire testing procedure; passage of flame or hot gases, transmission of heat, and inability to sustain the applied load [41]. The first of these failure modes is handled directly by an assessment of the percentage of openings, orifices, holes, or other means by which the passage of flame or hot gases may take place. Figure 1.5, from the GSA document, illustrates a judgement analysis of the probability of limiting fire spread versus the percent of openings for several types of barriers. This probability is designated by GSA as P{O}.

The other failure modes are dependent on the severity of the fire. Traditionally, fire severity is estimated by a relationship of the amount of combustibles to the standard ASTM fire test [42]. An estimate of probable fire severities for several furnishing conditions is shown in Figure 1.6. GSA estimates of the response of barriers to fires of differing severity are portrayed in Figures 1.7 and 1.8 for

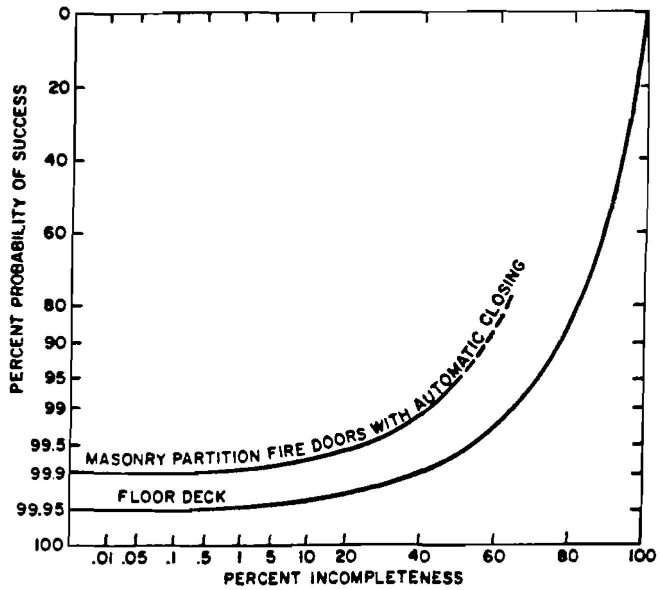

Figure 1.5

GSA O - Curves
Probability of barrier acting as effective block to passage of convected or radiated ignition

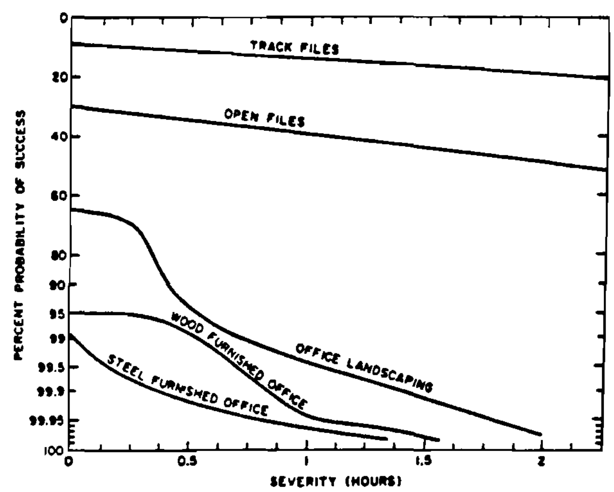

Figure 1.6

GSA H - Curves
Probability of fire severity for normal office building type construction and arrangements

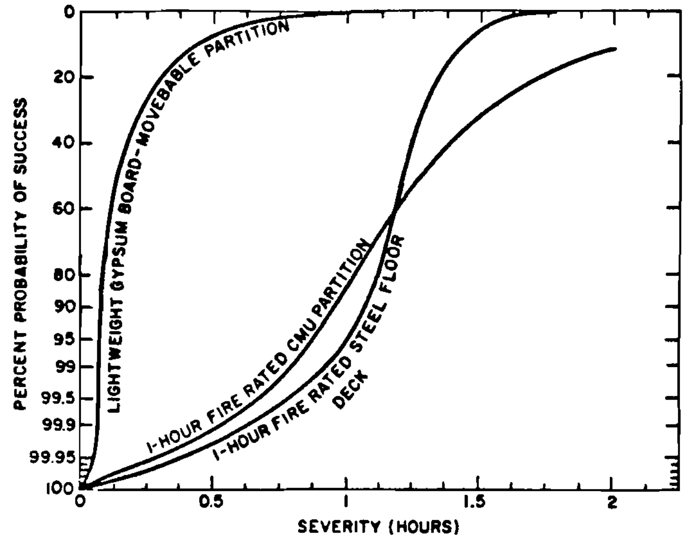

Figure 1.7

GSA T - Curves
Probability of barrier preventing the passage of ignition due to conducted energy

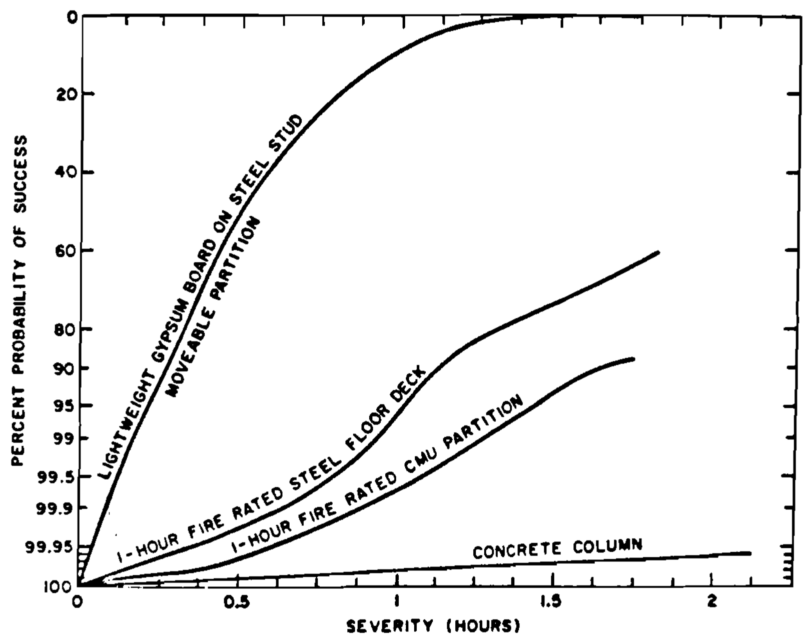

Figure 1.8

GSA D - Curves
Probability of element remaining intact or in place under its imposed load when subjected to given fire severity

thermal resistance (T) and structural integrity (D) respectively. The total probability for each of these is then found by conditioning on the severity probability. Thus if the probability of a fire of severity i is given by $P\{H_i\}$ and the conditional probability of thermal resistance is given by $P\{T/H_i\}$ then the total probability is:

$$P\{T\} = \sum_{i=1}^{n} P\{T/H_i\}\ P\{H_i\}$$

(A discrete representation is used since the method designated by GSA involves only empirical distributions). Similarly, when the conditional probability of sustaining the applied load is designated as $P\{D/H_i\}$ the total probability is:

$$P\{D\} = \sum_{i=1}^{n} P\{D/H_i\}\ P\{H_i\}$$

The determination of the probability of the success of a barrier in limiting the spread of fire now follows the Boolean logic of that portion of the fire safety tree indicated by Figure 1.9. Thus the probability of the success of barrier j is given by:

$$P\{F_j\} = P\{O_j + T_j + D_j\}$$

which is calculated by:

$$P\{F_j\} = 1.0 - P\{\tilde{O}_j\}\ P\{\tilde{T}_j\}\ P\{\tilde{D}_j\}.$$

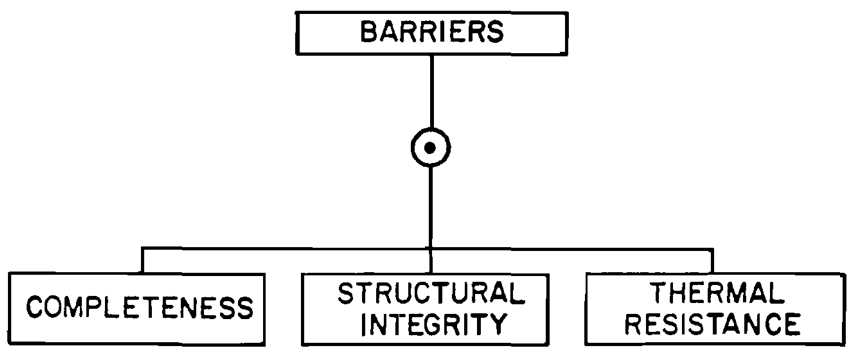

Figure 1.9

Barrier Branch of Fire Safety Tree

1.3.4 Construction of the L-Curve

The "L-curve" of a building is the current evaluative product of the Goal Oriented Systems Approach. It represents the cumulative probability of limiting fire spread at each of the spatial modules considered. The "L-curve" is derived in a step by step process of calculation at each module and at each barrier. The residual probability of failure, $P\{\tilde{L}\}$, at each step is reduced by the probability of success of the specific module or barrier, e.g.:

$$P\{L_{i+1}\} = P\{L_i\} + P\{\tilde{L}_i\}\ P\{F_i\}.$$

That is, the probability of success of limiting fire spread at a point on the L-curve, designated by L_{i+1}, is equal to the probability of success at the previous point, L_i, plus the residual probability of failure reduced by the probability of success of the ith barrier $P\{F_i\}$. The L-curve is then found by connecting these points as, for example, the points, "a" through "q" on Figure 1.10.

The resultant L-curve is compared to the identified goals of the owner or occupant of the building. In Figure 1.10 the fire protection does not meet the general level goal criteria of the General Services Administration.

1.4 Current State-of-the-Art of the Goal Oriented Systems Approach (1977)

The Goal Oriented Systems Approach is still in an embryonic stage of

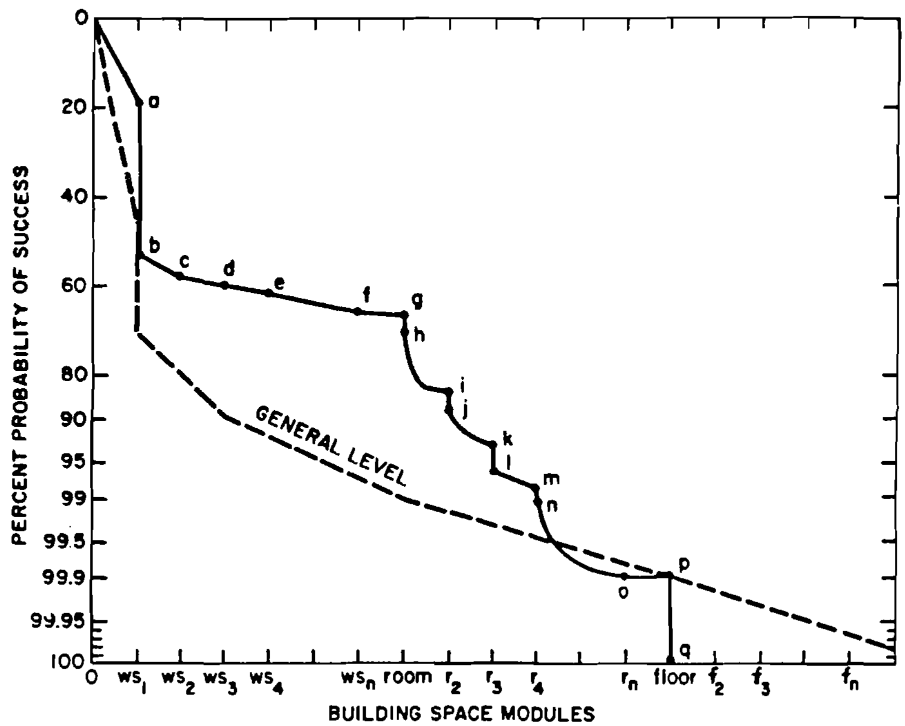

Figure 1.10

GSA L - Curve
ws = work station, r = room, f = floor

development. Application techniques are being refined by GSA and considerable attention is being given by the National Fire Protection Association. A number of engineering curricula have incorporated the concepts and there are impending developments of significance.

1.4.1 Refinement by GSA

A search of the available literature has discovered only one article in a technical journal which could be considered a response to the publication of the Goal Oriented Systems Approach by GSA in 1972. The article [43] suggests an electrical analog for the GSA Fire Safety Decision Tree to facilitate parametric studies of building fire safety by designers. Although an interesting proposal, it does not speak to the validity of the probabilistic aspects of the approach.

The dearth of formal reaction to GSA's approach cannot be ascribed to a lack of exposure. Nelson, who pioneered the approach, has presented the concepts in a variety of venues [18, 44, 45, 46] and the application of the Goal Oriented Systems Approach to the Atlanta Federal Building was well publicized [47, 48, 49]. While there has been negligible published technical response, unpublished and informal responses have been significant. The suggestions of Cornell [50] and the work of Ferguson [51, 52] and the GSA staff led to the revision of Appendix D in 1975 which was published by the National Bureau of Standards in 1977 as an appendix to a discussion of the approach [1].

1.4.2 Activities of the NFPA

The National Fire Protection Association as the fire protection standards development organization in the United States has been instrumental in the evolution of a goal-oriented systems approach to fire safety.

As reported to the Reconvened International Conference on Fire Safety in High-Rise Buildings, the NFPA formed an Ad Hoc Committee to review the report of the earlier conference [53]. This review resulted in the approval of a special committee of the Association with the scope of being "responsible for developing systems concepts and criteria for fire protection in structures" [38]. The primary accomplishment of the Committee on Systems Concepts has been the development of the NFPA "Decision Tree" mentioned in the previous section. A subsequent report on descriptions of the Decision Tree elements was given in 1977 [54]. The chairman of the Systems Concepts committee, H. J. Roux, has been active in presenting the concepts of the Decision Tree to European audiences [13,55].

In addition to the Decision Tree, the NFPA has published a compilation of non-technical articles relating to systems analysis in fire protection, which includes an informal discussion of the Goal Oriented Systems Approach [56]. The NFPA Committee on Libraries, Museums and Historic Buildings has recommended a goal-oriented systems approach to building fire safety as an alternative to specification and component performance codes [57, pp. 3-4].

The NFPA is presently under contract to the Department of Housing and Urban Development to study the application of systems analysis to residential fire safety [58]. Specifically, the project is directed toward providing a means to evaluate HUD's Minimum Property Standards and possible alternatives. While the NFPA Decision Tree is being utilized as a framework for analysis [59], a state-transition computer simulation is being employed rather than the parametric probabilities of the Goal Oriented Systems Approach [60, 61, 62]. In addition, the NFPA model attempts to cumulate all possible fire situations, whereas the Goal Oriented Systems Approach identifies the probability of a single, general fire scenario selected by experienced judgement.

1.4.3 Documentation by the SFPE

The Society of Fire Protection Engineers has received a grant from the National Fire Protection and Control Administration to develop a textbook that combines the state-of-the-art in fire protection technology with systems analysis [63]. Two of the editors on this project have been actively developing significant extensions to the GSA Goal Oriented Systems Approach [64, 65, 66, 67]. Their efforts have been directed toward facilitating the application of the technique rather than addressing the question of validity.

1.4.4 Research at the University of Maryland

Section 13 of the Fire Prevention and Control Act of 1974 [68] charges the National Fire Prevention and Control Administration to issue the information necessary for the preparation of "fire safety effectiveness statements". Toward fulfillment of this charge a contract to study the concept of fire safety effectiveness statements has been let to the Department of Fire Protection Engineering at the University of Maryland [69]. This study will evaluate all of the various approaches which have potential for creating quantified statements of the effectiveness of fire safety measures undertaken for a given structure, including the Goal Oriented Systems Approach.

1.4.5 Academic Exposure of the Goal Oriented Systems Approach

The Goal Oriented Systems Approach represents a significant variation to the traditional evaluation of fire safety. As such, it may be reasoned that to facilitate its implementation requires more than peripheral exposure to written or oral presentations. In this light, the extent to which the approach has been incorporated into educational programs is noteworthy.

The Department of Fire Protection Engineering at the University of Maryland includes the Goal Oriented Systems Approach in its course on Fire Hazard Systems Analysis and the Department of Civil Engineering at Worcester Polytechnic Institute offers a regular course based on the approach [70]. In addition, short courses have been offered at the University of Wisconsin; the University of California, Berkely, Virginia Polytechnic Institute and other locations [71].

1.5 Summary

Present-day fire protection problems are too complex for the traditional code approach. Deterministic solutions are unacceptably futuristic. The Goal Oriented Systems Approach developed by GSA is the most complete and rational fire safety design method available today. By virtue of the widespread application and interest, the GSA approach is on the verge of constituting a new technology. The present state-of-the-art of this technology is substantially intuitive; it behooves one to try to establish a scientific basis upon which the technology may be founded. To attain this basis answers are needed to questions such as the following:

- Are there underlying theoretical concepts in the GSA approach which may be used to develop a broad approach to the general question of determing a level of fire safety?

- How can the GSA approach be improved with respect to flexibility of scope, simplicity of application and validity of concepts?

- How sensitive is the approach to the limited availability of probabilistic data?

These questions will be answered in the following chapters through analysis, synthesis and evaluation of the concept of a goal-oriented systems approach to building fire safety.

The practice of fire protection engineering will long continue to be a combination of art and science, however, it is in the best interest of the public at large to identify and emphasize the scientific aspects where artistic failure would be disastrous.

CHAPTER II

ANALYSIS OF THE GOAL ORIENTED SYSTEMS APPROACH

The problem of fire safety in structures has heretofore defied engineering solution. The magnitude of the problem is overwhelming in the number of relevant variables and, since fire is a rare event, the absence of data. The established approach of building codes is recognized as inadequate for many structures in a modern built environment. The Goal Oriented Systems Approach appears an acceptable solution to the problem of building fire safety. This present research is directed toward the establishment of a theoretically sound basis for the approach as a first step toward validation. To this end, a systems analysis of the Goal Oriented Systems Approach is presented.

Systems analysis is the systematic analysis of a problem or question. The objective is to find the best solution or answer from among alternatives. This chapter provides a concise review of the most general features of systems analysis. It gives an idea of the nature of systems analysis and why it is so pervasive. The methodology identified in this research is a three part procedure. The first step is an initial analysis, not of the problem, but of the system within which the problem occurs. The second step is the synthesis of system activity into a conceptual model, and the third part is a comparison and questioning of the responsiveness of the model. This chapter treats the application of the analysis or formulation step of a systems analysis to the Goal Oriented Systems Approach. Both deductive and inductive analyses are presented.

Within a reasonable time frame, the problem of building fire safety is intractable. The present study is unique in that it addresses a solution to this problem rather than the problem itself.

2.1 Systems Analysis

Systems analysis is the systematic analysis of a question or problem. The operative word is systematic rather than system. However, it is appropriate to a systematic analysis to consider the system within which the question arises. Hence, the concept of a system is an inherent part of systems analysis.

2.1.1 Characteristics of a System

The concept of system in systems analysis is not significantly different from its everyday use, e.g.:

automobile exhaust system
digestive system
democratic system of government
sewer system
ecosystem
fire protection extinguishing system

There is a difference, however, and it is twofold. First, in systems analysis the system must be rigorously defined, i.e. in a systematic fashion, and second, in systems analysis the concept of a system is applied to many activities which may not ordinarily be thought of as systems, e.g.:

a ship at sea
supermarket checkout
a warehouse
bidding for a contract
a family
the world[1]

From the above it may be ascertained that a system can be highly complex. This often makes a rigorous definition of the system very difficult. All systems, however, have certain common characteristics which if properly identified will usually adequately define the system. These characteristics are:

1. boundary
2. input and output
3. variables
4. structure

These characteristics of systems will each be discussed briefly; their interrelationships are illustrated in Figure 2.1.

Boundary

The difference between systems analysis and a more generalized systems approach, e.g. Checkland [72], is the difference between closed and open systems. In systems analysis, a system is considered to be bounded in such a manner that the system behavior of interest is generated entirely

[1]Interestingly, the world has been systematically analyzed, see: Forrester, Jay W., World Dynamics, Wright-Allen, Cambridge, Massachusetts, (1973).

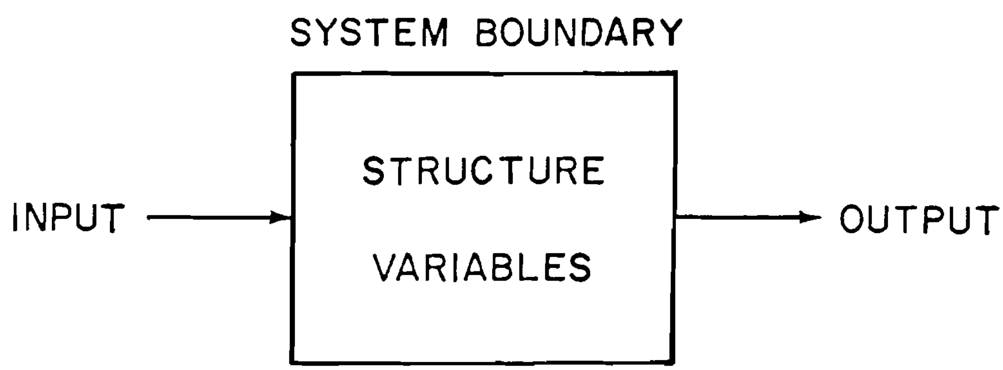

Figure 2.1

Characteristics of Systems

within the boundary, thus it is a closed system. This does not mean that the system is unaffected by its external environment, but exogenous events do not themselves govern the behavior of the system, i.e., there is no feedback mechanism between the system and outside elements. Power failure, for example, is an event which may affect a fire safety system, but the electrical generation and distribution system may not be included in the fire safety system boundary. The system boundary defined in the Goal Oriented Systems Approach consists of an office building and its contents.

Input and Output

That a system has input and output implies that it is functionally dynamic. The system must act in some manner to convert the input to output. The conversion mechanism is the essence of the system. For the fire safety system addressed by the Goal Oriented Systems Approach, the input is an ignition and the output is a measure of the success of the system, i.e., limitation of fire spread.

Variables

Certain factors of the system may be under the control of the designer. These are the decision variables of the system. A system usually consists of a very large number of interacting variables, many of which defy quantification. The complexity of the system is a rapidly increasing function of the number of variables. There are an exceedingly large number of decision variables in a fire safety system:

physical and chemical properties of the materials of the building and its contents, features of structural geometry, configurations of suppression systems, etc. The objective of a system analysis is to arrive at the most desirable values of these variables.

Structure

System structure or morphology is the overall framework relating the variables within the system boundary. There are many basic structural forms which systems take. Malasky [29] has enumerated descriptors for reticulate systems:

Series-parallel structure
Source-sink structure
Decision structure
Hierarchical structure
Time sequence structure
Logic structure
Information flow structure
Open-loop-closed-loop structure
Signal flow structure

This list is not exhaustive nor are the items necessarily mutually exclusive. Most systems are a combination of several such elemental structures, thereby creating a complex object for analysis. The Goal Oriented Systems Approach identifies fire safety as a logic structure in the form of what has come to be called a "Fire Safety System Decision Tree" [16]. Thus, a system may be described in terms of its characteristic boundary, input and output, variables and structure. Once so defined, it becomes amenable to analysis.

2.1.2 Systems Analysis - A Definition

Systems analysis may be defined as the systematic application of knowledge, skills, logic and intuition to solve a problem. Knowledge of the system undergoing the analysis is required as well as knowledge of the techniques which may be appropriate to the analysis. A systems analysis is often a multidisciplinary team project so that the knowledge of several individuals may be brought together. Skills and dexterity in the techniques of analysis are as necessary as in any other craft or profession. Logic is necessary for the overall structure of the analysis. The logical framework of a systems analysis is essentially the same used by most people implicitly or unconsciously in making everyday decisions such as which route to take or what to have for lunch. As the decision system becomes more complex, it becomes necessary to formalize the logic of the decision process. Intuition permeates systems analysis. A system of multifaceted complexity has many hiati in verifiable knowledge which must be bridged with judgement and intuition. It is this use of judgement and intuition that distinguishes systems analysis from more structured techniques and it is their systematic application that distinguishes systems analysis from visceral problem solving.

2.1.3 Systems Analysis - A Procedure

Most professors of systems analysis outline a sequence of tasks to be performed in a more or less iterative fashion. Many of these schemes are quite varied and complex and yet may be comprised of similar components. Systems analyses tend to take their character from the particular practitioner and from the problem addressed. Hence they often bear little resemblance to each other: "The techniques differ from study to study and there is but the thinnest thread of method that ties these studies together"[73, p. 2]. The most elementary representation of this thread of method appears to be that of Pantell [74]. Pantell's scheme for systems analysis is comprised of three basic steps: formulation, modeling and evaluation.

Formulation

Formulation is the first and most important step in a systems analysis. This step is also often referred to as problem definition. Concise definition of the problem is the output of this step; however, the process involved in its development is usually significant. Most real world problem arise in an amorphous state. It is necessary to reformulate the problems into a form convenient for analysis and this requires a qualitative understanding of the system. The formulation step is critical since it is difficult to extract a right answer from the wrong problem [75]. Thus, formulation is a two stage process involving a study of the system and the development of a well defined statement of the problem.

Problem definition usually comprises an identification of scope, objectives, measures of effectiveness, variables and interrelationships.

The scope limits the commitment to the problem within the system. The objectives are the desirable products of the system while the measures of effectiveness dimension the degree of achievement of the objectives. The variables are those items which are manipulated to achieve the objectives and the relationships identify the known interactions of the variables within the system structure.

Modeling

Modeling is the quantification of the qualitative understanding of the system gained in the formulation step. This quantification takes the form of a model of the system. A model is a symbolic abstraction of the essense of the system. To conveniently study a system's behavior, the model may be manipulated rather than having to manipulate the system itself. For such a study to have validity, the model must closely represent the systems behavior. However, the more the model is like the system, the more difficult it is to manipulate (like the system); therefore, approximations and simplifying assumptions are required to make the model tractable. Thus, an acceptable model must be sufficiently analagous to the real problem to evaluate alternatives with the accuracy to permit sound decisions yet simple enough to be amenable to quantitative analysis.

Evaluation

The evaluation step uses the model to examine alternative courses of action. The system model is manipulated to achieve the desired objectives. It is important in a systems analysis to maintain the perspective that it is the question, not the model that is important. The purpose of the evaluation step is to provide relatively simple rules that the decision maker can use to eliminate inferior alternatives.

Any scientific investigation is essentially an iterative process. The steps of formulation, modeling and evaluation are not always followed seriatim but more often cyclically. The modeling process may require a reformulation of the problem while the evaluation may suggest alterations to the model or a redefinition of goals. These interactions are illustrated in Figure 2.2

2.1.4 Applications of Systems Analysis in Fire Protection Engineering

In 1965 Hilton F. Jarrett [76] identified numerous areas of fire protection he deemed amenable to systems analysis, yet to this date, there have been exceedingly few definitive applications of systems analysis in fire protection engineering. Some areas of fire protection appear to be more amenable to systems analysis than others.

Areas of Fire Protection Engineering Conducive to Systems Analysis

One notable exception to the dearth of fire protection engineering systems analysis is in the area of the development of municipal fire fighting services. While there have been numerous recent studies of this topic, Fire Department Deployment Analysis [77], by The RAND Fire

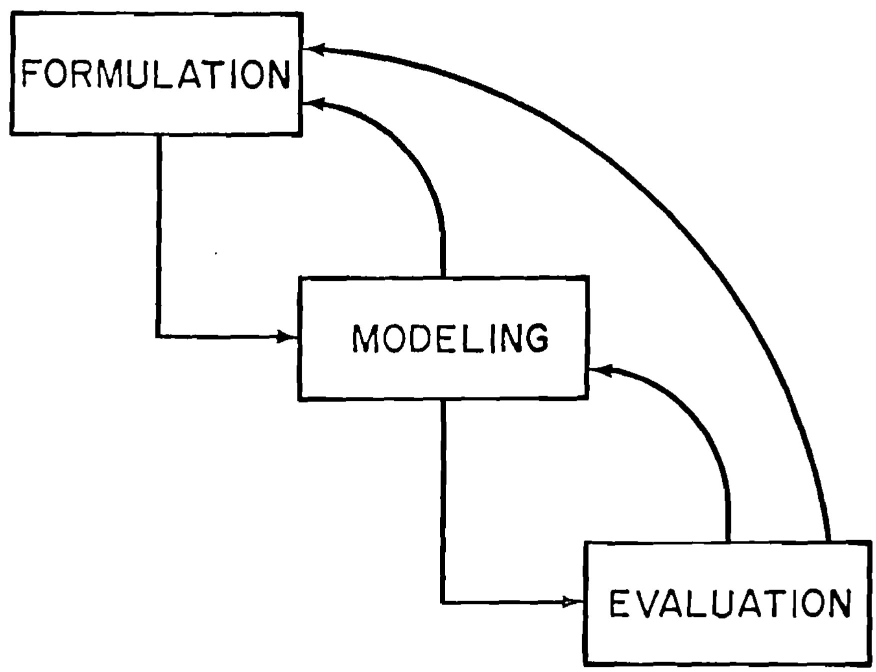

Figure 2.2

Steps of a Systems Analysis

Project stands out as a model for the application of systems analysis.[2]

There have been a number of significant systems analyses directed toward the problem of forest fires [78, 79, 80]. These studies, however, are concerned with planar, homogenous fuel covers. Thus, the wildland fire problem is significantly more tractable than the structural fire involving conglomerations of materials in three dimensional geometries.

Another area of fire protection which has been subject to a number of systems analyses is that of smoke movement. These studies have all resulted in computerized simulation models [81, 82, 83]. Movement of smoke in a structure is a problem in fluid dynamics where there are enough known relationships to adequately simulate the system. This does not carry over to the simulation of fire in general [84].

Three Systems Analyses of Structural Fire Protection

Systems analyses of building fire safety have not been concentrated in a single direction. Three studies of increasing complexity described below illustrate the variety of approaches that systems analysis may take:

[2]Two of the contributing authors of Fire Department Deployment Analysis, Peter Kolesar and Warren Walker, received the 1975 Lanchester Prize, awarded by the Operations Research Society of America for the best English language published contribution to Operations Research.

Fire safety evaluation. Shibe et. al. [85] recognized that systems analysis is effective in areas which lack accepted theoretical foundation because it makes a more systematic and efficient use of expert judgement than its alternatives. They have used this principal to produce a methodology for grading the level of fire safety in health care facilities and determining the equivalency of alternative fire safety systems. This methodology is based on the assumptions that risk factors are multiplicative while fire safety components are additive. A numerical scheme is developed using values obtained by a modified Delphi technique. The methodology is used to evaluate fire safety by computing a risk level and comparing it to a similarly computed safety level for a given facility. It is expected that this methodology will have wide acceptance in the health care field.

Economics of alternatives. An application of systems analysis to a more specific fire protection problem is illustrated by Shpilberg and DeNeufville [86, 87]. The question to be answered for an airport facility is: How much fire protection is enough? Alternative protection strategies are represented in a decision tree. Utility theory is used to measure risk aversion. Loss data are fitted to an exponential probability distribution and costs are estimated using reasonable guidelines. The results illustrate that one advantage of systems analysis is the identification of counter-intuitive alternatives which may be better, in this case the lack of fixed fire protection systems.[3]

A model of fire spread. Jane Hogg's study [88] is representative of a higher level of complexity of a systems analysis model and is more relevant to the research being herein reported.

Hogg, in the now popular fashion, considered fire in terms of stages of growth. The stages reported on were:

1. Confined to room of origin.
2. Spread beyond the room of origin, but confined to the floor of origin.
3. Spread beyond the floor of origin.

However, other stages may easily be defined depending on the availability of data. The data required is in terms of probabilities:

1. The proportion of fires in each stage at a given time.
2. The transition probabilities that a fire in one stage will grow to another stage.
3. The probability that a fire will terminate in a given stage.

This formulation is very similar to that of the ongoing effort by NFPA [58, 59, 60] however, Hogg presents an analytical model rather than a simulation.

[3]However, the results also support the intuitive alternative of higher deductibles. See: McCahill, F. X., Jr., "Avoid Losses Through Risk Management," Harvard Business Review, Vol. 49, No. 3, May/June 1971.

Hogg identifies two sets of fires in each stage of growth: those that spread to a further stage and those that don't (i.e. they go out). Difference equations are written for each set of fires and these are solved in terms of nonlinear regression equations. The problem is then reformulated after Beale [89] as one of minimizing the sum of squares of the residuals between the two sides of the regression equations. A Taylor's series approximation is made to obtain the derivatives and a steepest ascent gradient search technique [90] is employed to achieve the optimization. The resulting statistical model of fire growth was found to fit the data very well. The input data used by Hogg was gleaned from fire department reports. In order to extract the necessary parameters, it was necessary to make certain assumptions such as: the spread of fire does not continue after the arrival of the fire department. The results are interesting, especially the indication that the probability of fire spread is a linear function of time.

Hogg's model appears to be very efficient. It would seem appropriate that the model be applied to data presently being collected in this country [91, 92].

The above three studies have been somewhat arbitrarily identified as systems analyses. All that is reported on in the citations is their results; thus, they may or may not have been conducted in a manner similar to that described in this paper. As distinct as these studies are, they represent the closest similarity to the problem addressed by the Goal Oriented Systems Approach.

2.2 Analysis of the Goal Oriented Systems Approach

As an application of systems analysis to the Goal Oriented Systems approach and the problem it addresses, the formulation stage is considered in this chapter. In this formulation process, the objectives, criterion of effectiveness and scope are specified.

2.2.1 Objectives

It is noted that the quantitative component of the Goal Oriented Systems Approach has "mission continuity" as its objective [1, p. A7]. Mission continuity refers to a largely intangible functional role of a building space within some managerial construct, e.g. the accounting function of a corporation. Thus, the objective of the Goal Oriented Systems Approach refers to the extent that the overall managerial function is interfered with.

The choice not to use loss of life or fire damage as the objective is an important one. It would be anticipatory to try to include these ultimate measures at present. Relationships between fire spread and life loss and damage are not explicitly known. Obtaining them is clearly a long-term project. Immediate objectives may be met by substituting other measures of the performance of buildings in fires such as the probability of limiting the spatial development of fire. It may be that such measures can act as surrogates for more desirable goals of fire safety.

2.2.2 Criterion of Effectiveness

It has been asserted that a state of absolute safety does not exist [16, 17]. Therefore, the objective of mission continuity is measured in terms of its probability of success. There are political and other inputs to objectives which are beyond the grasp of the analyst, hence the decision maker must determine the desirable probability levels. Techniques to aid in the identification of such performance requirements are under development, e.g. Cronberg [93].

2.2.3 Scope

In defining the scope of the system, the parameters of the designed fire and the spatial modules of the Goal Oriented Systems Approach are considered.

Parameters of the Designed Fire

The concept of a designed fire was introduced by GSA at the reconvened International Conference on Fire Safety in High Rise Buildings [34], and has subsequently been incorporated in proposed guidelines for fire protection evaluation of nuclear power plants [94]. The parameters of the designed fire are the combustion process, suppression and physical confinement (Figure 2.3). These three components interrelate to determine the nature of a fire. Thus, by controlling these parameters through design, one can produce a "designed fire."

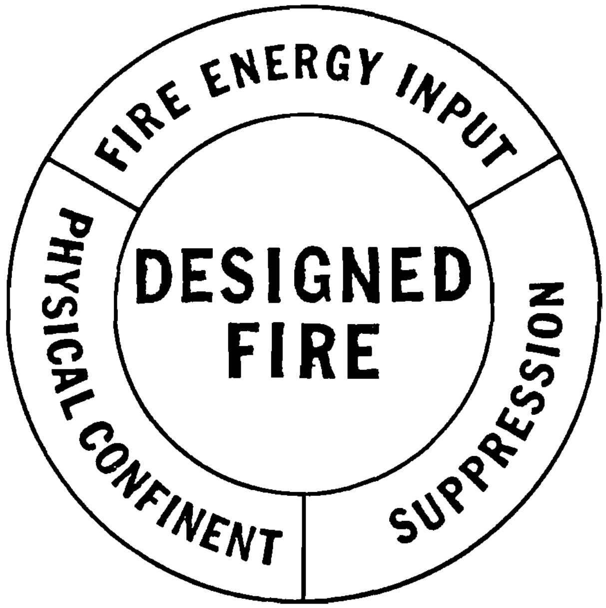

Figure 2.3

The Designed Fire

(70)

Combustion process. The combustion process is the continuing physicochemical reaction which is the essence of fire. Its extent is determined by a large number of material properties and environmental variables. The most dramatic characteristic of combustion within a compartmented structure is a phenomenon that has come to be called "flashover." Although as yet not rigorously defined, flashover refers to a stage in most room fires when combustibles ignite simultaneously producing a large body of flame within the room.

Suppression. Fire suppression has been formally defined as extinguishment or active limitation of fire growth [54]. Suppression actions are performed automatically by designed extinguishing systems or manually by occupants and/or fire service personnel. The former is significantly more definable as a design parameter than the latter. The probability of effectiveness of manual suppression over the period of interest is preponderantly a subjective evaluation. As such, it is excluded from the scope of the present study. Thus, within certain municipal jurisdictions, it will be appropriate to qualify the results of this study with consideration of the availability of a manual suppression activity. Such considerations are of themselves amenable to extensive research.

Physical confinement. A common feature of modern high rise buildings is compartmentalization. The walls which make up building compartments also comprise barriers to the spread of fire within the structure. These walls, and/or additional, specific "fire" walls, may be designed to physically confine a fire's spatial development.

The parameters of the designed fire discussed here do not constitute a collectively exhaustive set of possible parameters. In particular, they do not include designed mass transport of fire gases such as proposed by Harmathy [95]. The identified parameters do, however, cover the range of presently utilized approaches to fire control by design.

Spatial Modules

The Goal Oriented Systems Approach addresses itself to specific spatial models within a structure. GSA chose work spaces, rooms and floors as the modules of fire spread. These building space modules are illustrated in figure 2.4. For the scope of the present analysis, these modules are slightly altered. The modules considered in this report are rooms, zones, and buildings.

Rooms. A room or compartment represents a spatial area bounded by a barrier. This barrier represents the first level of physical confinement which would be encountered by a fire originating in the room. In most buildings, however, room barriers are designed as separations to aid the functional operation of the occupants of the structure and not as fire barriers.

Within a room, interest focuses on the pre-flashover stage of the combustion process and the phenomenon of flashover itself. The present Goal Oriented Systems Approach to the interroom fire development is to consider probabilistic fire spread among work stations or fuel packages within the room using experienced judgement. Recent work by the Illinois Institute of Technology Research Institute [40]

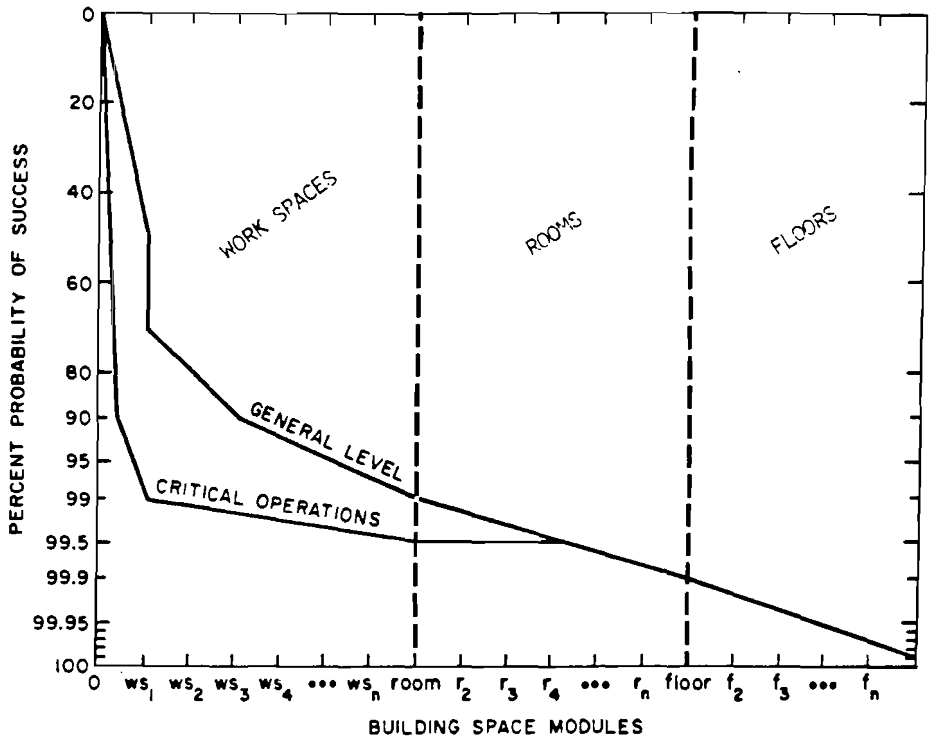

Figure 2.4

Building Space Modules

has made this type of analysis unnecessary and the recent emphasis on fire modeling [15] promises even more precise estimates of flashover probabilities in the near future. Using externally generated flashover probabilities also precludes the need to distinguish between rooms and compartments as defined by Fitzgerald and Wilson [64].

There are some aspects of the pre-flashover fire and flashover phenomenon which must still be considered. Within a room, the suppression design parameter most often materializes as automatic sprinklers.[4] The actuation of a sprinkler head usually occurs in the pre-flashover or flashover stages of a fire. Thus, the fire spread limitation effect of automatic sprinklers is dependent on pre-flashover fire conditions.

Zones. The concept of a zone as used in this report generally incorporates the concept of floor used by GSA (see Figure 2.4). However, it is extended to include more than one fire zone on a single floor of a structure. This concept of a fire zone is essentially that espoused by Shibe et. al. [84]: "a space . . . which is separated from other spaces by floors, horizontal exits or smoke barriers."

The boundary of a fire zone, then, is one which is specifically designed to impede fire. This is to be distinguished from a room boundary which is designed for functional use of the building space. Thus, there are two levels of barriers encountered by a spreading fire; barrier level one is the room boundary and barrier level

[4]And is so considered hereinafter.

two is the zone boundary.

The state of the combustion process which will impact on these barriers is the post-flashover fire. Only a fire in this free burning stage produces enough thermal energy to challenge a barrier. Specific types of barriers are tested empirically [41] and may be analyzed mathematically [96] for fire endurance. Unfortunately, no tests or standardized analytical procedures for the reliability of such barriers under conditions of field installation and use have been developed.

Buildings. A building is comprised of a number of fire zones. It is conceivable that a third level fire barrier could also be designed within a structure. In this case, the concept of a building could be used to represent the space within such a boundary and the structure would be comprised of a number of such "buildings". Thus, the modular concept may be continued for any number of levels of fire barriers. Most structures will be adequately represented by two barrier levels. Therefore, in the usual case, fire spread among zones will constitute loss of mission continuity for the entire building. There is, however, another means by which fire may cause failure of a building, and hence its mission.

The thermal energy of the fire may be sufficient to cause buckling or collapse of the building's structural frame. The probabilistic treatment of the fire endurance of the structural frame is analogous to the ultimate limit state design of structural engineering [97] and has been so treated by Lie [25] and Burros [26].

Components for Analysis

The scope of this analysis is summarized in figure 2.5. Certain components for analysis are identified by the interaction of the parameters of a designed fire with the spatial modules of a structure. These components are: 1) the pre-flashover fire 2) the post-flashover fire 3) automatic sprinklers, and 4) barriers of varying levels of fire resistance. Implicit in figure 2.5 is the assumption that the influence of automatic sprinklers does not extend beyond the room of origin. In cases where this may not hold, the assumption may be dropped with some complexity added to the analysis.

2.3 Inductive Analysis of the Goal Oriented Systems Approach

Being an intuited approach to a problem, there are many facets of the Goal Oriented Systems Approach which are not explicitly delineated in the GSA documents [1, 16]. One such facet is the fundamental principles of fire spread upon which the analytical procedure is based. The identification of these principles may be considered an induction of fire spread postulates.

2.3.1 Induction

Induction is a process of forming a general rule from particular cases [98]. It is usually contrasted with deduction in which a conclusion about a particular case is drawn from a universal premise.

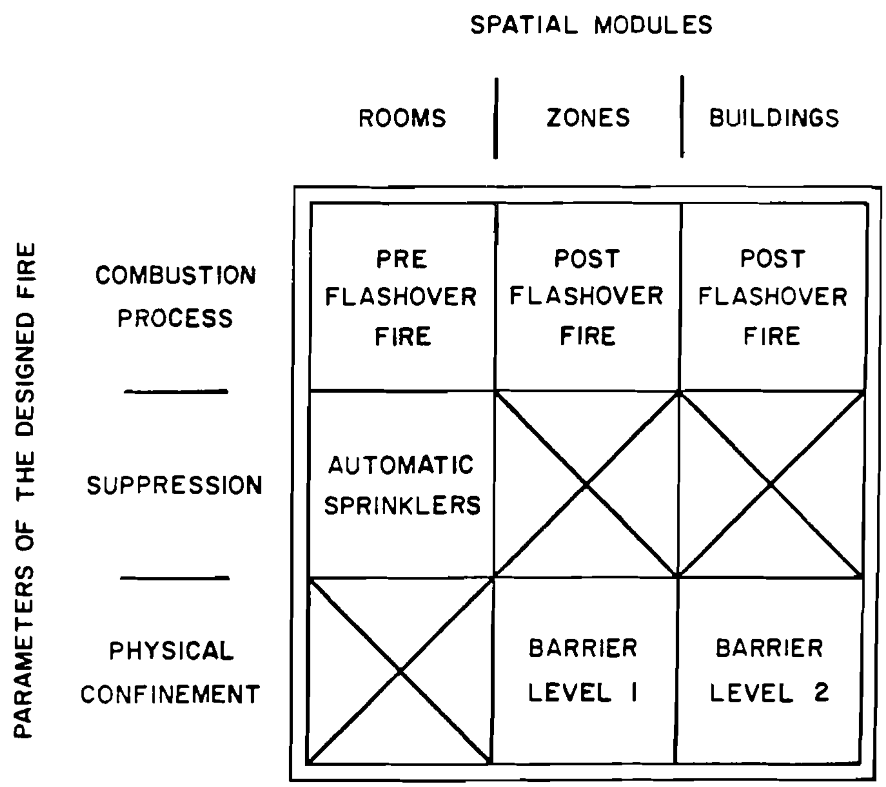

Figure 2.5

Components for Analysis

Induction takes many forms, ranging from mathematical induction as a technique of demonstrable proof, to what has been coined by Johnson [99] as "intuitive induction". Intuitive induction implies the apprehension of an abstract generalization by means of its exemplification in a particular instance [100]. Many general principles are formed by intuitive induction when more formal indications are unavailable or unnecessary. In the inductive analysis of the Goal Oriented Systems Approach, it will be reasoned that there are implicit principles in the approach which may be considered as general principles of fire safety. The inductive reasoning is as follows:

Premise: The Goal Oriented Systems Approach is an accepted methodology of evaluating fire safety. While this acceptance is not universal, use by the United States Federal Government and several major fire protection engineering firms as documented in Chapter I, constitutes a demonstration of this premise.

Premise: There are basic principles upon which the methodology is based.

Conclusion: Therefore it is induced that these principles are acceptable general principles of fire safety.

It should be noted that logical induction is not designed to demonstrate the truth of the conclusion as following necessarily from the premises but is intended to merely establish the conclusion as probable.

If the first premise is accepted, then it is only necessary to demonstrate the second premise to complete the reasoning.

2.3.2 Induced Postulates of Fire Spread

Postulates of fire spread in structures may be induced from a simplified expression of the quantitative component of the Goal Oriented Systems Approach. That these postulates are inherent to the approach may be confirmed by using them to regenerate the expression.

The Basic Equation

The quantitative application of the Goal Oriented Systems Approach to building fire safety is an iterative process which requires sequential calculations of the probability of limiting fire involvement in each of successive compartments. In an effort to simplify the calculations, a single mathematical expression has been developed for the probability of success in limiting the fire involvement to any prescribed compartment (see Appendix).

The basic equation:

$$P(L_n) = P[G_1 + \sum_{i=1}^{n-1} (F_i + G_{i+1}D_i)].$$

Where:

$P(L_i)$ = Probability of success in limiting the involvement of the ith room,

$P(F_i)$ = Probability of success of the compartmentation barrier between room i and room (i + 1),

$P(D_i)$ = Probability of structural integrity of the ith barrier, and $P(G_i)$ = Probability of success in limiting the fire involvement in room i if room i were the room of origin, i.e., limitation due to the fuel, environmental and control factors within the room.

The Postulates

In the process of deriving the basic equation a number of postulates of fire spread were induced. They are not explicitly stated in the GSA documents, but may be said to be implicit in the Goal Oriented Systems Approach.

These postulates are as follows:

1. Limitation of fire spread may be achieved by containment or by termination.

Limitation of fire spread represents an event or condition whereby fire will not spread from one module to the next and therefore implies that the next module is secure for mission continuity. Limitation of fire spread is thus equivalent to the event L in the basic equation. Containment is the event or condition by which heat transfer between modules is physically prevented. This will usually be effected by spatial separation or by a thermal barrier. Termination is the event or condition of cessation of the combustion reaction prior to the normal consumption of available fuel. Termination may be due solely to the physicochemical characteristics of the involved module or it may be abetted by a suppression methodology. Therefore, containment and termination are equivalent to events F and G respectively.

2. Termination will not occur if ignition is by massive energy transfer.

Massive energy transfer is an event or condition of modular fire spread which results in extensive fire involvement. Between compartments a massive energy transfer may be effected by the disintegration or collapse of a physical barrier. Thus massive energy transfer is equivalent to the complement of the event D in the basic equation.

A third postulate applies to the sequential fire spread among modules.

3. Limitation of fire spread to a sequential module is achieved if the fire is limited to any previous module.

This postulate is the essence of the combinative development of the "L-curve" in the Goal Oriented Systems Approach, and is similar to the principles of Hogg's [87] and other probabilistic models which produce a geometric distribution of the number of rooms burned.

Regeneration of the Basic Equation

The first two postulates of fire spread may be combined as a Boolean statement:

$$L = F \cup (G \cap \bar{D})$$

Where: $A \cup B$ = the union of A and B,

$A \cap B$ = the intersection of A and B.

This statement says that termination is the intersection of event G and the absence (complement) of massive energy transfer, and the limitation of fire spread results from the union of containment and termination. This expression holds in general within any module i.

Thus:

$$L_i = F_i \cup (G_i \cap D_i)$$

By the third postulate, fire spreads sequentially through spatial modules. Thus, the limitation at the nth module is the union of the limitation within all modules one through n.

$$L_n = L_1 \cup L_2 \cup \ldots \cup L_n$$

$$= \bigcup_{i=1}^{n} L_i$$

$$= \bigcup_{i=1}^{n} [F_i \cup (G_i \cap D\ )\ ]$$

We now have a Boolean statement as to the means by which the limitation of fire spread at any module in a structure is achieved. This statement may also be written in terms of probabilities:

$$P(L_n) = P\ \{\bigcup_{i=1}^{n} [F_i \cup (G_i \cap D_i]\}$$

Assuming independent, mutually exclusive events the equation can be written:

$$P(L_n) = P[\sum_{i=1}^{n} (F_i + G_i D_i)]$$

It is assumed that there is no barrier to the ignition of the first module. Hence, F_1 and D_1 do not exist and the equation becomes:

$$P(L_n) = P[G_1 + \sum_{i=2}^{n} (F_i + G_i D_i)]$$

which is equivalent to the basic equation as the subscripts are therein defined.

2.4 Summary

Systems analysis, like fire protection engineering, depends so strongly on experienced judgement and intuition that it still lacks a complete theoretical foundation. The essence of systems analysis is the systematic use of experienced intuition. Thus, the development of the Goal Oriented Systems Approach was essentially a systems analysis, a methodical approach to the problem of fire safety evaluation in buildings. However, the use of intuition alone without theoretically based structure is seldom adequate.

It has been shown, inductively, that there are three general postulates of fire spread implicit in the Goal Oriented Systems Approach. Having been stated explicitly, consideration of the validity of these postulates is now possible.

The spatial modules of the Goal Oriented Systems Approach and the parameters of a designed fire, form a convenient framework for analysis. The resulting components of pre-flashover fire, post-flashover fire, barriers and automatic sprinklers provide the basis for the development of appropriate theoretical models.

CHAPTER III

MODELS IN THE GOAL ORIENTED SYSTEMS APPROACH

Modeling is the essence of systems analysis. Therefore, it is appropriate to discuss this concept to some length. The original development of the Goal Oriented Systems Approach was not a rigorous attempt to model probabilistic fire spread but simply an intuitively derived heuristic approach to the problem. Yet, foundations of accepted theoretical models can be found in the approach, either explicitly or implicitly. In this chapter, these models are extended in a less heuristic fashion. The purpose is to lend additional credence to the approach and to identify the components of a more theoretical formulation.

3.1 Models and Model Building

Models are pervasive and are found in all walks of life. Models in systems analysis aspire to a certain degree of rigor and hence may be discussed within a certain context. The following discussion is illustrative and not restrictive. Useful models, like systems analyses themselves, exhibit little homogeneity.

3.1.1 The Concept of a Model

A model is simply a description of some aspect of the real world. Perceptions and thoughts are usually in terms of images. These images are in reality models of the contemplated systems. Information about the real world is gathered by the senses. This information is processed by the mind to infer interrelationships which produce the observed effects. These inferences constitute models.

A model provides an efficient way of viewing a system. It is not required to tell everything about the system's behavior, but only what we believe to be useful. This is referred to by Tukey as the "Principle of Parsimony viz. it may pay not to try to describe in the analysis the complexities that are really present in the situation" [101, p. 202]. Usefulness of the model will therefore be limited to the importance of the moment.

3.1.2 A Taxonomy of Models

Classification schemes for models are numerous. The purpose of presenting one here is not to surplant other classifications but to illustrate the diversity of models. The typology which follows is primarily that of Murdick and Ross [102] with some elaboration on the categories of structure

Classification by Function

Descriptive. Descriptive models identify relevant variables of a system and indicate the form of their relationships. Relations among variables are not made explicit and the model cannot be manipulated by changing values of the variables. Scale models are usually descriptive.

Predictive. Predictive models specify the future state of a given system. They do not necessarily require an understanding why a system behaves as it does, but only that a given input will produce a specific output. Predictive models answer "what if" questions. Correlations are predictive models.

Normative. Normative models indicate preferable courses of action. They are optimization models which provide a "best" answer to a problem.

Classification by Structure

Physical. Physical models are material representations of systems. They are either iconic or analog. Iconic models retain the physical appearance of the system such as a scale model. Analog models provide a parallel operation of the system such as a simulation.

Symbolic. Symbolic models utilize symbols to describe the system. They may be verbal, graphic or mathematical. Verbal models are narrative descriptions of the system such as are often generated in the process of formulating the problem. Graphic models utilize dimensional geometries to portray the system. Histograms and flow charts are graphical models. Mathematical models are sets of numerical functions that describe the analytical evaluation of a physical system. Most symbolic models may be translated from one form to another.

Classifications by Time Reference

Static. Static models are time independent.

Dynamic. Dynamic models account for changes in a system over time, Classification by Uncertainty Reference

Deterministic. Deterministic models produce unique output from specific input. Models in classical mechanics are deterministic.

Probabilistic. Probabilistic models respond to specific input with behavior which is not reproducible. They produce random outputs indicative of a system exhibiting stochastic variation. Most models of natural phenomena are probabilistic.

3.1.3 Model Building

Constructing models of systems is often an intuitive process. After formulating the problem in a manner conducive to analysis, a systems analyst may recognize a familiar structure in the system. In other cases, such as with statistical models, a more defined procedure may be followed:

1) Observations of the real world are used to develop a model.

2) After the preliminary model is designed, observations are used to compare the behavior of the model to that of the real world.

3) In most cases, the model thus tested will not be completely satisfactory. The model is then refined to become more realistic in its behavior.

4) Then a continued process of successive approximations proceeds until comparison indicates the model is acceptable.

Figure 3.1 is a graphical model of this model building process.

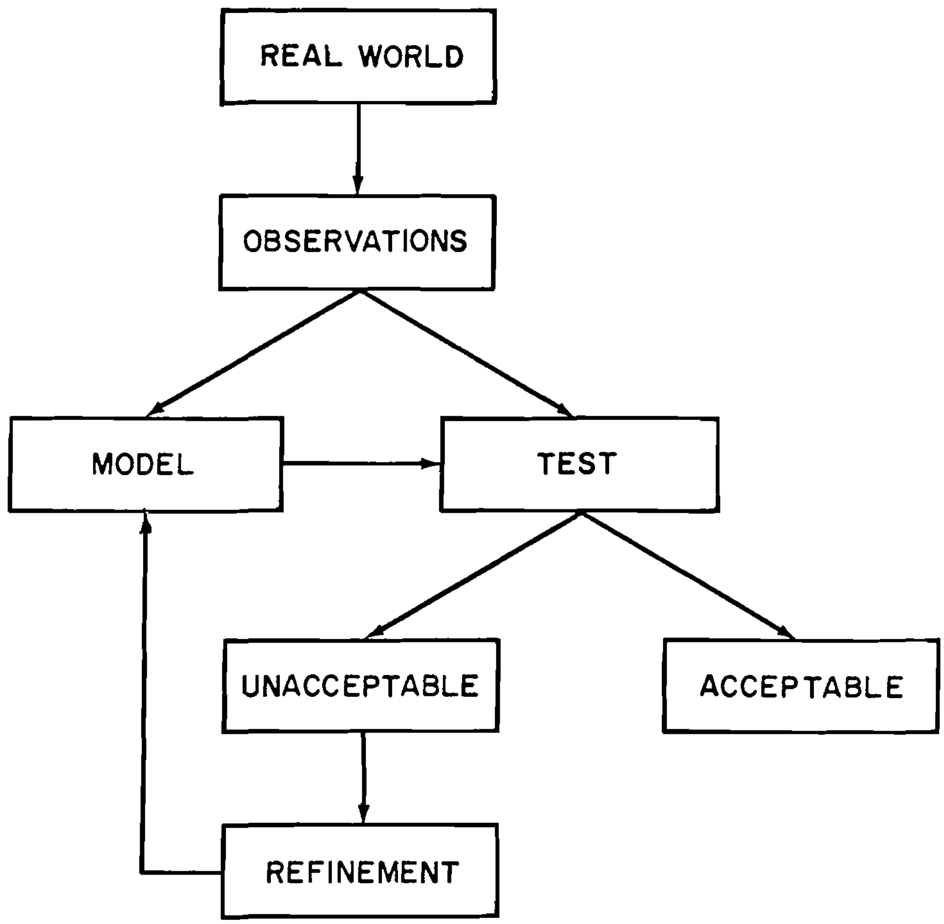

Figure 3.1

Model Building Model

3.1.4 Limitations of Models

In the process of model building, approximations and simplifying assumptions are required to make the model tractable. An assumption may be defined as a proposition which is neither self-evident not necessarily highly probable [103]. Assumptions in modeling should be explicitly identified. Implicit assumptions detract from the utility of the model by making evaluation of the model difficult. Although simplifying assumptions are almost always necessary, they should not be so overwhelming in importance that the real world representation of the model is compromised.

Omission of relevant factors in model building may be purposeful. Details which have the same effects for all alternatives need not be considered. In addition, some factors are simply not suited to numerical measures (e.g. life safety). On the other hand, such omissions may also represent the fallibility of the systems analyst and a lack of understanding of the system. All approximations, simplifying assumptions and judgments must be made explicit and thus subject the model to checking, criticism and disagreement.

3.2 Probabilistic Models

In systems analyses, phenomena which have uncertainty associated with them are always involved. Uncertainty is caused by inherent variation, either uncontrollable technological variation or inconsistencies of natural phenomena. Unless appropriate assumptions can be made to handle the uncertainty in an acceptable qualitative fashion, models of systems must incorporate quantitative treatment of the uncertainties. If the variation exhibits some degree of regularity, uncertainty may be quantitatively described by a probability model. Benjamin and Cornell [104] cover the subject of probability models comprehensively.

3.2.1 Uncertainties in Fire Safety

Many pronounced uncertainties occur in fire safety. The concept of safety itself is one uncertainty. Lowrance [17] makes the point in his study that human activity will always and unavoidably involve risks. Nothing can be absolutely free of risk; thus there are degrees of risk and consequently degrees of safety. The concept of fire is also uncertain. The NYC-RAND Institute concluded from a survey of the literature that "unwanted combustion is perhaps the least predictable common physical phenomenon" [105, p. 51]. Edward Prendergast, Fire Protection Engineer for the City of Chicago, also identifies the problem of uncertainty: "Although we know a great deal about it (fire) from a scientific standpoint, its occurrence in the real world remains largely random" [106, p. 33]. Nowhere is this more evident than in the results of "The Home Fire Project" [107]. In the first full scale room fire test, held as part of this project in 1973, it was more than seventeen minutes after ignition when flashover occurred in the form of large flames out the open door [108]. A second "identical" test was conducted in 1974 [109]. In the second test, flashover came in less than eight minutes after ignition or in less than half the time of the first test. Thus the uncertainties of fire phenomena are real and substantiated.

Quality control of manufactured or fabricated systems for confinement of suppression is another obvious source of uncertainty that prevails in the real world.

The Nature of the Uncertainties

Two types of uncertainty exist. Statistical uncertainty is measurable through the collection and analysis of data, such as fire load, fire frequency, etc. Engineering uncertainty accounts for factors which may not be included in the observed statistical data, such as relations between laboratory tests and field performance, miscalculations, and, in general, the deviation of the behavior of the actual from the ideal. That much of the uncertainty is of a fundamentally nonstatistical nature is not to say that it is nonprobabilistic, only that it is not measurable. Theoretical models facilitate the consideration of engineering uncertainty through parameter selection or by inclusion of safety factors.

In deterministic formulations, one deals with functions of variables. In probabilistic models, the values of the variables are never certain and hence they are referred to as random variables.

Handling the Uncertainties

Probability theory is that branch of mathematics which deals with uncertainty [104]. The likelihood that an event will occur can range from impossibility to absolute surety. The theory of probability provides a framework for assigning numbers to likelihoods of occurrence of events so that these likelihoods may be computed and compared.

Uncertainty cannot be ignored by using an average or expected value in lieu of the random variable itself. In general, the expected value of a function of several variables is not equal to the same function of the expected values of the variables.

Probabilistic models of fire growth have been suggested by Mandelbrot [110] Shpilberg [111] and Phung and Willoughby [112] and by numerous British researchers [88, 113, 114]. Thus, the application of probability theory to fire safety is a recognized approach.

Probabilistic modeling offers a rational method of dealing with the randomness of fire safety. As stated by Cornell, a probabilistic model is "the only kind of engineering representation which recognizes uncertainty and deals with it quantitatively and consistently" [115, p. 977].

3.2.2 Statistical Models

Significant use of statistical models in engineering has occurred only within the last quarter century. Earlier use was limited to "softer" sciences where fewer deterministic relationships exist. There are now many devotees who recognize the utilitarianism of statistical models in engineering. An appropriate review of the subject may be found in Hahn and Shapiro [116].

Probability Distributions

A probability distribution may be thought of as a function which defines the probability of any outcome of an event. For example, the probability distribution which describes the roll of a die is:

$$p(x) = 1/6 \text{ where } x = 1, 2, \ldots, 6 .$$

That is, all of the possible outcomes 1,2, ..., 6 have an equal probability of 1/6. One of the most commonly known probability distributions is the normal or Gaussian distribution. The normal distribution is of the form:

$$p(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp \frac{-(x-\mu)^2}{2\sigma^2} \quad , -\infty < x < +\infty$$

where μ and σ are the mean and standard deviation of the distribution.

Many different probability distributions are used to describe many different random phenomena. The selection of an appropriate distribution is the essence of statistical modeling.

Probability distributions of significance in this study include the normal distribution, the standard normal distribution and the lognormal distribution. The lognormal distribution is the model for a random variable whose natural logarithm is normally distributed. The lognormal density function is given by:

$$f(x) = \frac{1}{x\sigma\sqrt{2\pi}} \exp \frac{-(\ln x - \mu)^2}{2\sigma^2} \quad , \; x>0$$

where μ and σ are the parameters of the normally distributed logarithms. The distribution has many shapes for non-negative random variables as illustrated by the curves of Figure 3.2, representing lognormal distributions with different values of the parameters.

Fire Severity as a Lognormal Distribution

Selection of an appropriate probability distribution has been identified as the essence of statistical modeling. Two steps comprise this process: an *a priori* analysis of the physical processes being described and a verification of the model with observed data.

A priori analysis. The normal distribution is representative of so many randomly fluctuating phenomena, that it is usually a first choice where there is little information on which to base a selection. The normal distribution was chosen by Lie [25] as his model of fire severity. Burros [26] in his refinement of Lie's work, notes that negative fire severity is nonexistant and suggests a truncated distribution (range: zero to $+\infty$ rather than $-\infty$ to $+\infty$) such as the lognormal. Ramachandran [117] also assumed a lognormal distribution of fire severity in his work.

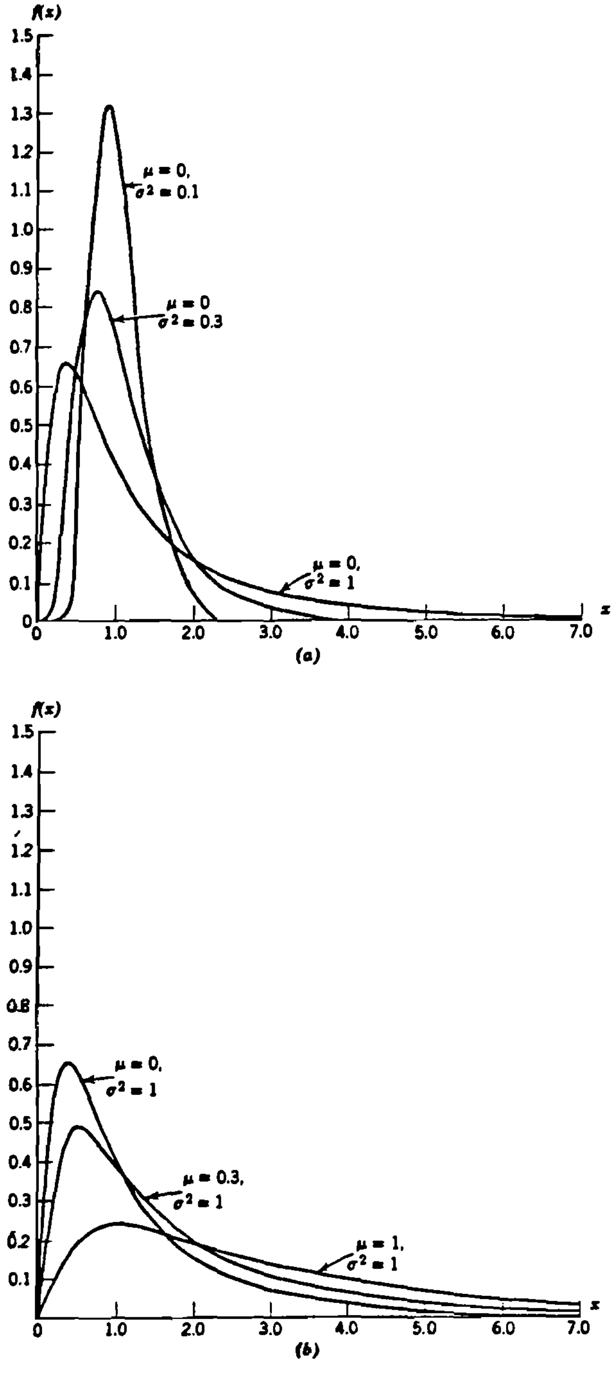

Figure 3.2

Lognormal Distribution with Various Values of μ and σ^2
Hahn and Shapiro [116] p. 98

95

Additional justification for a lognormal distribution of fire severity is found in the literature. The severity of certain other natural phenomena appears to follow this distribution: Hewitt [118] cites studies in which the dimension of the damage swath of tornadoes and the flood damage magnitude in the United States are described as lognormally distributed. Rennie [119] and Benkert [120] have employed the lognormal distribution as a model of fire damage based on insurance claims.

Thus there are a priori indications of the suitability of the lognormal distribution to be found in previous work and in the related literature.

Model verification. Fire load, the weight of combustibles per unit floor, has long been used as a measure or parameter of fire severity. The National Bureau of Standards [121] conducted a survey of fire load in 1044 offices in twenty-three federal and private office buildings throughout the country from two to forty-nine stories high. Results of this survey are summarized in Figure 3.3. Data from Figure 3.3 was plotted in three different forms: as an exponential distribution suggested by Baldwin et al. [122], as a normal distribution suggested by Lie [25], and as a lognormal distribution suggested by Burros [26]. The lognormal, shown in Figure 3.4, was the closest of these to a straight line fit (see Appendix A3).

3.2.3 Stress-Strength Models

Reliability is the probability that a component will function properly

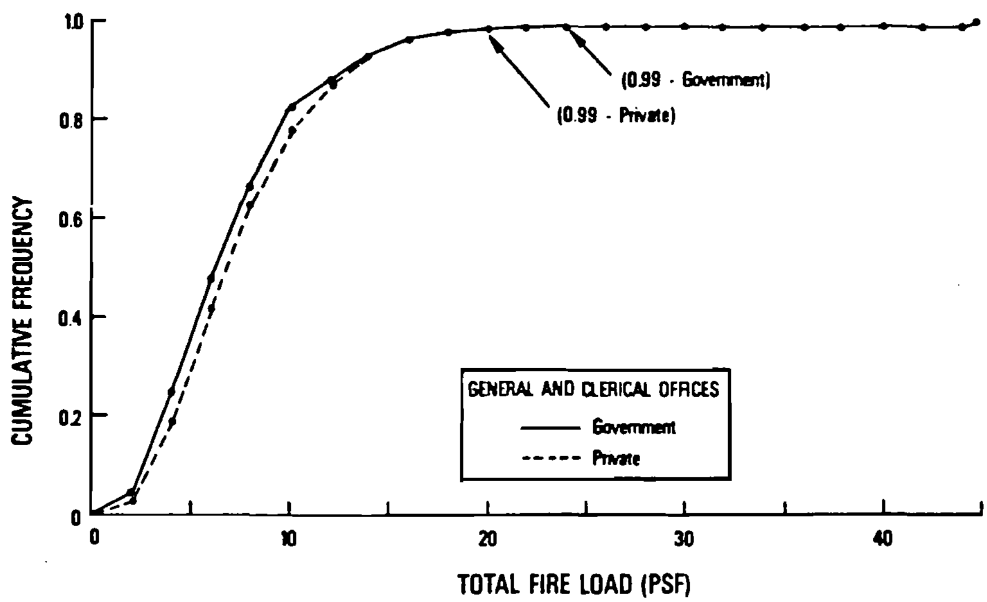

Figure 3.3

Cumulative Frequency Distribution for Room Fire Load
Culver [121] p. 66

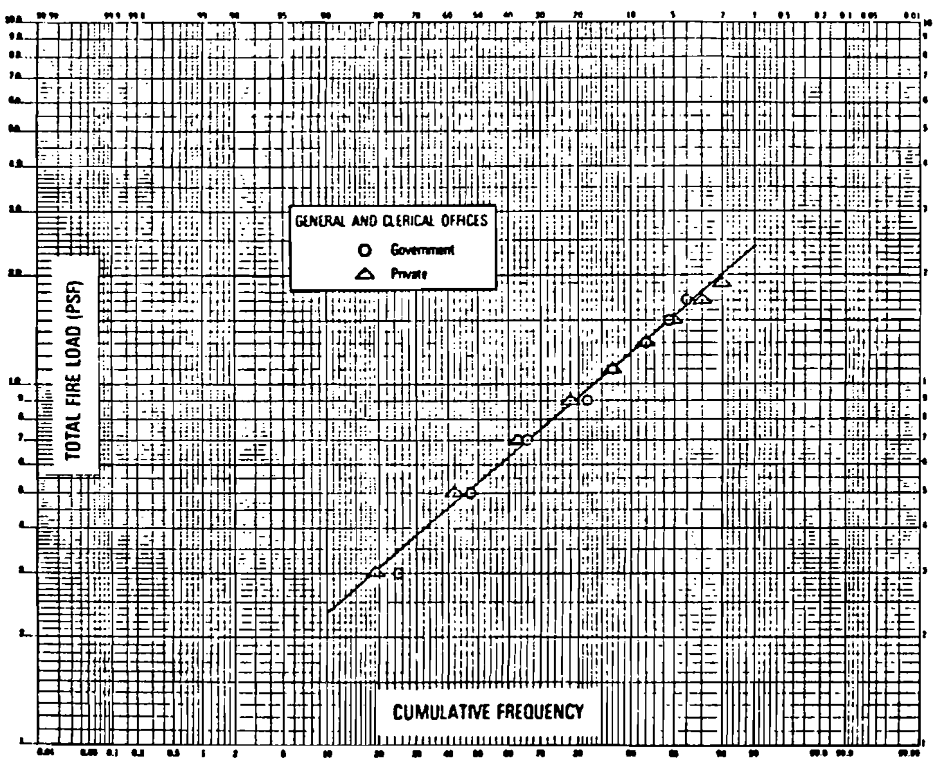

Figure 3.4

Lognormal Plot of Fire Load Data

at a specified time. Reliability per se is not normally considered for fire protection and no requirements exist in any code, standard or other approval specification. However, some of the methods of reliability theory have found application in a systems concept of fire safety. Stress-strength models are one such method.

Stress-Strength Models in Reliability Theory

Reliability theory is a body of mathematical models and methods which deals with problems in predicting, estimating, or optimizing the probability of the proper functioning of a system [123]. Among the more recent models in reliability theory are those depicting a stress-strength relationship. Bhattacharyya and Johnson [124] describe stress-strength models as applying to the situation where a component accomplishes its intended function provided it is strong enough to overcome the opposing forces of the operating environment. The reliability of the component to successfully complete its mission is defined as the probability that its strength exceeds the stress encountered during its operation.

Let X be a random variable denoting the maximum stress encountered and let Y be a random variable denoting the effecting strength. Since the units of stress and strength are the same, their probability density functions may be plotted on the same axes as shown in Figure 3.5. When strength of the system is y*, then the reliability of the system (i.e. the probability that the stress will be less than

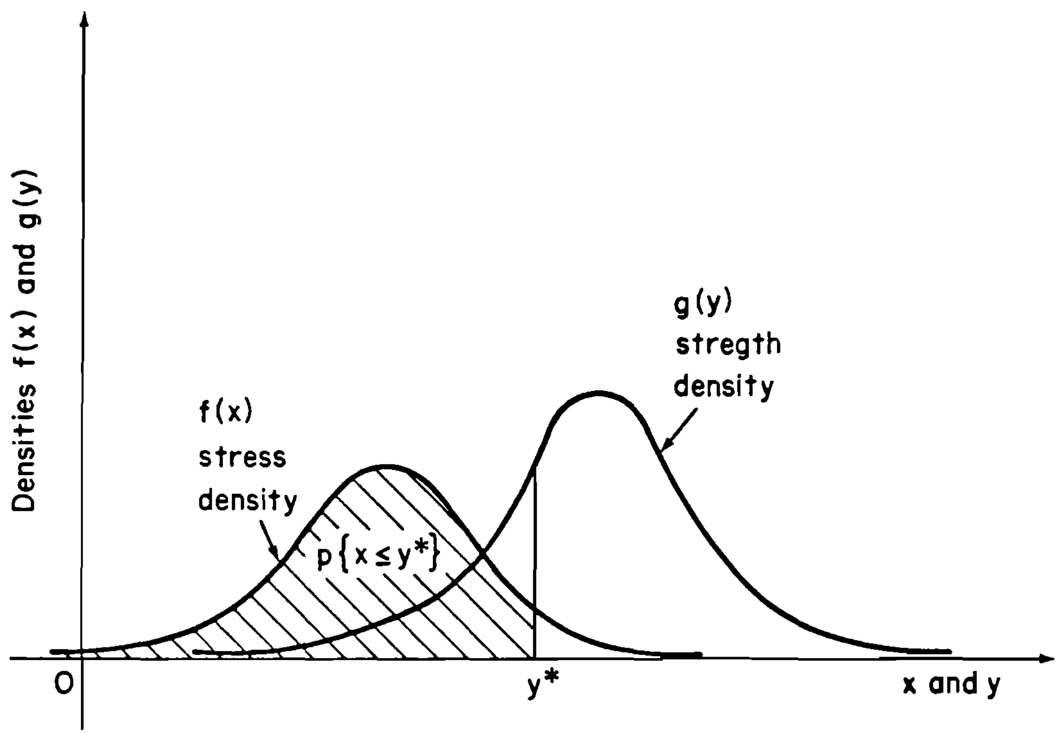

Figure 3.5

Stress-Strength Model

the strength) is the area under the stress curve to the left of y*:

$$P\{X \leq y^*\} = \int_{-\infty}^{y^*} f(x)\,dx\ .$$

If the exact strength y* is unknown, the reliability is also a function of the strength distribution g(y):

$$P\{X \leq Y\} = \int_{-\infty}^{\infty}\int_{-\infty}^{y} f(x)\,g(y)\,dx\,dy$$

$$= \int_{-\infty}^{\infty} F_x(y)\,g(y)\,dy$$

which is the usual form of the general stress-strength model. Stress-strength models are treated in depth by Kapur and Lamberson [125].

Applications of Stress-Strength Models

Stress-strength models have recently been advocated in the analysis of structural safety. Baldwin [126] reviews these aspects of structural probabilistic analysis and suggests applications in fire safety. Lie's model of structural fire protection [25] is also an application of the stress-strength concept. Witteveen [127] suggests that the application of stress-strength models to the limit states design of structural safety is directly transferrable to structural fire protection. Thus, the primary focus of stress-strength models in fire protection has been on the protection of the structural frame.

A Stress-Strength Model of a Fire Barrier

Let R be a random variable which represents the fire resistance of the barrier and let S represent the severity of the fire to which the barrier is exposed. Then the characteristic of interest is the probability that the fire resistance is greater than the fire severity:

$$P\{R \geq S\} = P\{(R/S) \geq 1\}$$

$$= P\{ X \geq 1 \}, \quad \text{where } X = R/S$$

and:

$$\ln X = \ln R - \ln S$$

by the properties of logarithms. Now, if R and S are lognormal random variables, then lnR and lnS are normally distributed. It has been frequently shown (e.g. Walpole and Myers [128, p. 150]) that a linear combination of independent, normally distributed random variables is also normally distributed. Assuming, therefore, that the fire severity and the fire barrier are independent,

$$Y = \ln X = \ln R - \ln S$$

is a normally distributed random variable with mean $\mu = \mu_{\ln R} - \mu_{\ln S}$ and variance $\sigma^2 = \sigma^2_{\ln R} + \sigma^2_{\ln S}$. Now the probability of interest may be expressed in terms of the normal random variable Y:

$$P\{ X \geq 1 \} = P\{ Y \geq \ln 1 \}$$

$$= P\{ Y \geq 0 \}$$

The standard normal variate is a normally distributed random variable with a zero mean and unit standard deviation. Any normal variate (x) may be represented as a standard normal (z) by the following transformation:

$$z = (x - \mu)/\sigma \ .$$

Thus:

$$P\ \{\ Y \geq 0\ \} = P\ \{\ Z \geq -\ (\mu/\sigma)\}.$$

Values of the standard normal distribution are tabulated in most texts on probability and statistics. For any standard normal variable:

$$P\ \{\ X \geq x\ \} \quad = P\ \{\ X \leq (-x)\ \}\ .$$

Therefore the probability may be written in the more usual form:

$$P\ \{\ R \geq S\ \} \quad = P\ \{\ Z \leq (\mu/\sigma)\ \}\ .$$

Thus the probability of a given barrier withstanding a given fire may be represented as a standard normal random variable.

In the revised GSA version of the Goal Oriented Systems Approach, use of the "total probability theorem" to calculate the thermal resistance and structural integrity of a barrier is a discrete form of a stress-strength model.

3.3 Graphical Models

It is frequently convenient to model a complex system symbolically. Conventions of symbols have arisen for many types of graphical models such as block diagrams, networks and trees. Fault tree analysis has been utilized as the basis for graphical modeling in the Goal Oriented Systems Approach.

According to Recht [129] fault tree analysis was developed in 1962 by H. A. Watson of Bell Telephone Laboratories. The technique was subsequently made famous by the Boeing Company in its application to the Minuteman Ballistic Missile Program [130].

The fault tree process utilizes a logic diagram to portray and analyze an undesired or "top" event. Conditions which may lead to the top event are diagrammed symbolically. Relationships of causative events are shown by the use of two basic symbols of logic gates - the AND gate and the OR gate. These gates represent the fundamental Boolean functions which form the basis for logic analysis, thus the fault tree relationships may be translated into expressions of Boolean algebra. Probabilities of occurrence of the independent bottom line or basic events may then be substituted into the Boolean expressions to calculate the probability of the undesired event.

Fault trees are based upon setting down a specific failure and examining the system in a logical, well organized way to determine what can go wrong to produce the failure. Alternatively, one can consider a desirable top event. An objective tree is based upon the analysis of the requirements and alternatives to achieve a specified goal [121]. Fire safety trees are of the objective type.

Use of logic diagram analysis requires an intimate knowledge of the system being analyzed. It is often time consuming but if thorough, will be revealing. It is this revealing or exposing of the predominant contributors to the system behavior which gives the technique its value. It often leads to the discovery of combinations of factors which otherwise might not have been recognized as causative of the event being analyzed. The tree becomes a record of the thought process of the analyst and serves as an excellent visual aid for communication with designers and management, as well as providing a convenient and efficient format helpful in the computation of the probability of the top event.

A commendable introduction to fault tree analysis is given by Lambert [30]. Discussion of the application of the technique in the Goal Oriented Systems Approach is found in the original GSA document [16].

3.4 Scenarios

Scenarios describe hypothetical sequences of events that could lead to some envisaged state. Their function is to identify conditions under which the system being analyzed is assumed to be performing. Thus, a scenario may be considered a descriptive model of the operating environment. Scenarios have recently been employed as an aid to developing a fire safety research plan [132, 133].

The concept of scenarios is implicitly utilized in the Goal Oriented Systems Approach. In estimating the probability of limiting spatial fire spread in the Goal Oriented Systems Approach, a specific potential path of spread must be identified. A scenario must be formed to identify the location of ignition, the first barrier to be challenged by the fire, the second barrier to be challenged, the number of barrier failures which produce spread to another zone, etc. Thus, each probability calculation represents a specific scenario. A complete building fire safety systems analysis would require many such scenarios - some stipulating typical conditions and constraints and some stipulating unique and even extreme situations. The ultimate objective of the scenarios is to relate the theoretical model to real, unplanned fires.

3.5 Summary

This chapter has been concerned with models in the Goal Oriented Systems Approach. The Goal Oriented Systems Approach has been shown to employ a number of modeling techniques, some explicitly and some implicitly. In particular, stress-strength models, fault trees and scenarios are inherent components of the Goal Oriented Systems Approach. More theoretical treatments of these models have been introduced and these will be synthesized into a reformulation of the approach in the following chapter.

CHAPTER IV

SYNTHESIS OF A GOAL-ORIENTED SYSTEMS APPROACH

Synthesis is the process of combining component parts into a coherent whole. The component parts in this synthesis consist of the basic concepts of the Goal Oriented Systems Approach identified in the analysis of Chapter II and the inherent theoretical models described in Chapter III. The objective is to develop a meaningful framework whereby intuition, experience and existing data may be utilized with theoretically sound analytical techniques to produce a probabilistic measure of fire safety. The resulting eclectic model represents a significant departure from the methodology of the original Goal Oriented Systems Approach but retains the underlying concepts. In order to distinguish the revised procedure, the term Goal-Oriented will be hyphenated. This also serves to grammatically emphasize the synergistic concept intended by this expression. Thus, the Goal-Oriented Systems Approach refers to the theoretically based methodology developed in this chapter. The Goal-Oriented Systems Approach aims to be theoretically valid, intuitively acceptable and easier to use.

4.1 Probability Distributions

The primary inputs to the revised methodology are probability distributions for the major components of fire safety: the pre-flashover fire, automatic sprinklers, the post-flashover fire, and barriers. The lognormal has been selected as the general distribution to represent each of these components. The lognormal is a nonnegative distribution which is amenable to the analytical techniques of the methodology and shows some a priori, empirical and/or theoretical justification for certain of the components. Thus, the identification of the appropriate probability distribution consists of selecting the parameters of a lognormal distribution.

4.1.1 Parameters

The lognormal is a two parameter distribution. The parameters are the mean μ and the standard deviation σ. The selection of these parameters is the essence of the revised methodology and there are a number of characteristics of the parameters and estimation techniques which can aid in the selection.

Relation of the Parameters of the Normal and the Lognormal Distributions

The most usual form of expression of the density function of the lognormal distribution is:

$$f(x) = \frac{1}{x\sigma\sqrt{2\pi}} \exp - \frac{(\ln x - \mu)^2}{2\sigma^2} \quad , \; x>0$$

The parameters μ and σ in this expression are the parameters of the normal distribution of $Y = \ln X$ where X is the lognormal random variable of interest. In the rare cases where there is actual data and the sample mean, $\bar{x}$, and sample standard deviation, s, are known or where these parameters are intuited or estimated, a transformation is necessary. By examination of the moments of X expressions for the parameters of the normal distribution, Y = ln X, may be derived [104, pp. 226-227]:

$$\mu = \ln \bar{x} - 1/2\sigma^2$$

$$\sigma^2 = \ln[(s/\bar{x})^2 + 1].$$

Shape and Scale

As noted by Aitchison and Brown [134], μ, although a location parameter for the normal variable Y = ln X behaves as if it were a scale parameter for the lognormal variable X. That is, it affects the height and width of the density function. In addition, Aitchison and Brown note that σ, originally a scale parameter for Y, behaves as a shape parameter for X. As can be seen in Figure 4.1, the form of the density function can vary greatly with the value of σ. A small value of σ produces a symmetric distribution, while a large value produces a very skewed distribution. The nature of these effects is significant when it is necessary to estimate parameters using engineering judgement. For example, if it is known that the distribution is skewed, but nothing more, it is appropriate to select a large value for σ.

The Cumulative Distribution

Where parameters must be intuited with meager information, the cumulative distribution function F(x) may be more facilitative than the density function f(x). In probability theory the cumulative distribution function is defined in terms of the density function:

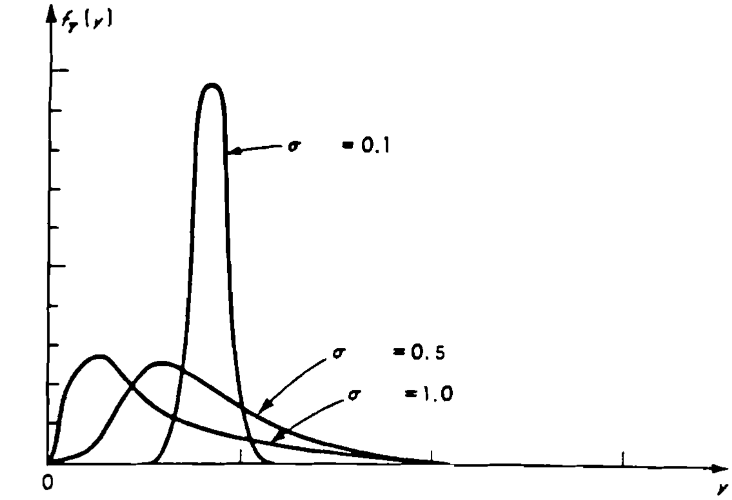

Figure 4.1

Lognormal Density Function with Various Values of σ

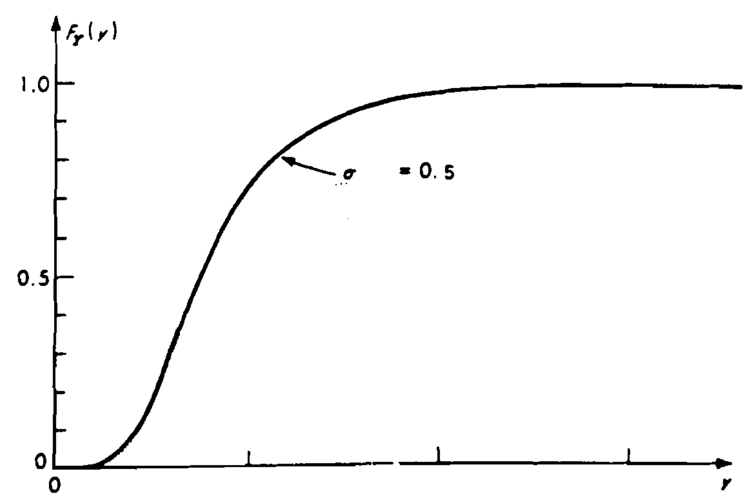

Figure 4.2

Lognormal Cumulative Distribution Function

$$F(x^*) = \int_{-\infty}^{x^*} f(x)\,dx$$

There is no convenient general expression for the cumulative distribution function of the lognormal distribution. However, a characteristic form may be visualized to illustrate the effect of various values of the parameters. Figure 4.2 is a typical plot of a lognormal cumulative distribution function. The ordinate of the cumulative distribution ranges from 0 to 1.0 the total possible range of probabilities. Thus, the cumulative distribution function indicates for some value x* on the abscissa, the total probability that the random variable X will be less than that value:

$$F(x^*) = P\{ X \leq x^* \}$$

The parameter μ locates on the abscissa the middle or most vertical part of the curve, thus a higher value of μ moves the curve to the right and a lower value of μ moves the curve to the left (Figure 4.3). The parameter σ suggests a slope closer to the vertical, indicative of less variation, while a higher value of σ moves the slope away from the vertical indicating greater variation (Figure 4.4). A few standard cumulative distribution plots may facilitate the identification of the relative position of an unknown component and hence approximate the parameters of its distribution. Appendix A4.1 lists a computer program with which alternative cumulative distributions may be examined. Also shown are resultant plots for the example data developed in this chapter.

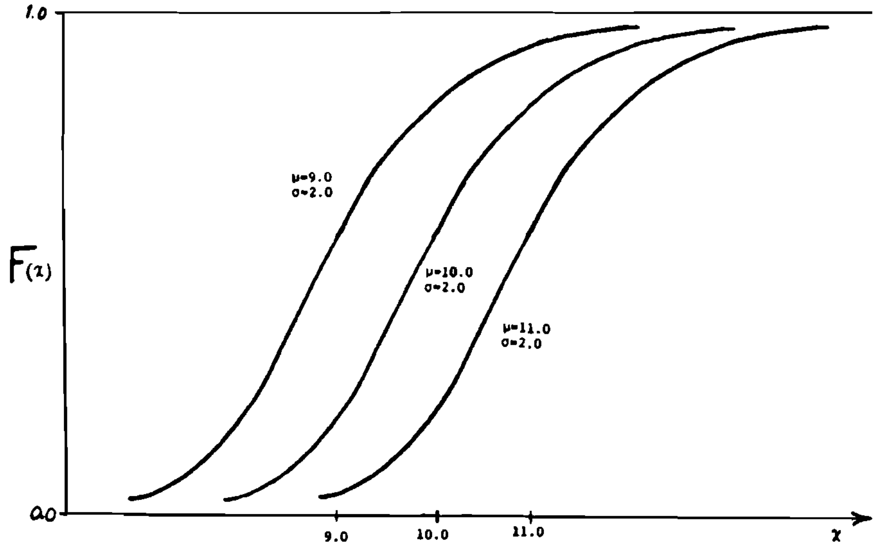

Figure 4.3

Lognormal Cumulative Distribution Function with Various Values of μ

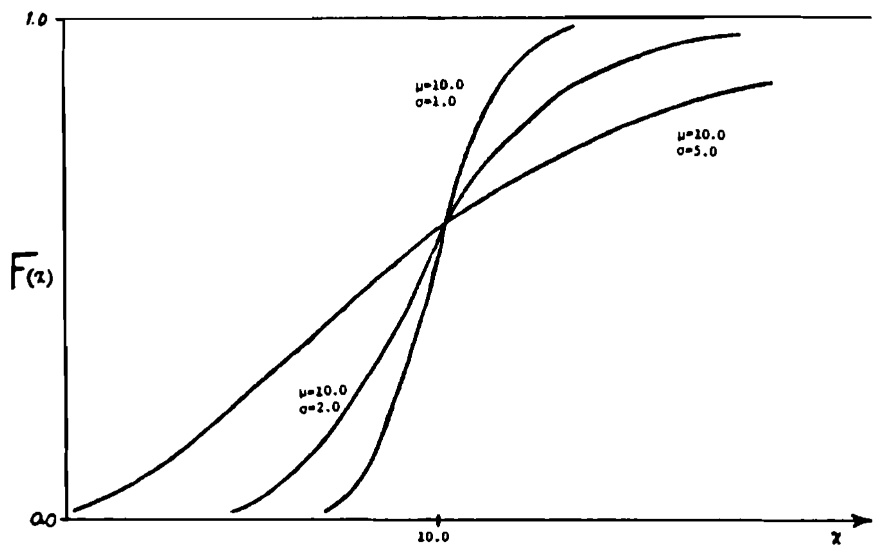

Figure 4.4

Lognormal Cumulative Distribution Function with Various Values of σ

Curve Fitting

For the few scant cases where there is empirical data, curve fitting techniques are appropriate for parameter estimation. Although the chi-squared test is the most widely used distributional test, this is not an appropriate test where there are a small number of observations [116, p. 302], which is most likely to be the case of fire safety data. There are other more appropriate distributional tests for assessing whether an assumed model adequately describes the observed data. Computer programs for applying a number of such tests as well as estimating parameters of the distribution are available, e.g. [135][1]. It is important to acknowledge that distributional tests can identify the suitability of a statistical model within a given level of confidence, but they do not prove the correctness of the model.

Judgement

Whenever experienced judgement or intuition is utilized in the estimation of parameters, it is important to recognize that a bias is being introduced. This bias must be considered in the evaluation of the results. This does not necessarily denigrate the use of judgement. There are many indications that human intuition and judgement are powerful analytical tools, e.g. Schneider [136]. The effect of bias in personal judgement may be controlled through the application of sophisticated delphic techniques, e.g. Linstone and Turoff [137]. Raiffa

[1]There are errors in this program as published, see Appendix A4.2.

[138, pp. 161 - 168] suggests an alternative technique for deriving judgemental probability distributions.

4.1.2 Component Distributions

Techniques of parameter estimation will be illustrated in the selection of example distributions of the components of fire safety. It is not within the scope of this study to discuss all of the possible severity, suppression and confinement measures for which distributions and corresponding parameters could be identified. The measures herein selected are intentionally traditional to lend confidence in the technique through the use of familiar concepts. More appropriate measures will be implemented with increased application.

Pre-Flashover Fire

The characteristic of interest in the pre-flashover fire is the rate at which heat is released by the burning fuel. The heat release rate is the product of the rate of the fuel weight loss and the effective heat content per unit mass of fuel. The effective heat content is a portion of the maximum combustion energy indicated by the fuel's heat of combustion. The appropriate magnitude of the percentage is an elusive parameter.

IITRI [40] has assembled a significant amount of data on the heat release rates of various furniture items. Figure 4.5, taken from the IITRI study, shows the probability density of the burning rate of cotton

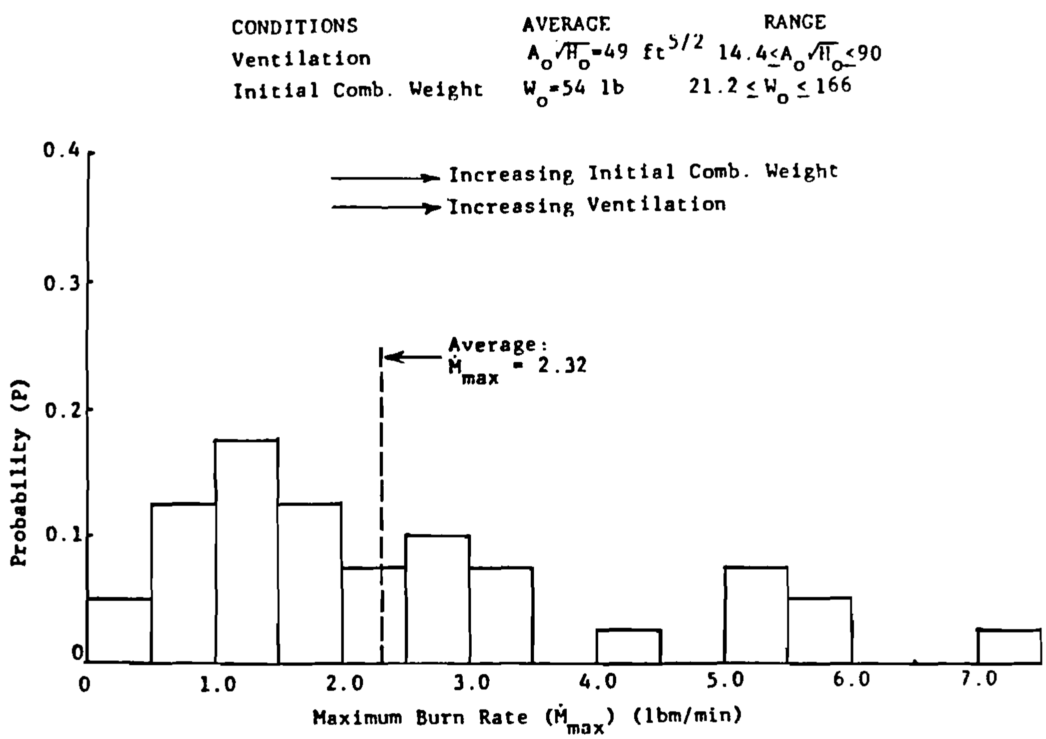

Figure 4.5

Burning Rates of Cotton Upholstered Chairs
Pape, et. al. [40] p. 38

upholstered chairs over the indicated range of conditions. Data were gleaned from several sources. The burning rates may be multiplied by the traditional effective heat content of cellulosic materials, 8000 Btu/lb., to give the heat release rates. These are changed to international standard units and fit to a lognormal distribution. A Kolmogorov-Smirnoff goodness of fit test showed the null hypothesis that the distribution is lognormal could not be rejected at the 0.01 level of significance (Appendix A4.3).

Automatic Sprinklers

The selection of appropriate parameters of the lognormal distribution representing the "strength" of automatic sprinklers is the most ambiguous task in the application of the Goal-Oriented Systems Approach. There are many intuitively appealing approaches to this selection, one will be suggested here.

A sprinkler system which is to meet insurance and legal requirements must almost invariably conform to Standard No. 13 of the National Fire Protection Association [139]. For example, a hydraulically designed system in a light hazard occupancy (e.g. office) must deliver a minimum of 0.10 gallons of water per minute per square foot [139, p. 20] over a maximum area of 225 square feet [139, p. 68] or 22.5 GPM. Conversion to SI units and multiplication by a latent heat of vaporization of water of 539 cal/g [140, p. 563] yields a heat absorption capability of approximately 3.2 MW.

The state of the art of sprinkler system design is such that the required density may be delivered almost with certainty. Variation would be due to fluctuations in the water supply. There is significantly more uncertainty in the efficiency of the extinguishing effect of water. The use of the latent heat of vaporization to estimate the cooling capacity of water neglects the additional heat absorbed to raise the temperature of the water. However, it is highly unlikely that all the water delivered will be converted to steam nor even that all will be raised above its initial temperature. To account for these factors, the calculated cooling capacity will be reduced by an efficiency coefficient of 50% and a relatively large variance will be assumed.

Post-Flashover Fire

The measure of fire severity selected for the post-flashover fire is hours of fire duration. The limitations of this measure are recognized [19] and its use here does not constitute condonance, merely a temporary concession.

Culver reports a mean fire load of 6.6 psf (pounds per square foot) and a standard deviation of 4.1 psf for his sample of 1044 offices [121, p. 112]. These values have been adjusted to account for the estimated quantity of combustibles which will burn in a fire [141]. Fire load may be converted to hours of fire duration by the Ingberg relation which is simply a factor of 6 min/psf for fire loads less than 30 psf [142, p. 9].

Barriers

Barriers represent the strength response to the stress of a post-flashover fire, thus they must have the same measure. Although thousands of tests have been conducted on fire barriers, the available data is useless for probabilistic evaluation. Barriers are <u>not</u> required to be tested to failure. They are tested to a predetermined level of fire endurance and the test is stopped [41]. Thus there is presently no convenient method for estimating the variance of a barrier's fire endurance.

For this example, the published results of standard fire tests will be used as an estimate of the mean fire endurance and it will be assumed that the quality control of building materials is such that the variation about this mean will be relatively small. Underwriters Laboratories' design number U410 [143, p. 433] is a nonbearing wall assembly rated at one hour fire endurance.

Distributions Summarized

The parameters of the component distributions for this example are summarized below:

Component	Mean	Standard Deviation
Pre-Flashover Fire	362 KW	352 KW
Automatic Sprinklers	1.6 KW	1.5 MW
Post-Flashover Fire	39.6 min.	24.6 min.
Barriers	60 min.	5 min.

4.2 Application

Once the distributions of the basic fire safety components have been identified, the stress-strength probabilities may be calculated. It is necessary, however, to identify additional input parameters to account for discontinuities observed in the real world. The identification and implementation of appropriate scenarios is the final step in the application process.

4.2.1 Application of the Stress-Strength Model

The basic components of fire safety constitute the random variables of two stress-strength models. The pre-flashover fire is the stress component and the automatic sprinklers the strength component of a model of fire suppression, while the post-flashover fire is the stress component and the barrier the strength component of the model for confinement.

The probability of success of either suppression or confinement is calculated as the probability that one lognormal random variable is greater than another. These calculations are performed in four steps:

1) The parameters of the lognormal distributions are transformed to parameters of the normal distributions: $Y = \ln X$.
2) The parameters of the normally distributed difference between the two normal random variables is calculated from the transformed parameters.

3) The zero normal variate of the difference is transformed to a standard normal variate.

4) The value from the standardized normal cumulative distribution is identified from tables or by numerical methods.

For the distributions identified in the previous section, the probability of success of the automatic sprinkler system is computed to be 0.89 and the probability of success of the barrier is 0.84. However, these probabilities do not account for the likelihood of a sprinkler valve being closed or of a door in a fire barrier being left open.

4.2.2 Adequacy and Reliability

For many decades, fire protection engineers have been evaluating municipal water supply systems in terms of adequacy and reliability. These are the major components of the insurance grading of water supplies [144]. Unfortunately, this concept of a two component evaluation has not been extended to other areas of fire safety. Consideration of adequacy and reliability may help to resolve the problem of discontinuous factors of system success.

As noted, there are conditions or events which affect the probability of success of a fire safety strategy, but are not reflected in the stress-strength model. In addition to the examples above, a sprinkler system may be knocked out by an earthquake or explosion, while improper installation may render a membrane fire barrier worthless. These situations denote a significantly non-zero probability that a strength component will be unable to resist even the smallest applied stress. The approach to handling this problem will be to consider the output of the stress-strength model as a measure of the adequacy of the fire safety component and to reduce this by the reliability that the component will perform as designed. Thus the probability of system effectiveness is the product of the system adequacy and the system reliability.

Adequacy

Adequacy may be thought of in terms of the expected capacity of the component to limit fire spread. As such, for a given stress, adequacy may usually be determined by calculation or by test. However, there is an associated level of confidence in the calculation or test procedure, thus producing a probability distribution of component strength. The stress-strength model represents the calculation of the adequacy of a component of random strength to resist a random stress.

Reliability

Reliability is the probability that the component will function as designed. Examples have been given of conditions or events which comprise component reliability. Although the system safety techniques of failure modes and effects analysis[2] and quantitative fault tree analysis would be appropriate for estimating the reliability of fire safety

[2] See, for example, Hammer [145], pp. 148 - 156.

components, the data are largely unavailable. Qualitative fault tree analysis may be used to guide experienced judgement as to a reasonable estimate of reliability.

There are rough indications of sprinkler system reliability available in the literature [146, 147, 148]. Based on the NFPA performance tables [147], a reliability of 0.97 will be assumed for the sprinkler system in the present example. Then the probability of system effectiveness as the product of adequacy and reliability is: (0.89) (0.97) = 0.86.

There is less information available on the reliability of barriers, thus a greater need for intuition and judgement. Consider a concrete block wall and a gypsum wallboard wall which have a similar fire endurance rating by conventional test. The gypsum wall has a greater variety of materials (studs, wallboard, fasterners, joint sealant, etc.) and is generally more susceptible to physical damage in use, thus less likely to be integral in the event of fire. Intuitively, then, the reliability of the concrete wall is greater than the reliability of the wallboard wall.

It is apparent that the most dominating influence in barrier reliability will be the status of the door. An open doorway would reduce the barrier reliability to almost zero while a closed, adequately fire resistant door would yield a reliability near 1.0. Thus the barrier reliability may be estimated by analysis of such information as the type of door, the existence of automatic door closers and what percentage of the time the self-closing doors are chocked open.

For the present example, assume a well-maintained, self-closing, fire door producing a barrier reliability of 1.0. Therefore, the probability of barrier effectiveness remains unchanged.

4.2.3 Probability of Limiting Fire Spread

The linking together of the calculated probabilities to compute the probability of limiting fire spread follows identified postulates of fire spread and appropriately prescribed scenarios.

Postulates of Fire Spread

The synthesized model assumes the postulates of modular fire spread implicit in the original Goal Oriented Systems Approach. These postulates are:

1. The limitation of fire spread may be achieved by containment or by termination.
2. Termination will not occur if ignition is by massive energy transfer.
3. The limitation of fire spread to a sequential room or module is achieved if the fire is limited to any previous module.

There is an important corollary to the first postulate which is also implicit in the examples given in the GSA documents. The example cases which involve an automatic suppression system do not include the extinguishment probability of such a system in any module other than the first. This may be explained by considering that in a low hazard occupancy (e.g., offices) the entire building is usually serviced by a single automatic suppression system and most failure modes are such that the entire system is affected. Therefore, there is a single probabilistic factor for automatic suppression which remains unchanged regardless of the number of modules involved and the limitation of fire spread may not be achieved by suppression in any module other than the first.

The first postulate indicates that the probability of limitation of fire spread in a room is the Boolean sum of the probability of termination and the probability of barrier effectiveness (containment).

Termination refers to a cessation of combustion by its own accord (self-termination) or by an extinguishing action. The probability of termination, therefore, is the Boolean sum of the probability of self-termination and the probability of suppression. Isolated small quantities of fuel, such as a curtain or drape, may be completely consumed with no further fire spread. Sometimes, even major furniture items may burn without any large flame buildup. The possibility of fires to self-terminate causes the fire severity distribution to exhibit bimodal behavior. Figure 4.6 is a histogram of the nineteen full scale corner tests conducted by Fang [149]. The bimodality of fire severity as measured by gas temperature is clearly indicated. Using Fang's results, and assuming a uniform distribution of the conditions tested, the probability of self-termination is estimated as 0.5.

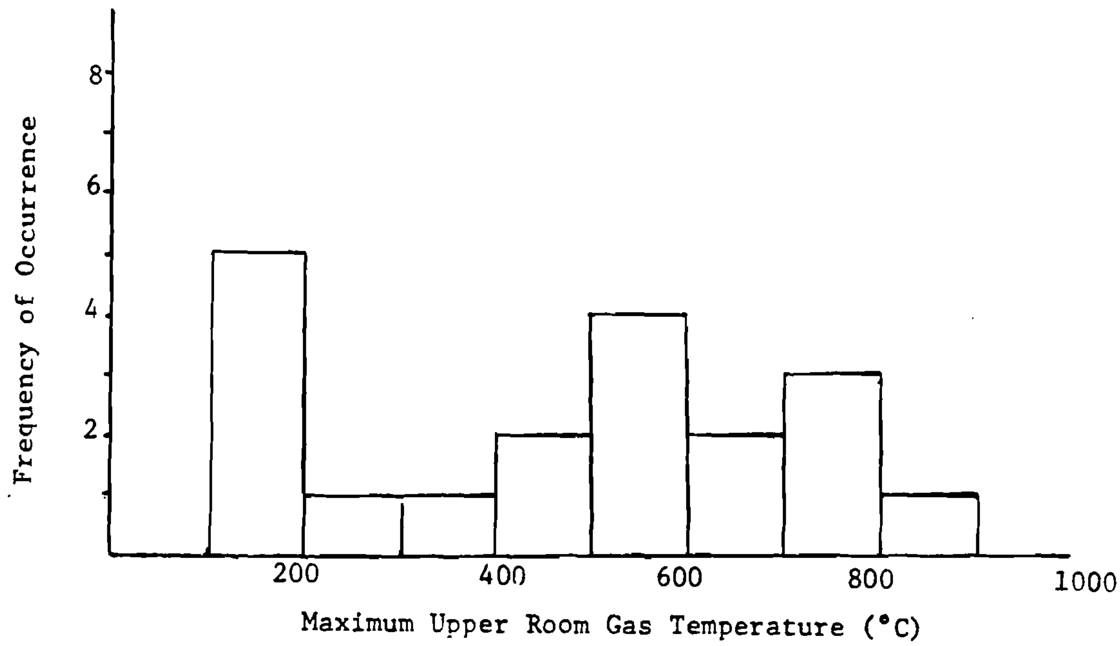

Figure 4.6

Bimodality of Fire Severity

The Boolean operations suggested by the first postulate and the adequacy/reliability concept are summarized in the objective tree of Figure 4.7. This tree indicates the variables and their relationships which determine the probability of the limitation of fire spread within a compartment or structural module.

By the logic tree of Figure 4.7, the probability of limitation of fire spread is the Boolean sum of the probability of termination and the probability of containment, or barrier effectiveness, $P(E_b)$. The probability of termination is, in turn, the Boolean sum of the probability of self-termination, $P(T)$, and the probability of the suppression system effectiveness, $P(E_s)$. Thus, if ρ_i is the probability of fire limitation within module i, then:

$$\rho_i = P(T)_i \cup P(E_s)_i \cup P(E_b)_i$$
$$= 1 - \left[1 - P(T)_i\right]\left[1 - P(E_s)_i\right]\left[1 - P(E_b)_i\right] \quad \text{(equation 1).}$$

For the example under consideration, the values of the respective variables have been identified as 0.5, 0.86 and 0.84. Thus by equation 1:

$$\rho_i = 1 - (1 - 0.5)(1 - 0.86)(1 - 0.84)$$
$$= 0.989.$$

Consider a sequence of three similar (for the purposes of the model, identical) modules. Then the probability of effective suppression in the second and third modules is zero by the corollary to the first postulate. Therefore:

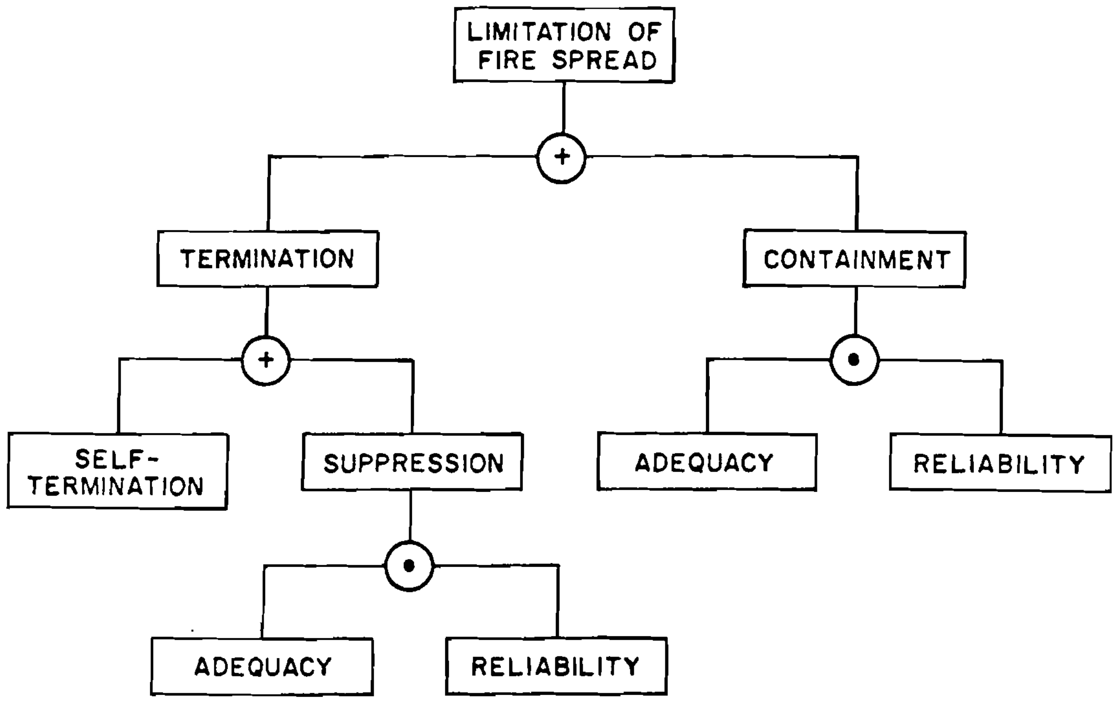

Figure 4.7

Fire Spread Logic Tree

$$\rho_2 = \rho_3 = 1 - (1 - 0.5)(1 - 0.0)(1 - 0.84)$$
$$= 0.92.$$

The massive energy transfer condition of the second postulate is implicit in the fire severity distribution.

The third postulate indicates the additive nature of the fire limitation potential in sequential modules. If ρ_1 and ρ_2 represent the probabilities of limiting fire spread to within the first module and within the second module respectively, and P_1 and P_2 are the cumulative probabilities that the fire does not spread beyond the first and second module respectively, then $P_1 = \rho_1$ and P_2 is the probability of limitation in the first module, ρ_1, plus the probability of limitation in the second module should the fire not be limited to the first; $(1 - \rho_1)\rho_2$. Thus:

$$P_2 = \rho_1 + (1 - \rho_1)\rho_2.$$

Which may also be written:

$$P_2 = 1 - (1 - \rho_1) \quad (1 - \rho_2).$$

The relationships of these probabilities is illustrated graphically in Figure 4.8. In general, for the sequential spread of fire from module 1 to module n, it can be shown by mathematical induction that the probability of fire limitation at the nth module is:

$$P_n = 1 - \prod_{i=1}^{n} (1 - \rho_i) \qquad \text{(equation 2).}$$

Thus, for the example, the probability that the fire will not spread beyond the third module is given by:

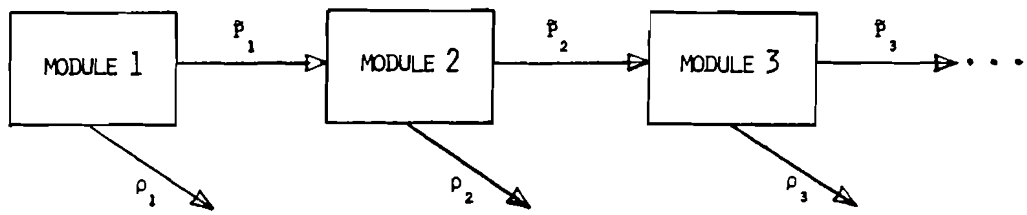

Figure 4.8

Probabilistic Modular Fire Spread

$$P_3 = 1 - (1 - 0.989)(1 - 0.92)^2$$
$$= 0.999^+.$$

Scenarios

The selection of actual scenarios to be evaluated is a process which calls upon engineering judgement. The complete enumeration of all possible scenarios in a modern structure would be prohibitively time consuming, even by computer. The number of 10 room scenarios in a 100 room building is approximately 10^{15} which is also approximately the number of nano-seconds in two weeks. While there are many ways to reduce this number, the most direct is by the selection of several appropriate scenarios. The primary criteria for such selection should be the identification of dominating conditions combined with an engineering judgement of the most likely path of fire spread. Where there are a number of distinct sets of conditions or a number of likely paths, a corresponding number of scenarios should be selected. For example, if an office building has large suites on some floors and small cubicles on others, scenarios dealing with both types should be identified.

4.3 The Goal-Oriented Systems Approach

By way of summarizing the calculation procedure of the new Goal-Oriented Systems Approach, the model is presented in notational form. The example is repeated in terms of the input, processing and output characteristics of the methodology.

4.3.1 Input

The required inputs to the model are the parameters of lognormal distributions for the pre-flashover fire severity (μ_{Pre}, σ_{Pre}), the capacity of the suppression system (μ_s, σ_s), the severity of the post-flashover fire (μ_{Post}, σ_{Post}) and the barrier capacity (μ_b, σ_b). For the example cited:

μ_{Pre} = 0.36 MW	σ_{Pre} = 0.35 MW
μ_s = 1.6 MW	σ_s = 1.5 MW
μ_{Post} = 39.6 min.	σ_{Post} = 24.6 min.
μ_b = 60 min.	σ_b = 5 min.

Also required as inputs are the reliability probabilities of the suppression system $P(R_s)$, and the barrier $P(R_b)$. These were given in the example as:

$$P(R_s) = 0.97 \qquad P(R_b) = 1.0.$$

Finally, the probability of self-termination, P(T), was estimated as:

$$P(T) = 0.5.$$

It is important to note that these inputs must be repeated for each different module, e.g. a room with different contents, a barrier of different materials or construction, a different suppression system, a barrier with a different opening configuration, etc. Thus, each module may have a distinct set of input parameters.

4.3.2 Process

The processing of the inputs is an iterative procedure whereby for each room or module the adequacy and effectiveness of the suppression system and barrier are computed. The adequacy (A), is determined by the stress-strength relationship (Φ):

$$P\ (A_s)_i = \Phi(\mu_{Pre},\ \sigma_{Pre},\ \mu_s,\ \sigma_s)_i = 0.89$$

$$P\ (A_b)_i = \Phi(\mu_{Post},\ \sigma_{Post},\ \mu_b,\ \sigma_b)_i = 0.84$$

Effectiveness (E), is the product of adequacy and reliability:

$$P\ (E_s)_i = P(A_s)P(R_s) = (0.89)(0.97) = 0.86$$

$$P\ (E_b)_i = P(A_b)P(R_b) = (0.84)(1.0) = 0.84$$

As has been noted, the effectiveness of a suppression system protecting several modules, is considered to be zero for other than the first module protected.

Finally, the probability of fire limitation within each module (ρ_i) is given by equation 1:

$$\rho_i = 1 - \left[1 - P(T)_i\right]\left[1 - P(E_s)_i\right]\left[1 - P(E_b)_i\right]$$

$$\rho_1 = 0.989$$

$$\rho_2 = 0.92$$

$$\rho_3 = 0.92.$$

4.3.3 Output

The output of the model is the probability that the fire does not spread beyond a given module in a given fire spread scenario. The general expression for this value is given by equation 2:

$$P_n = 1 - \prod_{i=1}^{n} (1 - \rho_i).$$

For the example, the scenario is a fire originating in one of three similar rooms and spreading sequentially to the second and third rooms. Therefore:

$$P_3 = 1 - (1 - 0.989)(1 - 0.92)^2$$
$$= 0.999^+.$$

Thus there is a relatively high probability that the fire represented by this scenario will not spread beyond the three rooms.

4.3.4 Calculations

The calculation procedures in the Goal-Oriented Systems Approach, while relatively straight-forward, could become tedious with widespread application. In order to avert this situation, a program has been written which performs all the necessary computations on a hand-held calculator.

Input to the program is the same as the model input discussed in section 4.3.1. Calculation of the stress-strength functions utilizes Simpson's Rule [150, p. 386; 151, pp. 370 - 376] to approximate values of the standard normal distribution. Probabilities of fire spread are computed according to equations 1 and 2.

Detailed information on the program and its use is given in Appendix A4.4.

4.4 Summary

In application, the Goal-Oriented Systems Approach offers several advantages over its predecessor. Of primary consequence is the theoretical basis which is explicitly identified and applied in a standard fashion. This should create a more favorable acceptance by users familiar with the principles of probability theory. Similarly, the explicit identification of the underlying postulates of fire spread and other assumptions should make the Goal-Oriented Systems Approach intuitively acceptable to those who are in accord with these principles. Finally, the application of the Goal-Oriented Systems Approach is facilitated by simplified input requirements and calculations. The primary inputs are four probability distributions which are of a standard format and can be identified with available data or by experienced judgement. Discontinuities are handled by the reliability factors which may similarly be either generated or estimated. Thus, the input is minimal and of a uniform nature. The calculation procedures are well-defined and onerous computations may be obviated by the use of a hand-held programmable calculator. These characteristics of the Goal-Oriented Systems Approach contribute to the appropriateness of probabilistic measures of fire safety.

CHAPTER V

EVALUATION OF THE GOAL-ORIENTED SYSTEMS APPROACH

The essence of the probabilistic approach to building fire safety developed by GSA has been reformulated into the Goal-Oriented Systems Approach. In this chapter, the new technique is evaluated. That the new methodology has an explicit theoretical foundation is not necessarily adequate substantiation in a practical or real world environment. To validate the approach statistically would require decades of data or megadollars of full scale testing. In a more mundane sense, acceptance by the fire protection engineering profession would indicate a confirmation. Though still a prolonged process, much less tangible commitment would be required. To this end, the evaluation of the Goal-Oriented Systems Approach is directed toward the sensibilities of the fire protection professional. Two facets are considered in the evaluation: comparison to the existing method of probabilistic fire safety determination and analysis of the sensitivity of the approach to changes or errors in the input data.

5.1 Comparison to the Existing Method

The Goal Oriented Systems Approach as developed by GSA constitutes the existing method of probabilistic building fire safety evaluation. Since the GSA approach has acquired a certain amount of acceptance, it is requisite that any new or altered approach be tested by comparison. This will be done by calculating fire spread probabilities for each of the application examples presented in Appendix D of the GSA

Building Fire-safety Criteria. The probabilities of fire spread generated by the new Goal-Oriented Systems Approach will be compared to the probabilities given by the GSA approach.

5.1.1 Application Examples in GSA Appendix D

Four examples of the application of the Goal-Oriented Systems Approach were presented by GSA. The examples are for office buildings with homogeneous compartmentation throughout. They represent two types of partitions and the presence or absence of an automatic sprinkler system.

Example 1

The first example involves a lightweight partition as a potential fire barrier. The partition is constructed of noncombustible material but is not specifically designed as a fire resistant barrier. Ordinary doors with ordinary hardware comprise ten per cent of the surface area of the partition wall. This barrier is referred to as partition X.

Example 2

The barrier in the second example is specifically designed to restrict fire spread. It is a partition which will pass a two-hour fire resistance test according to ASTM E-119 [41]. The openings in this partition are protected with fire doors which will pass a one and one-half hour fire resistance test according to ASTM E-152 [152] and are fitted with the appropriate self-closing hardware [153]. This barrier is refered to as partition Y.

Example 3

The third example repeats the first case of partition X with the addition of an automatic sprinkler system.

Example 4

The remaining condition, an automatic sprinkler system with partition Y, constitutes the fourth example.

5.1.2 The Data

The input used by GSA is found in various forms. It is necessary to convert the data to the distributional parameters required as input to the Goal-Oriented Systems Approach. This, in some cases, comprises an estimate of equivalent approximations. The approach taken is to describe the required lognormal distributions by straight line plots on lognormal probability paper. The parameters of the distributions may then be estimated from the probability plots.

Parameter Estimation from Probability Plots

Any normal distribution is symmetric about its mean. Thus the median and mean are equal. Therefore, the mean of a plotted normal distribution (Y) may be read directly as the point y such that:

$$P\{Y \leq y\} = 0.5$$

i.e., the median.

For a lognormal distribution (X), the ordinate of the probability plot represents the logarithm of the normal distribution Y = ln X. The mean μ_y of this distribution is, therefore, given by ln x where:

$$P\{X \leq x\} = 0.5$$

The mean μ_y of the corresponding lognormal distribution is given by the transformation:

$$\mu_x = \exp(\mu_y + 1/2\sigma_y^2).$$

The standard deviation of a plotted normal distribution may be estimated from the slope of the line. A small slope indicates a small variation while a large slope shows a large variation. The slope may be determined from any two points on the line. For example, the points y_1 and y_2 may be identified such that:

$$P\{Y \leq y_1\} = .90 \quad \text{and}$$

$$P\{Y \leq y_2\} = .10$$

where Y is a normally distributed random variable with mean μ and standard deviation σ. Then from a table of the cumulative standard normal distribution:

$$(y_1 - \mu)/\sigma = 1.282 \text{ and}$$

$$(y_2 - \mu)/\sigma = -1.282.$$

Thus: $$(y_1 - \mu)/\sigma - (y_2 - \mu)/\sigma = 2.564$$

and: $$\sigma = 0.39\ (y_1 - y_2).$$

The ordinates of the lognormal probability plot are the logarithms of the normal distribution Y = ln X. Thus, consider the points:

$$P\{X \leq x_1\} = .90 \quad \text{and}$$

$$P\{X \leq x_2\} = .10$$

where X is lognormally distributed such that the mean and standard deviation of the normal distribution Y = ln X are μy and σy respectively.

Then:

$$\sigma_y = 0.39 \ (\ln x_1 - \ln x_2).$$

The standard deviation of the corresponding lognormal distribution is given by:

$$\sigma_x = \{\exp(2\mu_y + \sigma_y^2) \ [\exp(\sigma_y{}^2) - 1]\}^{\frac{1}{2}}$$

$$= \mu_x \sqrt{\exp(\sigma_y^2) - 1}$$

Estimation of Inputs from Examples

Lognormal parameters are required for five different distributions as input to the examples. These distributions are for post-flashover fire severity, fire resistance of partition X, fire resistance of partition Y, pre-flashover fire severity, and suppression capacity of the automatic sprinkler system. For each distribution, the relevant corresponding data or information from GSA is identified, a lognormal probability plot is drawn, and the parameters are estimated. Detailed information for each distribution is given in Apprendix A5.1.

Reliabilities and the probability of self-termination are also estimated from the GSA data.

Post-flashover fire severity. Figure D-38.5 of GSA Appendix D gives a plot of the post flashover fire severity used by GSA in their examples. The points from this curve, identified in Appendix D figure D-39.2, were plotted on lognormal paper and found to fall on a straight line. The parameters were estimated from the probability plot as μ = 18.5 minutes and σ = 10.3 minutes.

Partition X. GSA estimates of distributions of thermal resistance (T) and structural integrity (D) for partitions X and Y are included in the Appendix D figure D-38.4. Barrier strength is taken to be the product of these two failure modes. Thus, values from the GSA curves were multiplied and replotted on lognormal paper. The parameters estimated from the plot are μ = 10.5 minutes and σ = 7.8 minutes.

Partition Y. The procedure for partition Y duplicates that of partition X. The estimated parameters are μ = 82.6 minutes and σ = 28.8 minutes.

Pre-flashover fire severity. Because of the more judgement based approach to sprinkler protection by GSA, equivalent approximations to the input are more difficult to develop. The stress distribution was estimated from the Appendix D figure D-19.1. The six conditions identified in this figure were plotted against the end point or room probabilities. The parameters so estimated were μ = .054 gpm/ft^2 and σ = .049 gpm/ft^2.

Automatic sprinklers. The above stress distribution represents the water application density required to achieve a level of protection between extinguishment and control. The strength distribution is based on the two points from Appendix D figure D-19.1 which identify the density difference between extinguishment and control. For a system designed to deliver 0.1 gpm/ft^2, the estimated parameters of the extinguishing capacity are μ = .152 gpm/ft^2 and σ = .048 gpm/ft^2.

Note that the units of the parameters of the above two distributions are not actual discharge densities but equivalent densities based on the GSA estimates of extinguishing effectiveness.

Reliabilities. The barrier reliabilities may be considered equivalent to the completeness factors identified from Appendix D figure D-38.3. These are 0.75 for partition X and 0.997 for partition Y.

Since no comparable component is considered in the GSA examples, the reliability of the sprinkler system is considered to be 1.0.

Probability of self-termination. The probability of self-termination within the room of origin is given directly in the GSA examples, i.e., P(T) = 0.66.

5.1.3 Calculations and Comparisons

The adequacies of the barriers and the suppression system were calculated by the log-normal stress-strength relationship. These and the other input data are summarized below:

	Partition X	Partition Y	Sprinklers
Adequacy	0.22	0.994	0.939
Reliability	0.75	0.997	1.0
	Probability of Self-termination = 0.66		

The probability of fire limitation within each module, i, is given by:

$$\rho_i = 1-[1 - P\ (T)_i]\ [1 - P(A_b)_i\ P(R_b)_i]\ [1 - P(A_s)_i\ P(R_s)_i]$$

Where:

T = Self-termination
A = Adequacy
R = Reliability
b = barrier
s = suppression system

The probability that the fire does not spread beyond module n is given by:

$$P_n = 1 - \prod_{i=1}^{n} (1 - \rho_i)$$

<u>Example 1</u>

The first example has partition X and no suppression system:

$$\rho_i = 1 - (0.34)\ [1 - (0.75)(0.22)] \quad i = 1, 2, \ldots$$
$$= 0.716$$

The resulting limitations of fire spread for each of the first three modules or rooms are shown together with the corresponding values given by GSA:

	P_1	P_2	P_3
NEW	0.716	0.919	0.977
OLD	0.705	0.864	0.938

Example 2

The second example is partition Y with no suppression:

$$\rho_i = 1 - (0.34)\ [1 - (0.997)(0.994)] \quad i = 1, 2, \ldots$$
$$= 0.997$$

	P_1	P_2	P_3
NEW	0.997	0.9999^+	0.9999^+
OLD	0.997	0.9999^+	0.9999^+

Example 3

The third example combines partition X with the automatic sprinkler system:

$$\rho_1 = 1 - (0.34)\ [1 - (0.75)(0.22)]\ [1 - (1.0)(0.939)]$$
$$= 0.981$$

$$\rho_i = 1 - (0.34)\ [1 - (0175)(0.22)] \qquad i = 2, 3, \ldots$$
$$= 0.717$$

	P_1	P_2	P_3
NEW	0.983	0.995	0.999
OLD	0.997	0.999	0.999

Example 4

This last example has partition Y and the suppression system:

$$\rho_1 = 1 - (0.34)\ [1 - (0.997)(0.994)]\ [1 - (1.0)(0.939)]$$
$$= 0.9998$$

$$\rho_i = 1 - (0.34)\ [1 - (0.997)(0.994)] \qquad i = 2, 3, \ldots$$
$$= 0.997$$

	P_1	P_2	P_3
NEW	0.9998	0.9999^+	0.9999^+
OLD	0.9999^+	0.9999^+	0.9999^+

Discussion

Looking at examples two through four, the maximum variation in the probabilities computed by the two methods is a 1.4% difference in the first module of example three. All other variations in those examples are less than one-half of one percent. In example one, the differences in the results of the two methods ranges from 1.6% in the first module to 6.4% in the second module (the results for the third module differ by 4.2%). It is suggested that even the differences in example one are not inordinate considering that the input data was not the same for both methods. That is, the differences exhibited could be directly attributable to the inability to reproduce the GSA input data. This leads quite naturally to the question of sensitivity, or how susceptible the Goal-Oriented Systems Approach is to vagaries or gross errors in the input.

5.2 Sensitivity Analysis

Sensitivity analysis is succinctly defined by Rappaport as "a study to determine the responsiveness of the conclusions of an analysis to changes or errors in parameter values used in the analysis" [154, p. 441]. Assessment of the sensitivity to input variations is essential to the evaluation of the model. Machol describes a "technique for weighing hawgs" which illustrates this point:

> "Select a perfectly symmetrical plank and balance it on a sawhorse. Place the hawg on one end of the plank, and pile rocks carefully on the other end until it has just returned to an equilibrium position. Then guess the weight of the rocks" [155, p. 63].

It is important to avoid such an absurdity of highly precise work rendered highly imprecise by a single gross approximation. A sensitivity analysis provides, first of all, a feel for those elements of the calculations which are most sensitive in determining the criteria of choice and, secondly, gives one an idea of the credibility which can be placed on any such criterion. Measuring the responsiveness of model results to possible variations in parameter values offers valuable information for appraising the relative risk of acting on the basis of indefinite data. More confidence can be placed in the findings if it can be shown that the output estimates are robust to input estimate errors over their probable range of deviation.

The subjective nature of the input to the GSA approach is one of its limitations, yet its sensitivity to variations in the input has not been tested. The following sections deal with the sensitivity of the Goal-Oriented Systems Approach to variations in the GSA input data used to compare the two approaches.

5.2.1 Sensitivity of Stress-Strength Model

Stress-strength functions are the essence of the Goal-Oriented Systems Approach. Three such relationships were estimated in comparing the GSA approach with the new methodology. Sensitivity of these relationships to the input parameters is significant to the evaluation of the methodology.

Sensitivity to Individual Parameters

Sensitivity to variation of individual input parameters was tested first. Each of the three stress-strength relationships was subjected to computerized iterations whereby a single parameter was varied over a range of $\pm$ 100% of its original estimated value. Computations were carried out for each of the four parameters (μ_1, σ_1, μ_2, σ_2) which constitute the input to a lognormal stress-strength model.

Partition X. Sensitivity of the stress-strength relationship for partition X (the lightweight partition) is illustrated in Figure 5.1. The abscissa of the figure represents the percentage by which a single input parameter is varied and the ordinate shows the resultant probability of success of partition X to withstand the design fire. (The

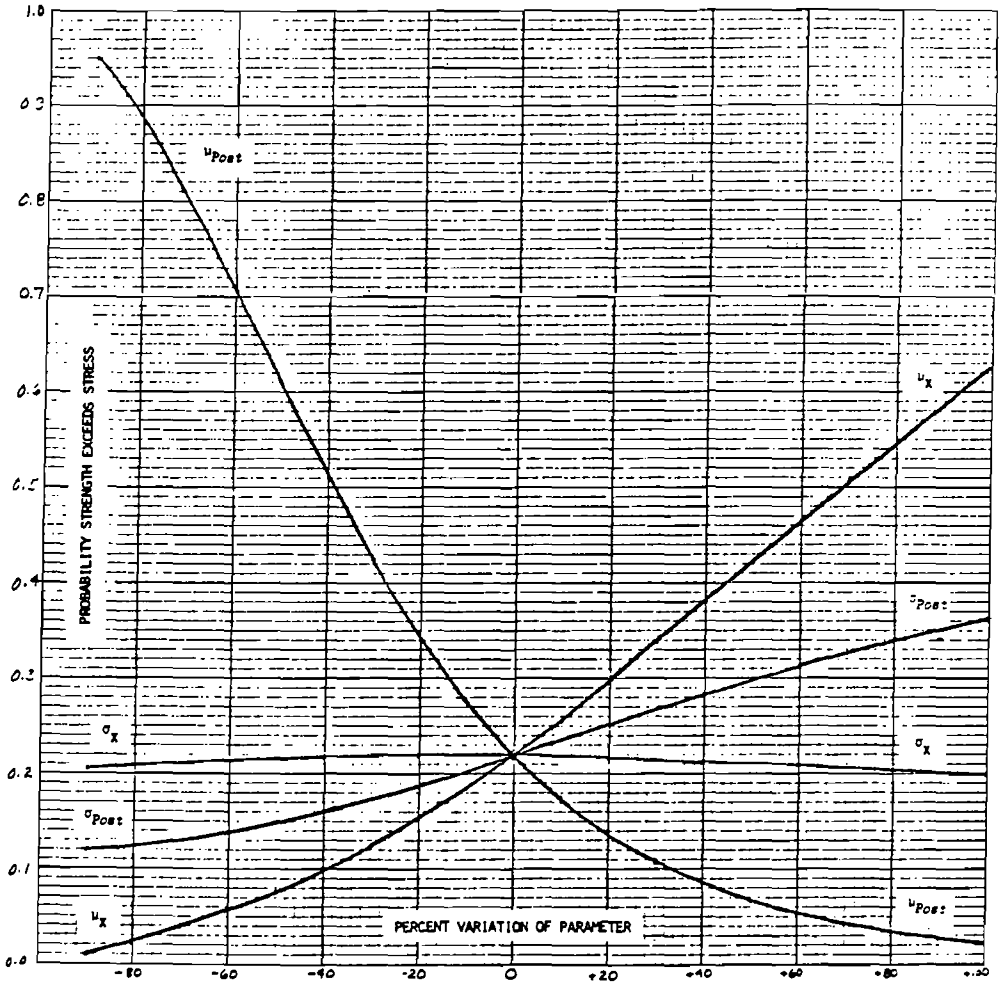

Figure 5.1

Sensitivity of Stress-Strength Relationship for Partition X originally calculated probability of success is 0.22). With the exception of the partition standard deviation (σ_x) the probability of success is generally sensitive to the input parameters. Sensitivity to the means is greater than to the standard deviations. Sensitivity to the mean severity of the design fire (μ_{Post}) is greater than to the other parameters.

Partition Y. Sensitivity of the stress-strength relationship for partition Y (the fire-resistant partition) which is portrayed by Figure 5.2, is markedly different from that of partition X. In Figure 5.2 it can be seen that the probability of success is relatively insensitive to all input parameter variations except for large decreases in the estimated mean partition resistance (μ_y). The calculated probability of success of partition Y from the original estimates is 0.994.

Automatic sprinklers. Figure 5.3 represents the stress-strength sensitivity computations for the probability of success of the automatic extinguishing system. These curves are quite similar to those of Figure 5.2. Like partition Y, there is a high calculated probability of success (0.937) and there is a much greater sensitivity to lower values of the strength mean (μ_s) than to any other parameter variation. In general, the other parameters effect a relatively greater sensitivity than in Figure 5.2

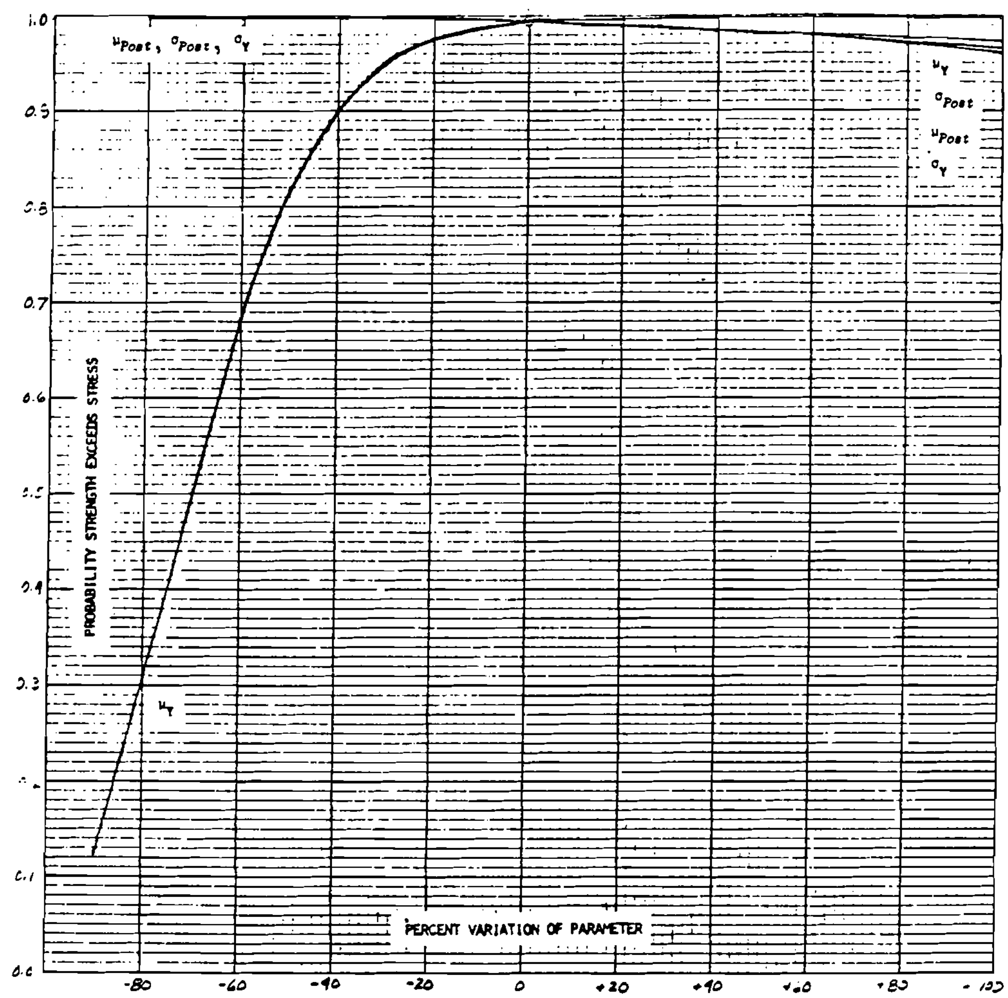

Figure 5.2

Sensitivity of Stress-Strength Relationship for Partition Y

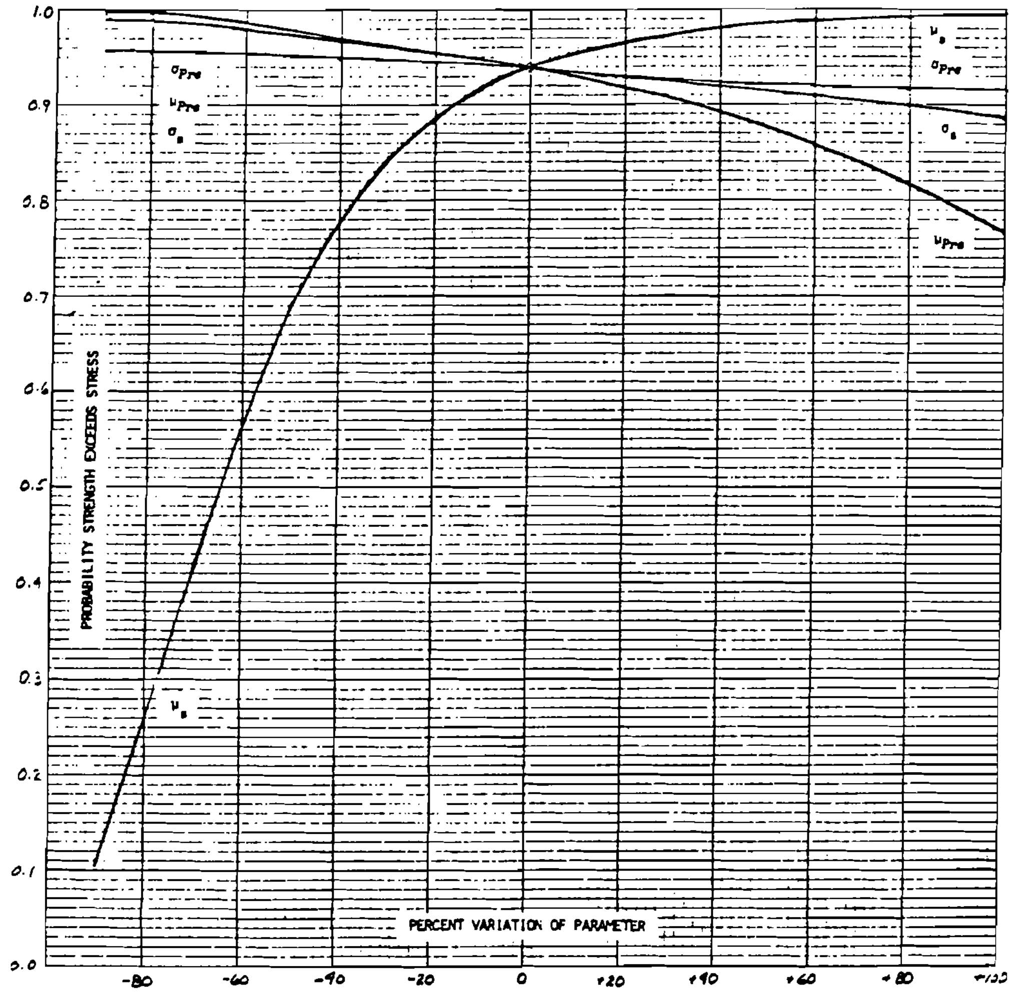

Figure 5.3

Sensitivity of Stress-Strength Relationship for Automatic Suppression System

Discussion. There are a number of observations of the stress-strength sensitivities of Figures 5.1, 5.2 and 5.3 which can be readily explained. The greater sensitivity to the means than to the standard deviations is due to the greater distributional displacement caused by changes in the mean. The lower sensitivity of the high probability relationships results from the initially large difference between the distribution means which, on a percentage basis, is only significantly affected by changes in the higher mean.

Sensitivity to Multiparameter Variation

While the above analysis provides some insight into the relative sensitivity of stress-strength models to the individual distribution parameters, it is unlikely that in the real world there will only be one parameter which cannot be determined with absolute certainty. It is more likely that all of the parameters will be subject to approximation or to possible errors in determination. Figure 5.4 illustrates the sensitivity of the three stress-strength relationships to simultaneous variation of all parameters by the percentage indicated on the abscissa. Again it is noted that the higher probability relationships are relatively less sensitive. Comparision with Figures 5.1, 5.2 and 5.3 reveals similar curvalinear patterns which suggests a dominance of the large mean parameter. Where the probable range of individual parameters is known or can be estimated, the sensitivity may be analyzed over these ranges rather than uniformally as in Figure 5.4.

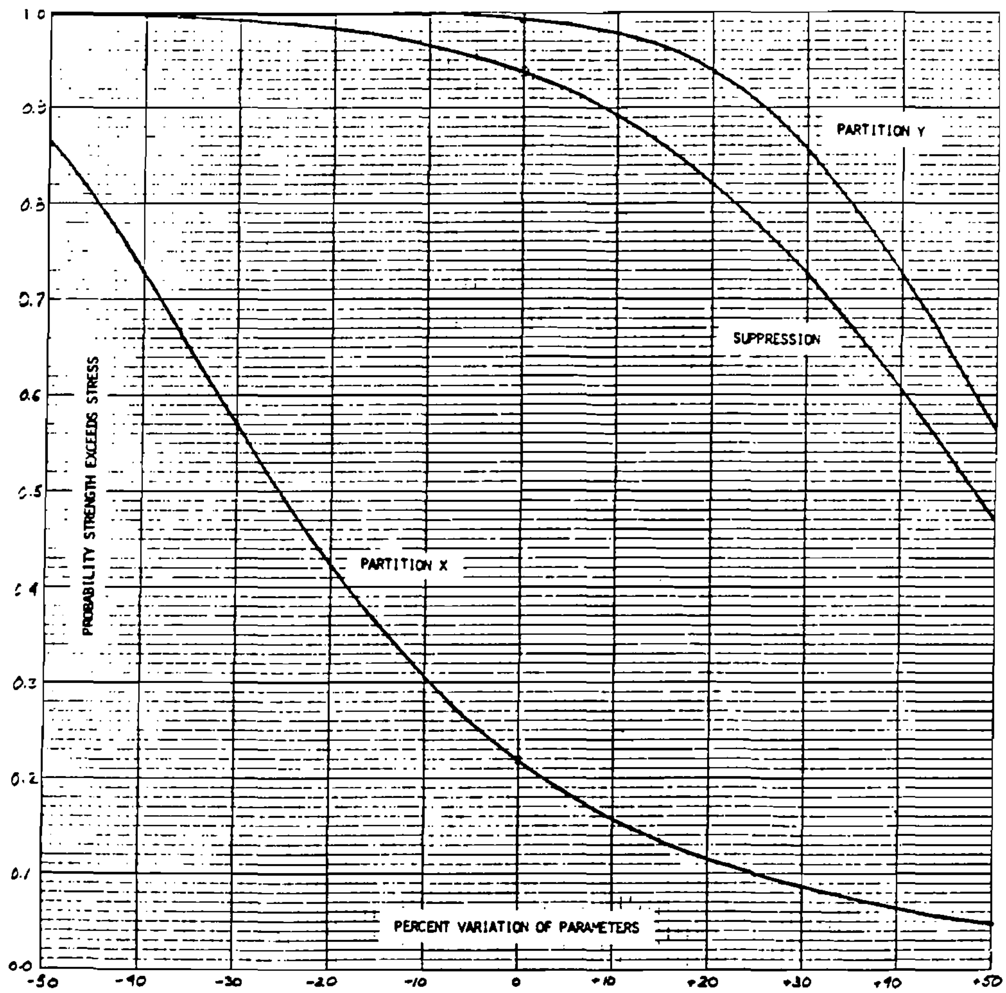

Figure 5.4

Multiparameter Sensitivity of Stress-Strength Relationships

5.2.2 Sensitivity of Fire Spread Model

The stress-strength relationships analyzed above are inputs to the determination of the probability of fire spread limitation. In analyzing the sensitivity of the fire spread model, each of the four examples used in the comparison in the previous section is considered. For each example, each of the input parameters is varied individually over its entire range of possible values, from zero to one. Resultant probabilities for rooms one and three of the fire spread scenario are shown graphically, numerical results of the computations are given in Appendix A5.3. Figures five through eleven show the parameter values on the abscissa and the probability of limiting fire spread on the ordinate. Dotted lines indicate the GSA general level, mission-focused goals for limiting fire extent: 0.99 for the first room and 0.995 for the third room.

Example 1

The sensitivity of the lightweight partition example with no sprinklers is shown in Figures 5.5 and 5.6. The parameters varied are the barrier adequacy (A_b), the barrier reliability (R_b) and the probability of self-termination (T). Figure 5.5 indicates that no value of the barrier parameters can individually raise the probability of fire limitation to the GSA level for room 1, and only a very high probability of self-termination can achieve this goal. Figure 5.6 shows fire limitation in room 3 to be more sensitive to the input parameters than room 1. The GSA goal may be reached with an increase of the

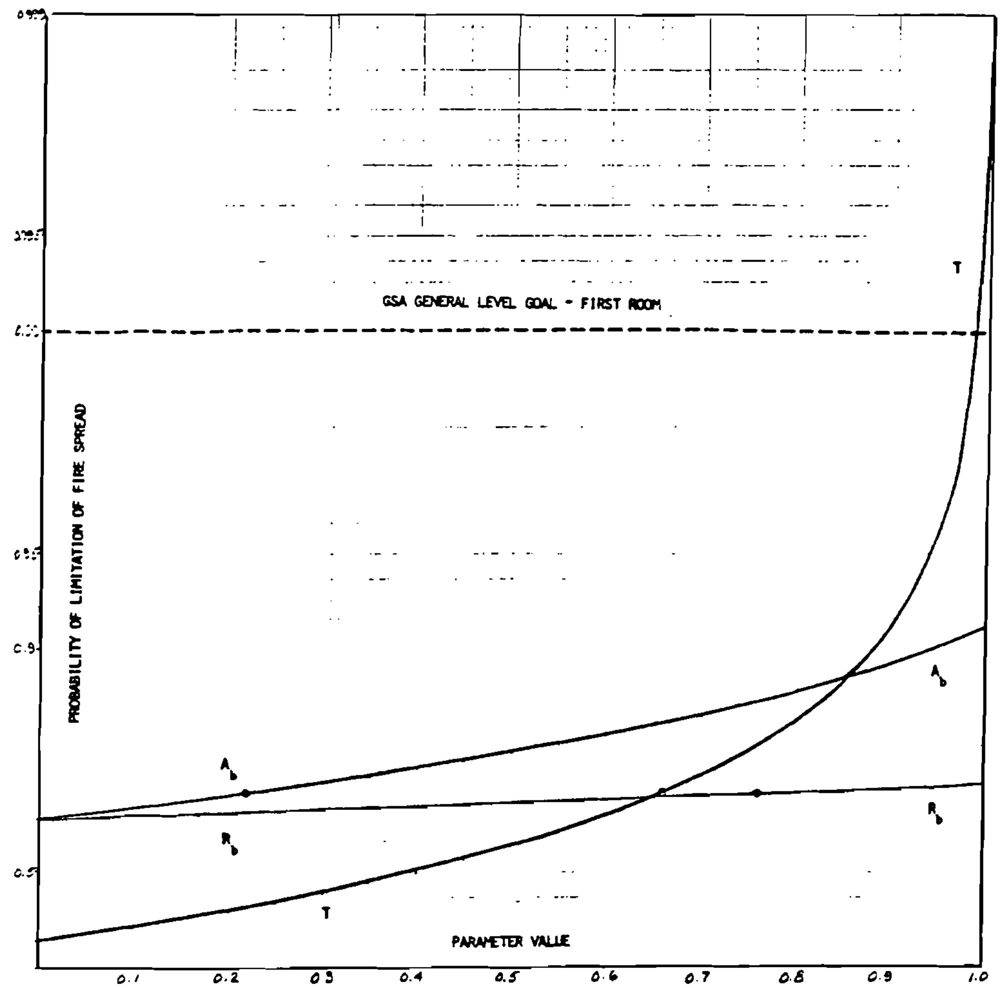

Figure 5.5

Sensitivity of Example 1 First Room Fire Spread

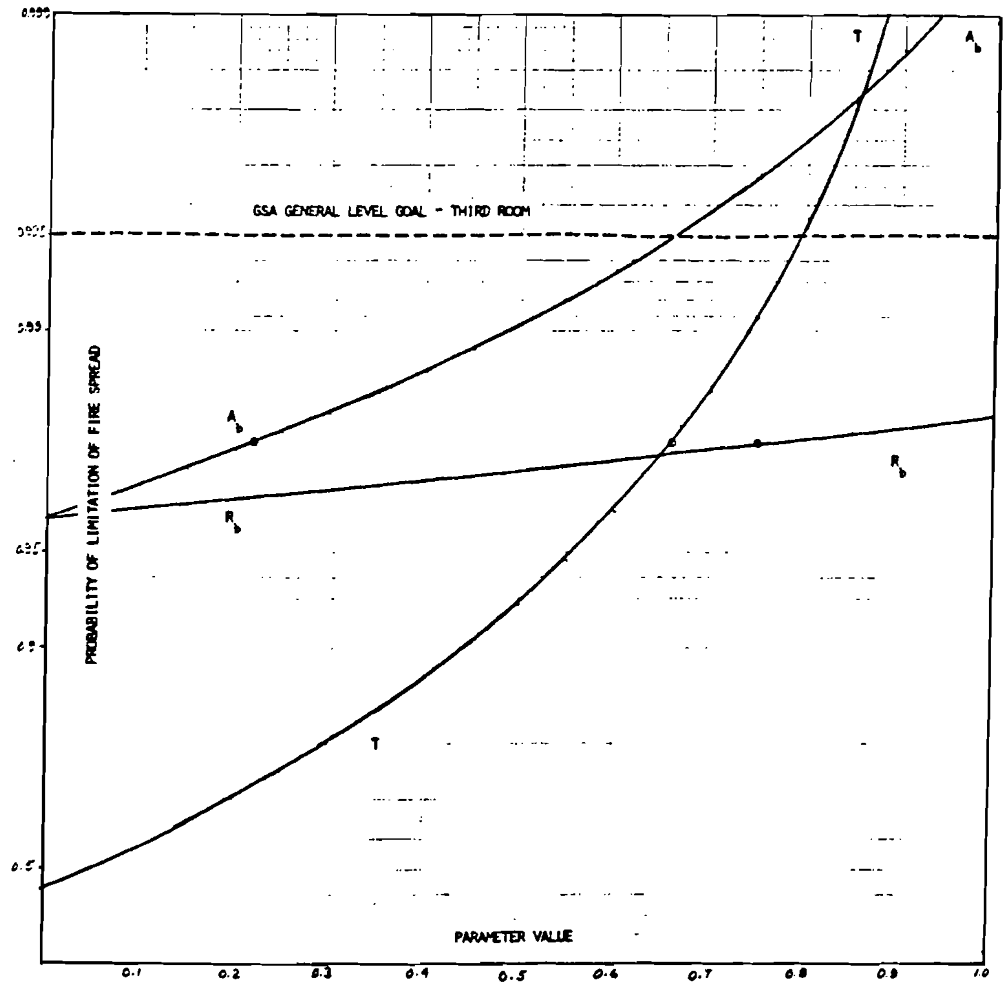

Figure 5.6

Sensitivity of Example 1 Third Room Fire Spread

barrier reliability to approximately 0.65 or by an increase in the probability of self-termination to approximately 0.8. The room 3 fire limitation probability is relatively insensitive to the barrier reliability.

Example 2

The sensitivity of the example with a fire rated partition and protected openings is clearly distinct from that of example 1. Figure 5.7 indicates that the GSA level will be met even with a zero probability of self-termination, but that a decrease in either the barrier adequacy or reliability to less than approximately 0.97 will cause the room 1 fire limitation probability to drop below the GSA goal. In Figure 5.8, the barrier adequacy and reliability are seen to be collinear. A decrease in either parameter to less than 0.5 would result in a failure to meet the GSA room 3 level. The room 3 fire limitation probability for example 2 is not affected by variation in the probability of self-termination. (See Appendix A5.3).

Example 3

The lightweight partition with sprinklers has five input parameters; barrier adequacy (A_b), barrier reliability (R_b) and probability of self-termination (T) which are the same values as in example 1, plus the sprinkler system parameters; suppression adequacy (A_s) and suppression reliability (R_s). Thus, there are five curves in Figures 5.9 and 5.10. No values of the reliabilities, either barrier or

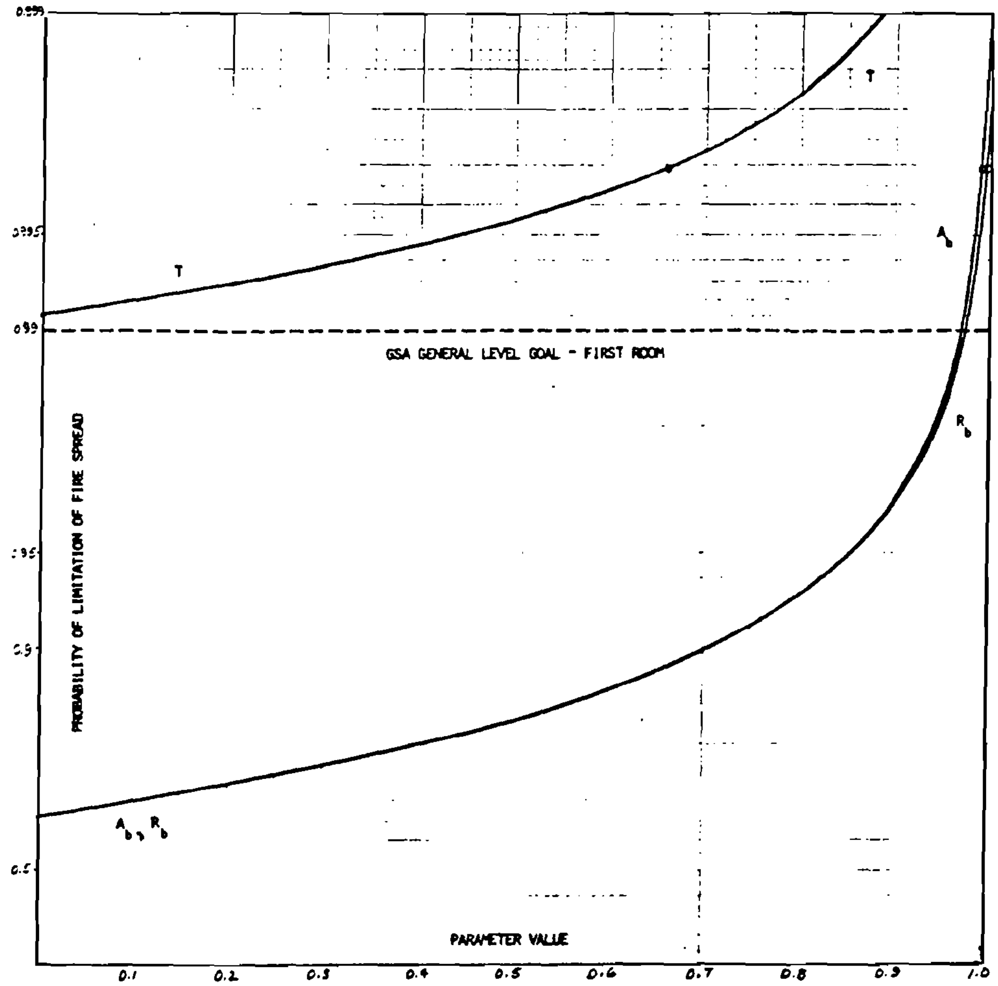

Figure 5.7

Sensitivity of Example 2 First Room Fire Spread

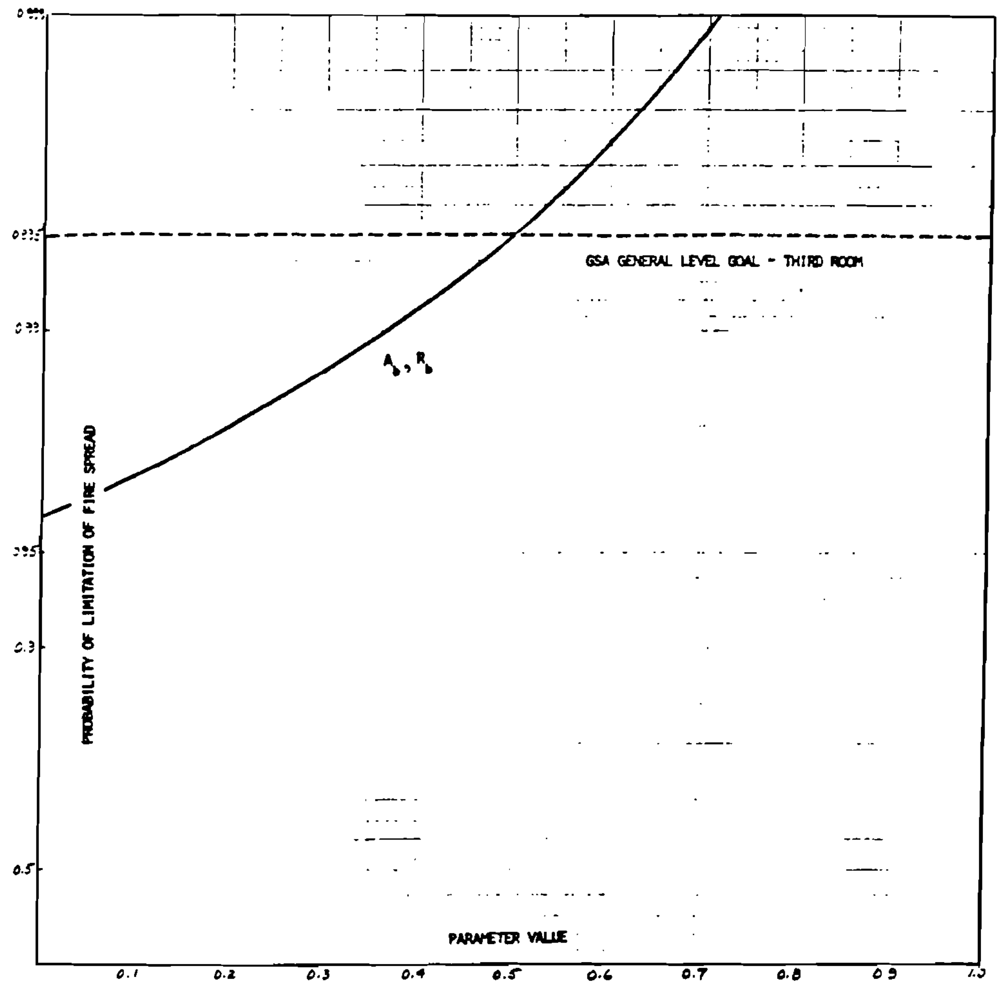

Figure 5.8

Sensitivity of Example 2 Third Room Fire Spread

suppression, can cause the GSA room 1 level to be achieved, whereas the barrier adequacy, probability of self-termination and suppression adequacy have "critical values" of approximately 0.7, 0.8 and 0.6 respectively. From Figure 5.10, the barrier parameters do not affect the GSA room 3 goal achievement, while the probability of self-termination, suppression adequacy and suppression reliability are critical at approximately 0.47, 0.77 and 0.83 respectively.

Example 4

For the case of the rated partition in conjuction with an automatic sprinkler system, only the barrier parameters affect the achievement of the GSA room 1 level. Figure 5.11 shows these parameters to be coincident at a critical value of approximately 0.76. The room 3 probabilities are not plotted as there is no individual parameter variation which causes the value to decrease below the GSA goal.

Discussion

Figures 5.5 through 5.11 indicate that the sensitivity of the fire spread model is always dominated by one of the three input components, barrier, suppression or self-termination. Further inspection reveals that the component with the highest probability of success dominates the sensitivity. This may be explained by considering that the product of two numbers is proportionally sensitive to the smaller, and the fire spread model multiplies the complements of the success probabilities. Thus the highest probability becomes the smallest multiplicand and hence the dominant component in the sensitivity analysis.

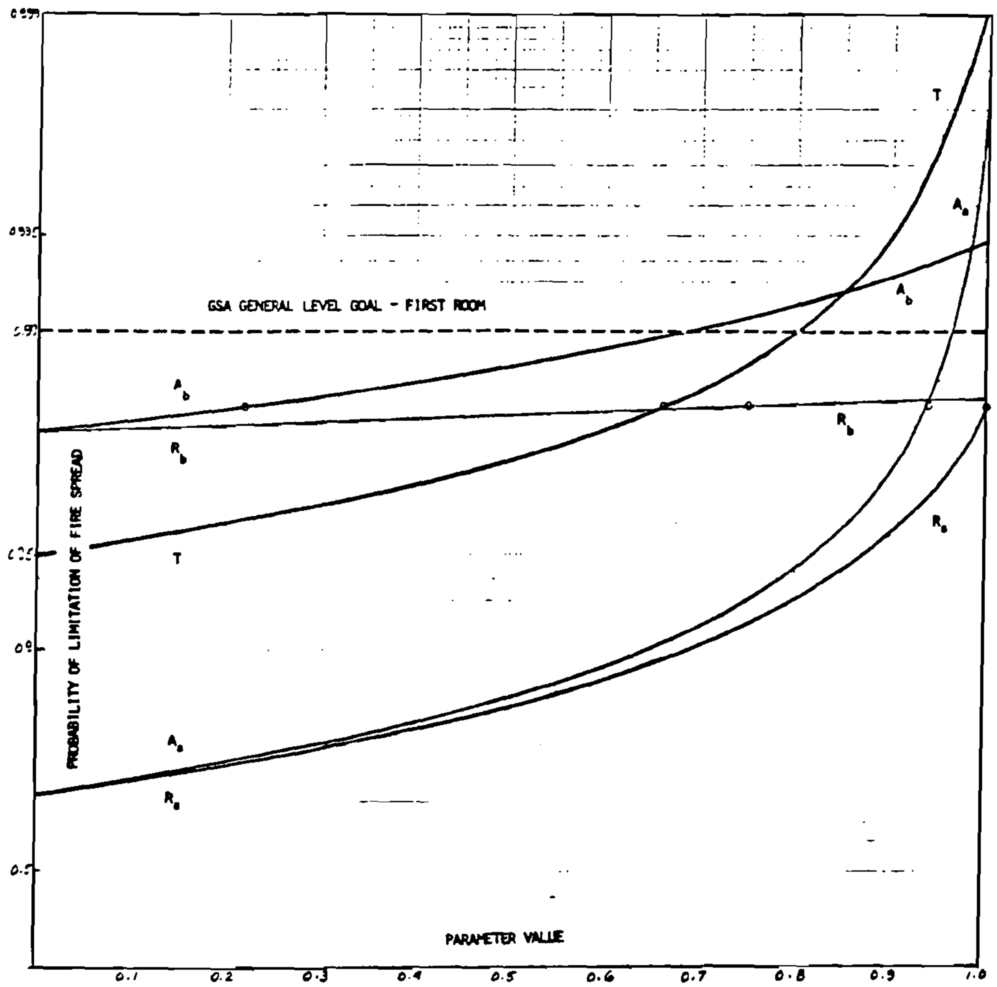

Figure 5.9

Sensitivity of Example 3 First Room Fire Spread

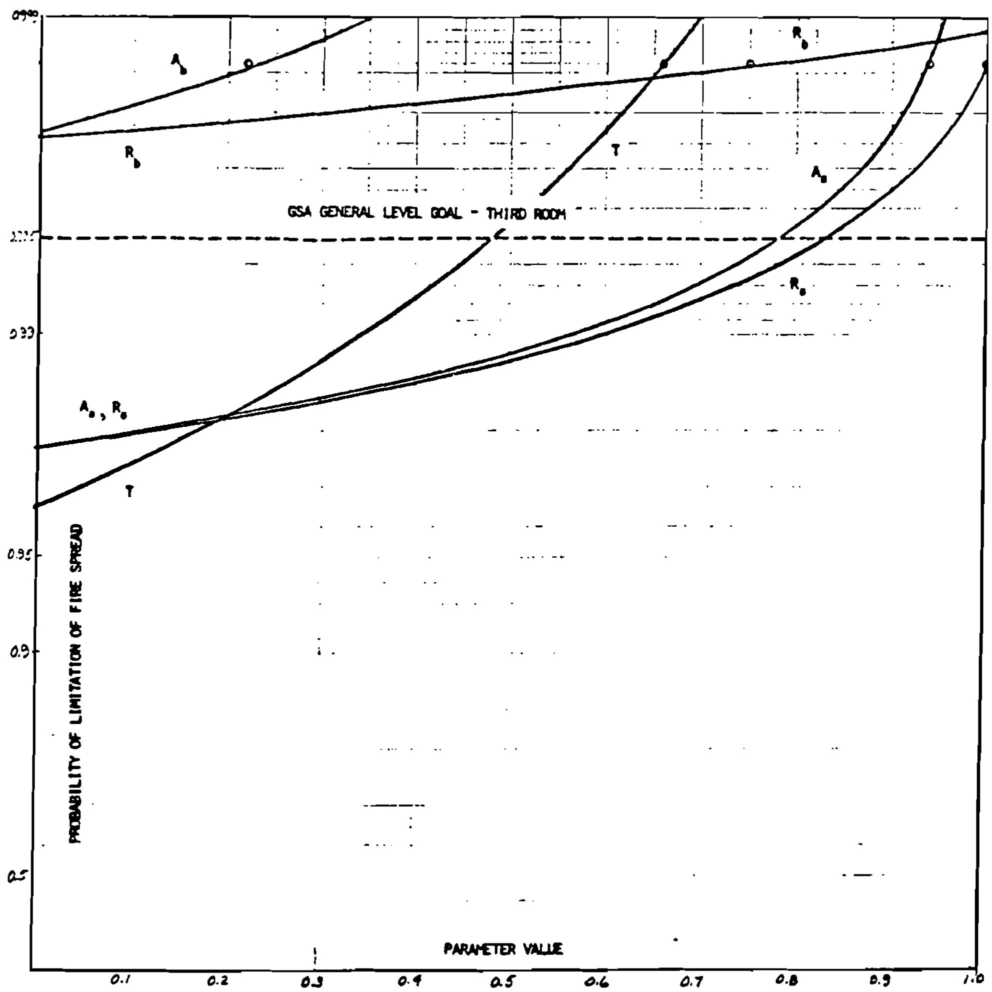

Figure 5.10

Sensitivity of Example 3 Third Room Fire Spread

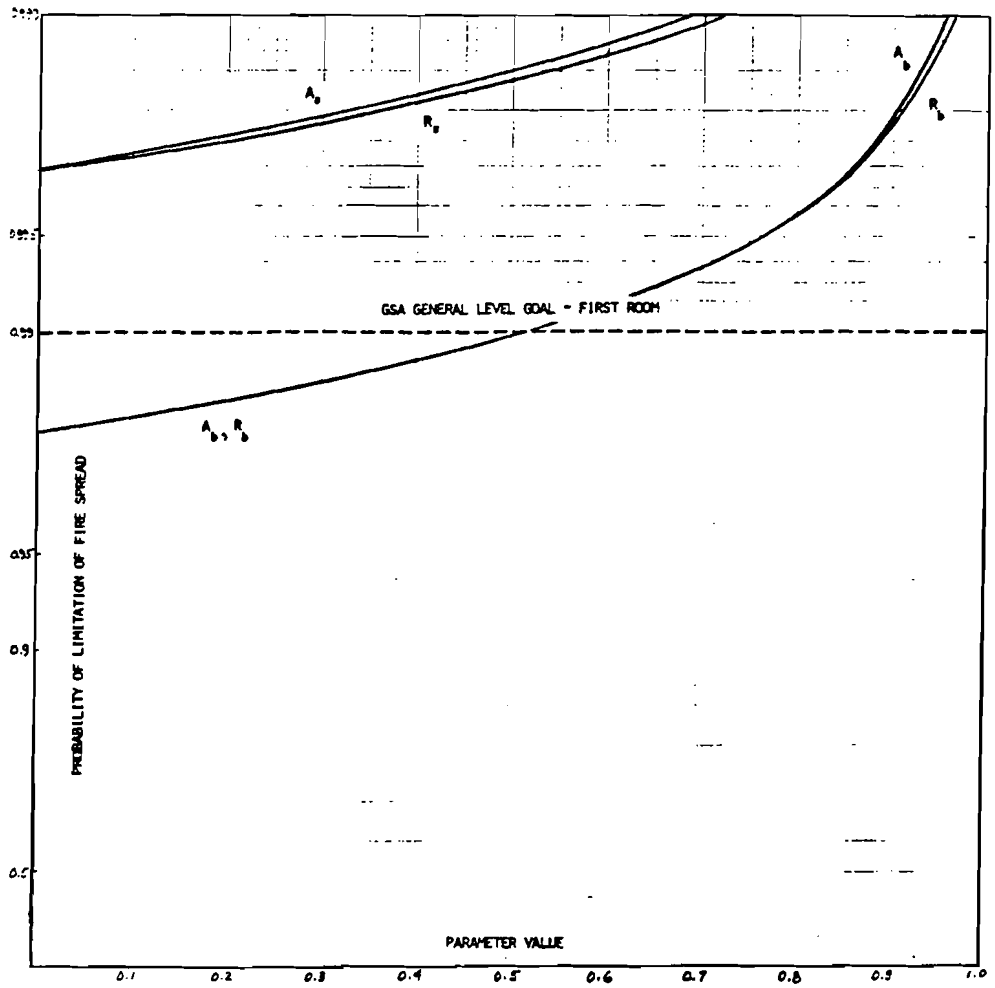

Figure 5.11

Sensitivity of Example 4 First Room Fire Spread

This marked dominance of one component has important ramifications. The stronger effect of variation in a single parameter indicates that a significant difference in the level of precision among input parameters is tolerable. That is, the inputs for the components which do not dominate need not be as carefully determined as the input for the dominant component.

5.3 Summary

There are a number of significant points raised by the comparisons and sensitivity analysis of the Goal-Oriented Systems Approach as applied to the GSA examples.

5.3.1 The Comparisions

The comparison of the Goal-Oriented Systems Approach to the GSA methodology is generally close for the examples cited. Where there are variations, they can generally be explained in terms of the sensitivity analysis. The differences observed for the first room of Example Three may be attributed to the sensitivity to suppression system parameters. Data for the automatic sprinkler system was the most difficult to extract from the GSA information and hence is the most susceptible to variation. The sensitivity to these parameters shown in Figure 5.9 indicates that a small variation in the sprinkler system adequacy (i.e. approximately an 0.05 increase in (A_s) could produce the difference observed.

The largest differences in the comparisons were for Example One.

Figures 5.5 and 5.6 show the fire spread model for this example to be quite sensitive to the probability of self-termination (T). In fact, the difference for room three of this example can only be explained by the self-termination probability, since no variation of the other parameters can produce the result obtained by GSA. This identifies a significant difference between the two methods which results from a previous assumption. The second postulate of fire spread which was induced from the GSA approach, conditioned the probability of termination on the absence of a massive energy transfer. In the Goal-Oriented Systems Approach, the massive energy transfer is considered to be implicit in the fire severity distributions. This causes a greater sensitivity to the probability of self-termination. From Figure 5.5 it can be seen that a small decrease in the value of this parameter (approximately 0.02) can account for the observed difference. In the other examples, the probability of self-termination is not dominant and thus they are not as sensitive to it.

5.3.2 The Stress-Strength Relationships

The sensitivity of the stress-strength relationships is illustrated in Figures 5.1, 5.2 and 5.3. From these it has been noted that the greatest sensitivity among the four parameters is to the larger mean. This is significant in that it indicates the selection of a conservative value of the highest mean in the stress-strength relationship will minimize the sensitivity of the results. That is, choosing a slightly low value of this parameter increases the chance of a positive deviation, to which the stress-strength model is less sensitive. Thus more confidence may be placed in the results.

5.3.3 The Fire Spread Model

As was observed from Figures 5.5 through 5.11, the sensitivity of the fire spread model applied to the GSA examples is always dominated by a single component. In combining this with the stress-strength sensitivities of Figure 5.4, a nullifying effect is observed. In Figure 5.7, it can be seen that the probability of limitation of fire spread is very sensitive to high values of the barrier parameters, but not as sensitive to low values. While in Figure 5.4, the adequacy of partition Y is seen to be sensitive at low values but not sensitive at high values. For example, a decrease in the barrier adequacy, A_b, from 0.994 to approximately 0.97 would lower the probability of limiting fire spread in room 1 to the GSA general level (Figure 5.7). However, for such a variation to occur, it would require the simultaneous variation of all parameters in the stress-strength relationship by 13% (Figure 5.4) or a variation of the mean strength by 22% (Figure 5.2). Similarly, an increase in the suppression adequacy, A_s, in Example 3 from 0.939 to approximately 0.965 would raise the room 1 fire spread limitation probability to the GSA level (Figure 5.9). This would require a simultaneous variation of 10% of all parameters in the stress-strength relationship (Figure 5.4) or an increase of strength mean of 20% (Figure 5.3). Thus the stress-strength relationships are least sensitive where the fire spread model is most sensitive.

In summation, the Goal-Oriented Systems Approach reasonably duplicates the results of the GSA examples while adding the ability to demonstrate that a level of confidence may be placed on the results even where the input data is inexact.

CHAPTER VI

SUMMARY AND CONCLUSIONS

The rationale for an innovative approach to fire safety can be appreciated in the light of the prevailing traditional code approach. Traditional building codes deal with fire safety as an absolute. In this study it is axiomatic that safety in general and fire safety in particular is not an absolute state. More pragmatically, fire safety is a relative condition dependent on the goal values of the population at risk. That which is judged acceptable by that population is considered to be safe. The traditional codes dictate specific requirements purported to achieve a minimum level of safety that is neither defined nor consistant. Not only does the traditional approach ignore the pragmatic concept of safety but in doing so the codes restrict the flexibility of design, thereby impeding technological progress in fire protection engineering and the building industry.

The second axiom of fire safety implicit in this paper, deals with the stochastic nature of fires in structures. A fire safety system is a highly complex interaction of men, machines and combustion phenomena. The system performs unpredictably, malfunctions and occasionally fails completely. Such systems require description by mathematical statistics and probability theory for a rational approach to fire safe design.

6.1 Assumptions

A number of simplifying assumptions have been made in the development of the Goal-Oriented Systems Approach. These assumptions evolved primarily from the analysis of the original GSA approach. Specifically, the assumptions pertain to the identification of system components, the postulates of fire spread, and the modeling structure.

6.1.1 Components of a Fire Safety System

In the analysis of GSA's approach, four basic system components were identified. These components are herein referred to as the pre-flashover fire, the post-flashover fire, fire suppression, and barriers to fire spread. These components are paired to produce a probability of fire control by suppression in the pre-flashover stage and a probability of fire control by confinement of the post-flashover fire. The fire stages have intentionally not been rigorously defined in order to permit flexibility and adaptability. It is assumed that the severity of the fire in each stage can be described by a single parameter corresponding to the characteristic of interest; "suppressibility" of the pre-flashover stage and "containability" of the post-flashover stage, and that these parameters can be expressed in terms of probability distributions. Similarly, it is assumed that these same parameters define the adequacy of the fire control components; suppression and containment. In addition, each of the fire control components has an associated reliability which can be derived as an expected value. There is also a comparable parameter of the combustion process identified as the probability of self-termination.

6.1.2 Postulates of Fire Spread

Inductive analysis of the original GSA approach revealed several implicit postulates describing the spread of fires in buildings. These postulates, in brief, are:

1. Limitation of fire spread occurs by containment or termination.
2. Termination does not occur in the event of massive ignition.
3. Fire spreads sequentially through a series of modules.

In addition, a corollary to the first postulate states that a suppression system can be effective only in the first module. In the Goal-Oriented Systems Approach, developed in this paper, the first postulate dictates the Boolean logic by which the components of fire safety are related. The second postulate is assumed implicit in the fire severity distribution, while the third postulate leads to a Markovian treatment of probabilistic fire spread among rooms.

6.1.3 Fire Safety System Structure

Assumptions about the structure of a fire safety system are also largely inspired by the GSA approach. The stress-strength relationship as a model of fire control strategy effectiveness is implicit in the GSA barrier analysis procedure. The Boolean logic model of component relationships and the Markovian model of modular fire limitation stem from the induced postulates described above. These latter models assume that the components of the fire safety system are independent, which generates conservative probabilities of limiting fire spread.

6.2 Major Findings

The GSA systems approach has attained a significant status in the fire protection community, primarily as an instigator for rethinking the problem and initiating the "systems approach". But the approach has also gained acceptance as a design tool. Yet, there has been no rigorous attempt made to either substantiate or refute the GSA approach. This study has attempted to answer a number of significant questions leading to a theoretical rationalization of a Goal-Oriented Systems Approach. These questions relate to underlying theory, refinement and sensitivity.

6.2.1 Theoretical Concepts

The first question is: are there underlying theoretical concepts in the GSA approach which may be used to develop a broad approach to the general question of determining a level of fire safety? This question is addressed in Chapters II and III where the approach is analyzed and found to have a basis in a number of intuitively acceptable postulates and implicit theoretical models. These concepts have been reformulated into a revised Goal-Oriented Systems Approach in Chapter IV.

6.2.2 Refinement

The second question asks: How can the GSA approach be improved with respect to flexibility of scope, simplicity of application and validity of concepts? The reformulated Goal-Oriented Systems Approach of Chapter IV is a direct answer to this question.

The generalizations built into the Goal-Oriented Systems Approach permit its application to a wide range of occupancy types. It would be particularly amenable to modular loss evaluation in warehouses and other storage facilities. The explicitly identified structure of the revised approach makes it a candidate for evaluation of the achievement of other goals in addition to mission continuity.

The rational development of the Goal-Oriented Systems approach simplifies understanding and application. Input has been reduced to the identification of four probability distributions and three other probabilistic values. There are numerous procedures by which these curves and parameters can be estimated or intuited in a logical fashion consistant with the information available to the fire protection profession. Calculations have been reduced from complex iterative procedures to a relatively simple process which has been programmed for use with a hand-held calculator.

The Goal-Oriented Systems Approach has increased validity through the explicit exposure of assumptions and limitations and through the use of models consistant with mathematical theory.

6.2.3 Sensitivity

The third question is: How sensitive is the approach to the limited availability of probabilistic data? In Chapter V, the question of sensitivity of the Goal-Oriented Systems Approach is addressed. It was found that fire safety as measured by this approach, is generally insensitive to most of the input parameters for the cases examined. This result together with the introduction of standard estimating techniques reduces the significance of the problem of data availability. The Goal-Oriented Systems Approach is not intended to be a substitute for intuition and experience, but merely a tool to organize them and thereby achieve a higher level of understanding.

The GSA approach represents a concept with a significant impact on the field of fire protection engineering. Through analysis and reworking, this study has attempted to fully explain and adequately simplify this concept so as to be conducive to additional consideration.

6.3 Limitations

The Goal-Oriented Systems Approach is not without significant limitations to its application. The limitations can be generally described as imperfections in dimensionality, comprehensiveness and interpretation.

6.3.1 Dimensionality

The Goal-Oriented Systems Approach in application addresses only inanimate objectives, thus it is sufficient to consider fire only in relation to spatial development. If animate goals are to be considered, i.e. life safety, then it can be argued necessary to introduce a temporal factor to model the mobility of the exposed in relation to the progress of the fire. That is, the undesirable event is the simultaneous exposure to fire in the dimensions of both space and time.

6.3.2 Comprehensiveness

The Goal-Oriented Systems Approach does not represent an entire fire safety system. The approach is only one element of the system and is highly dependent for its appropriateness on the selection of scenarios. No formal methodology is proposed for determination of these likely paths of fire spread. The process is basically one of applying the professional judgement of experienced fire protection engineers. Insofar as there are relatively few fire protection engineers in the world today, this represents a limitation of the Goal-Oriented Systems Approach.

6.3.3 Interpretation

The interpretation of compliance with the prescriptive building codes is facile and definite -- it complies or it doesn't. In contrast, interpretation of probabilistic information is somewhat ambiguous. It is difficult to adjudge the significance of a probability value without some guidelines. In the absence of any such guideline it would be necessary to assign costs or benefits to alternative levels of fire safety and try to optimize the situation. Both the guidelines and the costs may be elusive values.

6.4 Suggestions for Additional Research

In the light of the limited formal response to the original 1972 GSA approach, the rate at which alternative approaches to fire safety will be developed through research activities is questionable. While there may be innumerable avenues of research that might be productively pursued, it would appear to be necessary to progress laterally as well as forward. That is, it is necessary to expand upon concepts as they are developed, addressing the problems of application, be they technological or not. With this in mind, there are at least three significant areas deemed appropriate to further research.

6.4.1 Extensions

The components of the fire safety system as identified in the GSA approach and as defined for the Goal-Oriented Systems Approach represent only a subset of common fire safety measures. Other strategies such as manual suppression, heat and smoke venting, detector actuated door closers, pressurization, etc., could be incorporated into the approach.

6.4.2 Integration

The Goal-Oriented Systems Approach is amenable to integration into where there is an expressed desire to achieve more than a "minimum" level of fire safety, then the Goal-Oriented Systems Approach offers a theoretically rational alternative.

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APPENDICES

APPENDIX A1

Availability of the Interim Guide for Goal Oriented Systems Approach to Building Fire Safety

Originally published in 1972 as Appendix D to the GSA Building Fire-Safety Criteria, the Interim Guide for Goal Oriented Systems Approach to Building Fire Safety was updated in 1975 by H. E. Nelson just prior to his transfer from GSA to the National Bureau of Standards. Although not formally issued by GSA, the 1975 revision is the basic working document for practitioners of the Goal Oriented Systems Approach both within and external to the Federal government. To facilitate its availability to those interested in this research, the revised guide was published by the National Bureau of Standards as an Appendix to the Grant Report, NBS-GCR-77-103, The Goal Oriented Systems Approach. This document is available from the National Technical Information Service, 5825 Port Royal Road, Springfield, Virginia 22161. The Order Number is PB-273174.

APPENDIX A2

PROBABILITY CALCULATIONS IN THE GOAL ORIENTED SYSTEMS APPROACH

1.0 Introduction

The concept of a Goal Oriented Systems Approach to building fire safety was promulgated by H. E. Nelson of the U. S. General Services Administration.* This approach is basically an application of the principles of fault tree analysis. A portion of the GSA developed tree has been used for quantitative analysis of fire safety in structures. Most notably, the Atlanta Federal Building was designed in accord with the numerical techniques outlined by GSA.

The quantitative application of the GSA approach involves the calculation of the probability of limiting fire involvement in each of successive modules (work stations, rooms and floors). These probabilities are then plotted on a graph (solid line of Figure 1) and compared to the established goals of the organization (broken line of Figure 1). Where the line of calculated probabilities of success is above the objective line, the goals are not met. The probabilities are determined by iteratively progressing from one module to the next and calculating the cumulative probability.

The following attempts to simplify the determination of these probabilities by developing a single expression for the probability of success at any module.

2.0 The GSA Example

This development is based on the procedure outlined in the first example of the GSA document (p. 91). In this example there is no suppression activity and interior partitions are lightweight and noncombustible.

2.1 Room of Origin

The fire involvement within the room of origin is represented by points "a" through "g" of the solid curve in Figure 1. These points are not computed but are taken directly from a similar curve proposed by GSA to represent such involvement. The value at point g is significant with respect to the development of additional probabilities. In GSA notation:

P_{Lg} = Probability of success in limiting the fire involvement of the room of origin.

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* GSA, Building Fire Safety Criteria, Appendix D, "Interim Guide for Goal-Oriented Systems Approach to Building Firesafety," Washington, DC 1972.

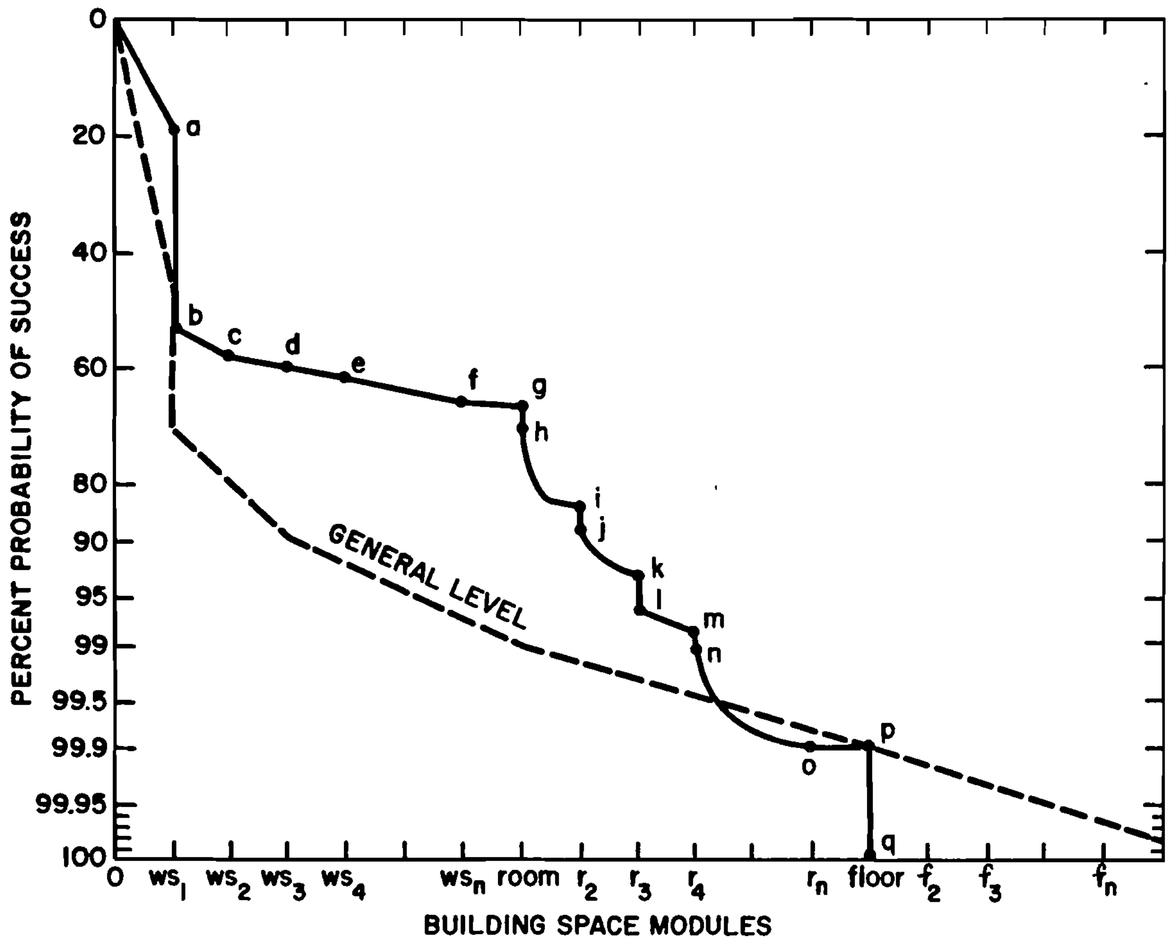


Figure 1. Calculation and desired limitation of fire involvement (GSA). WS = Work Station, r = room, f = floor.

2.2 Barrier

Given the probability of full room involvement, the next step is the calculation of the probability of success of limiting the fire at the first barrier. Again by the GSA notation:

P_{Lh} = Probability of success in limiting the fire at the first barrier, and

P_R = Probability of success of the compartmentation barrier withstanding the impact of the fire.

Then by equation (1), paragraph b, page 91 of GSA:

$$P_{Lh} = P_{Lg} + (1 - P_{Lg})\, P_R$$

$$= P_{Lg} + P_R - P_{Lg}\, P_R \text{ by expansion of terms}$$

$$= P(Lg + R) \text{ by definition of the Boolean operator + (OR gate).}$$

This last expression says that the probability of success in limiting the fire at the first barrier is the probability of success in limiting the involvement to the room of origin <u>or</u> success of the compartmentation.

2.3 Involvement of the Second Room

GSA considers that failure resulting from collapse of the barrier causes a massive transfer of ignition energy to the next room leading to prompt and total involvement. Thus the probability that fire will not spread throughout the second room is reduced by the probability of structural failure of the compartmentation element. By GSA:

P_{Li} = Probability of success in limiting the involvement of the second room and

P_{DX} = Probability of structural integrity of compartmentation barrier.

Then by equation (2), paragraph c, page 93 of GSA:

$$P_{Li} = P_{Lh} + K_x\,(1 - P_{Lh})$$

where $K_x = P_{Lg} - (1 - P_{Dx})\, P_{Lg}$

$$= P_{Dx}\, P_{Lg}$$

Which assumes that if the second room were the room of origin, the probability of success in limiting the involvement in the second room is the same as for the first room. That is to say, the assumption is that the fuel, environmental and control factors are the same for each room. To drop this assumption, additional notation will be introduced:

$P_{Lg'}$ = Probability of success in limiting the involvement of the second room if it were the room of origin.

Then:

$$P_{Li} = P_{Lh} + P_{Dx} P_{Lg'} (1 - P_{Lh})$$
$$= P_{Lh} + P_{Dx} P_{Lg'} \bar{P}_{Lh} \quad \text{by expansion}$$
$$= P(L_h + L_{g'} D_x) \quad \text{by definition.}$$

This says that the probability of success in limiting the involvement to the second room is equal to the probability of success of the first barrier or the success in limiting involvement to the second room and the success of the structural integrity of the barrier. And, from the previous development and the nature of the events under discussion:

$$P_{Lh} = P(L_g + R) \Rightarrow L_h = L_g + R$$

Thus $P_{Li} = P(L_g + R + L_{g'} D_x)$

2.4 Second Barrier

This step is the same as that for the first barrier: however, the notation $P_{R'}$ will be introduced to distinguish the second barrier.

P_{Lj} = Probability of success in limiting the fire at the second barrier.

$$= P_{Li} + (1 - P_{Li}) P_{R'} \quad \text{by GSA equation (1) paragraph d p. 93}$$
$$= P_{Li} + P_{R'} - P_{Li} P_R$$
$$= P(L_i + R')$$
$$= P(L_g + R + L_{g'} D_x + R') \quad \text{from section 2.3 above}$$

2.5 Third Room

This calculation is similar to that for the second room. The notation $P_{Lg''}$ will be used to signify the probability of success in limiting the involvement to the third room if it were the room of origin.

P_{Lk} = Probability of success in limiting the involvement of the third room.

$$= P_{Lj} + (1 = P_{Lj})\ K_x$$ GSA equation (1) paragraph e page 93

$$= P_{Lj} + (L - P_{Lj})\ P_{DX}\ P_{Lg"}$$

Here, it is assumed in the example that the probability of structural integrity is the same for the second barrier as for the first:

To drop this assumption and procede with the calculations, the GSA notation becomes cumbersome.

3.0 Revised Notation

To simplify the relaxation of the assumptions of homogeneity of barriers and compartments, the following notation is introduced:

Let $P(L_i)$ = Probability of success in limiting the involvement of the ith room.

$P(R_i)$ = Probability of success of the compartmentation barrier between room i and room (i + 1).

$P(D_i)$ = Probability of structural integrity of the ith barrier.

$P(G_i)$ = Probability of success in limiting the fire involvement in room i if room i were the room of origin, i.e., limitation due to the fuel, environmental and control factors within the room.

The GSA notation for the probability of success of the second barrier i.e. P(Lj) will temporarily be retained.

Then, the equation of section 2.5 above may be written:

$$P(L_3) = P(Lj) + (1 - PLj)\ P(G_3)\ P(D_2)$$

$$= P(Lj) + P(G_3)\ P(D_2) - P(Lj)\ P(G_3)\ P(D_2)$$

$$= P(Lj + G_3\ D_2)$$

We can also write from section 2.4:

$$P(Lj) = P(G_1 + R_1 + G_2\ D_1 + R_2)$$

Thus $P(L_3) = P(L_3) = P(G_1 + R_1 + G_2\ D_1 + R_2 + G_3\ D_2)$

Which is to say that success in the third room is the culmination of success in room one or at barrier one or in room two or at barrier two or in room three.

4.0 Generalization to "n" Compartments

It may now be shown by mathematical induction that the probability of success in limiting the involvement to any arbitrary room n, is given by the following general expression which will be herein identified as equation 1.

$$P(L_n) = P[G_1 + \sum_{i=1}^{n-1} (R_i + G_{i+1} D_i)] \qquad \text{(equation 1)}$$

In application, equation 1 states that success in room n is the result of success in any previous room or at any preceding barrier or in room n itself.

To mathematically calculate a value for $P(L_n)$ given probabilities of the G_i's, R_i's, and D_i's, one may use the equivalent expression:

$$P(L_n) = 1.0 - P(\overline{G}_1) \prod_{i=1}^{n-1} \{P(\overline{R}_i) [1.0 - P(G_{i+1}) P(D\ )]\} \qquad \text{(equation 2)}$$

Where the bar (e.g. $\overline{G}_1$) implies the complement i.e. $P(\overline{G}_1) = 1 - P(G_1)$. For entirely homogeneous compartments equation 2 reduces to:

$$P(L_n) = 1.0 - P(\overline{G}) [P(\overline{R})]^{n-1} [1.0 - P(G) P(D)]^{n-1} \qquad \text{(equation 3)}$$

5.0 Numerical example

Using the data from the GSA example:

$P(G) = P_{Lg} = 0.66$ (p. 91)

$P(R) = P_R = 0.12$ (p. 92)

$P(D) = P_{DX} = 9.80$ (p. 92)

Then the probability of success in limiting the involvement of the third room is given by equation 3:

$$P(L_3) = 1.0 - (1.0 - 0.66)(1.0 - 0.12)^2 [1.0 - (0.66)(0.80)]^2$$
$$= 0.94$$

Which is also the GSA result (p. 94).

It will be noted that the probabilities given by equations 1, 2, and 3 are for the success in limiting involvement to a specific room. For the GSA example, they are points g, i, k, m, and p in Figure 1. These peaks would normally be the points of interest with respect to the curve representing the institutional goals since they are the highest points on the success curve. If these points are below the goal curve, all points in between will also be below the goal cuve.

6.0 Other Points on the Success Curve

If there is interest in points other than the peaks of the success curve, they may be similarly calculated. The intermediate steps representing the probabilities of success of the compartmentation barriers are expressed as follows:

$P(L'_i)$ = Probability of success in preventing the spread of fire to the next room (i + 1)

Then for any arbitrary room, n:

$$P(L'_n) = P[G_1 + \sum_{i=1}^{n} (R_i + G_i D_{i-1})] \qquad \text{(equation 4)}$$

And for calculation when the characteristic probabilities are known:

$$P(L'_n) = 1.0 - P(\overline{G}_1) \prod_{i=1}^{n} \{P(\overline{R}_i) [1.0 - P(G_i) P(D_{i-1})]\} \qquad \text{(equation 5)}$$

where $P(D_o) = 0$

7.0 Summary and Conclusions.

General equations for calculating the probability of success in limiting fire development have been developed. These expressions may be used to calculate the probability of success at any room or compartment without calculating the success in other rooms. In addition, the equations do not assume homogeneity of the room or walls (barriers) and hence may be used where compartments of varying content and construction are found.

APPENDIX A3

Probability Plots of NBS Fire Load Data*

---

*Culver, C. G. Survey Results for Fire Loads and Live Loads in Office Buildings, Center for Building Technology, National Bureau of Standards, Washington, D.C. (1976).

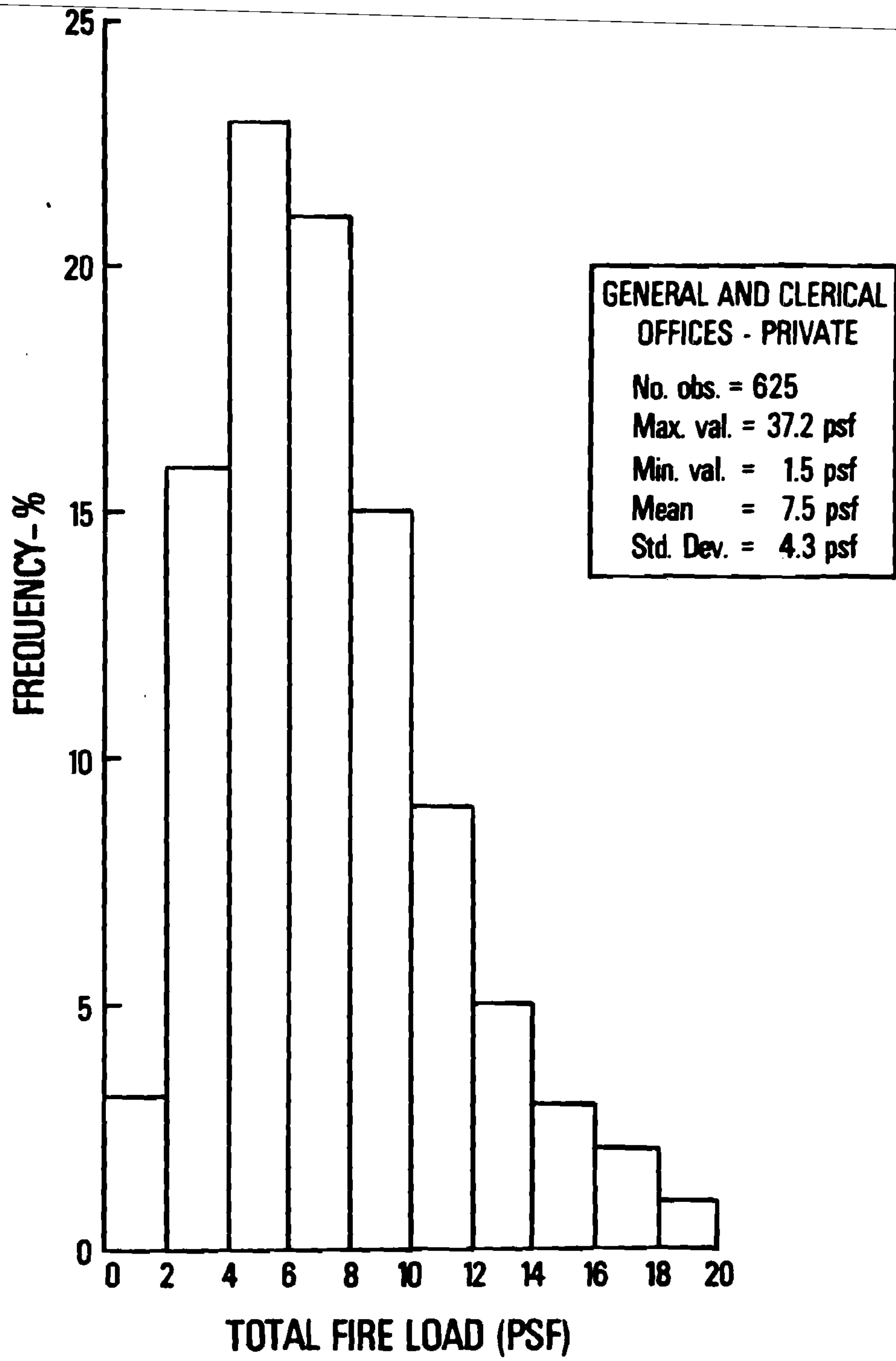


Figure 2. Frequency Distribution of Room Fire Load Data for Private Office Buildings (Culver, Figure 11)

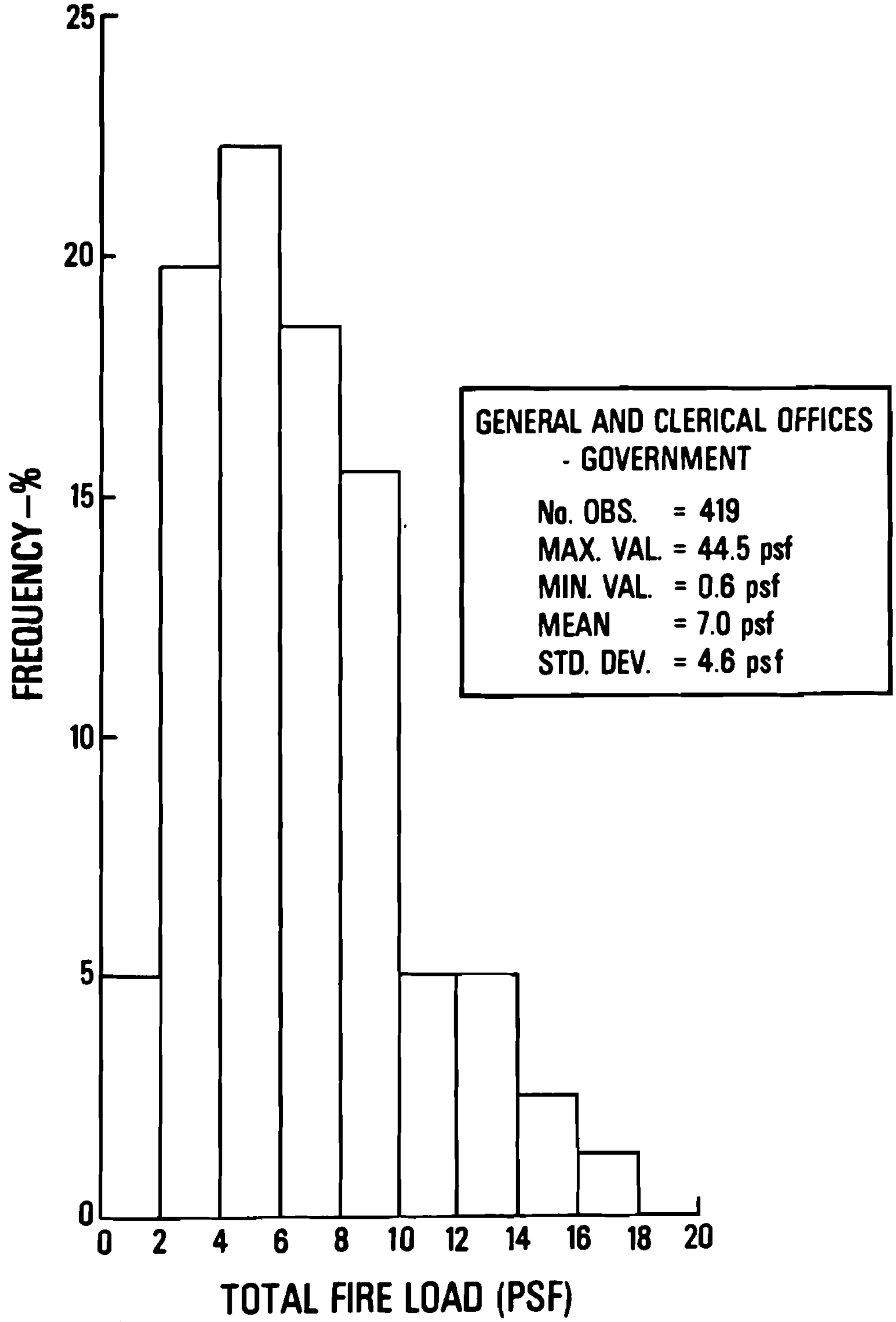


Figure 1. Frequency Distribution of Room Fire Load Data for Government Office Buildings (Culver, Figure 10)

TABULATED CUMULATIVE FIRE LOAD FREQUENCIES

(From figures 10 and 11 of Culver)

Total Fire Load (PSF)	Cumulative Percent of Observations	
	Government	Private
1	5	3
3	25	19
5	47.5	42
7	66	63
9	82	78
11	87	87
13	92	92
15	94.5	95
17	96	97
19	-	98
20	-	99
24	99	-

Table 1. Tabulated Cumulative Fire Load Frequencies

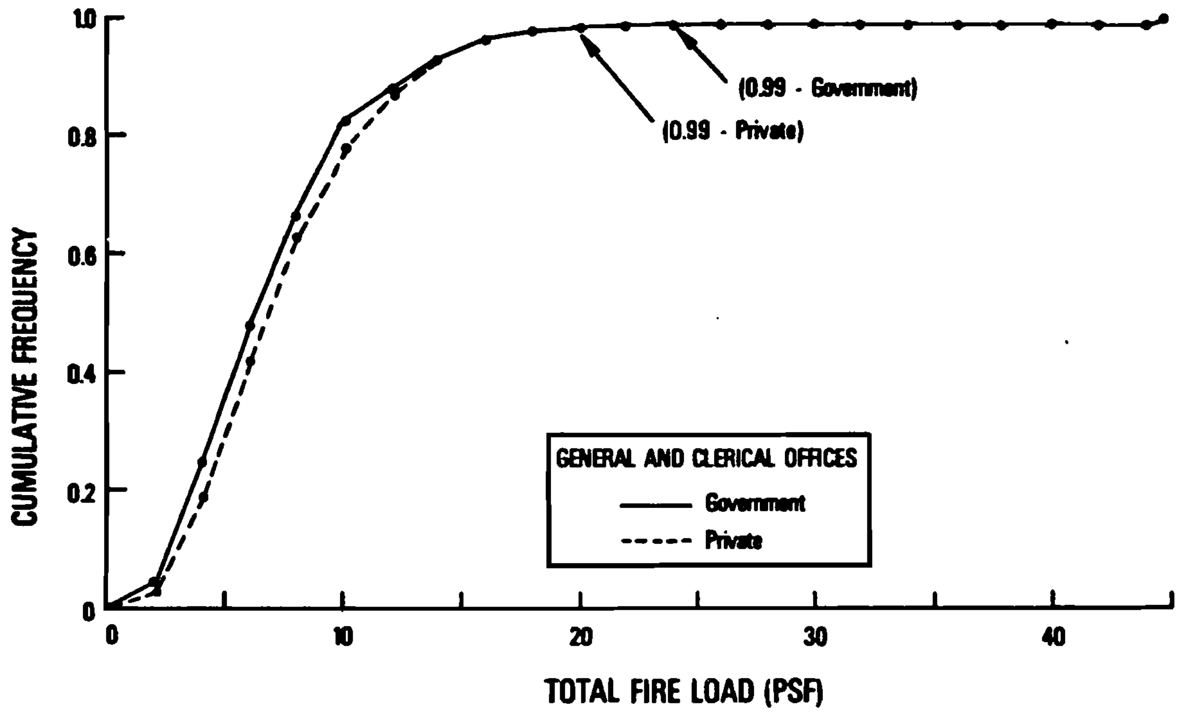


Figure 3. Cumulative Frequency Distribution for Room Fire Load (Culver, Figure 15)

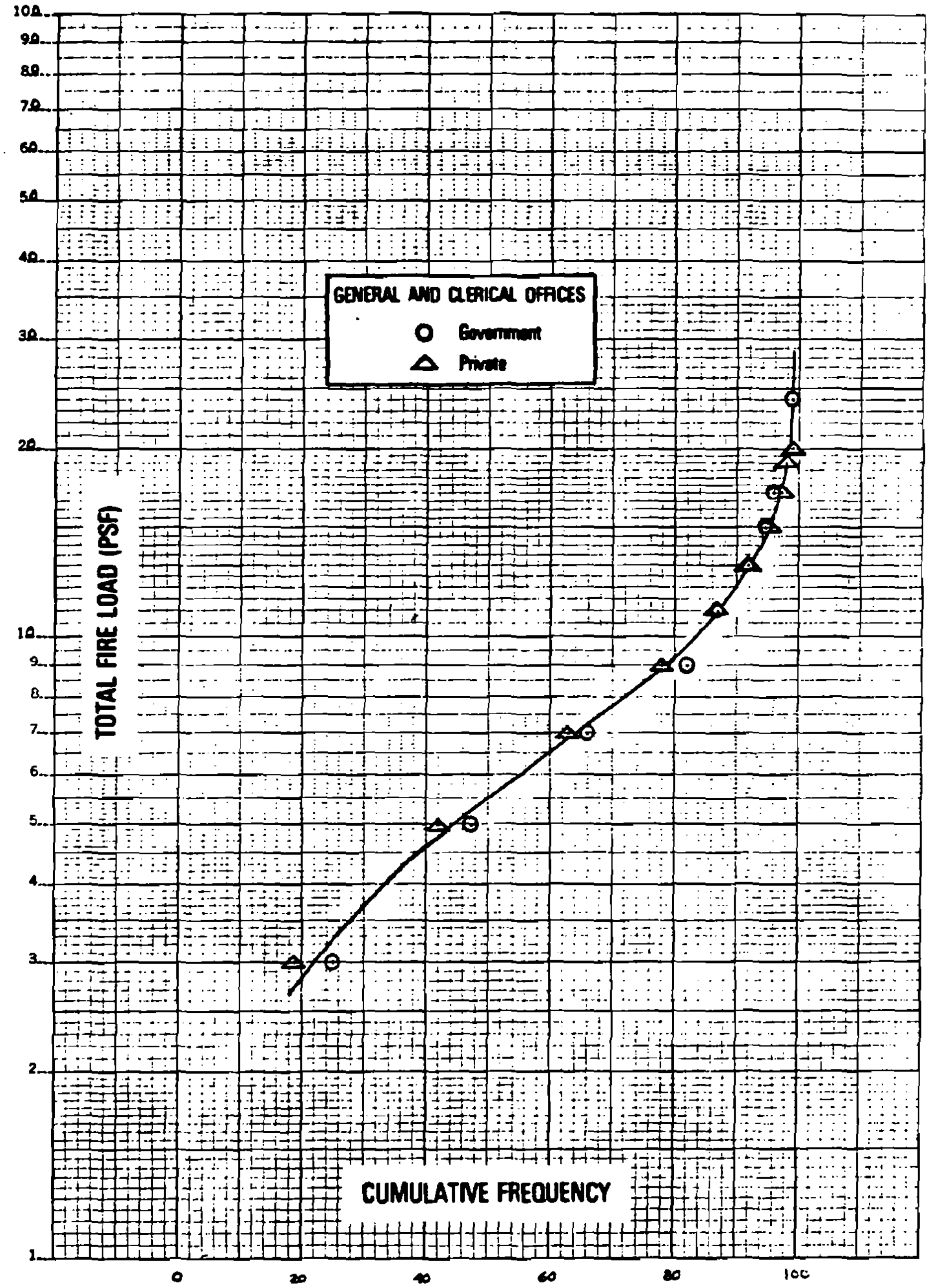


Figure 4. Exponential Plot of Cumulative Fire Load Frequency

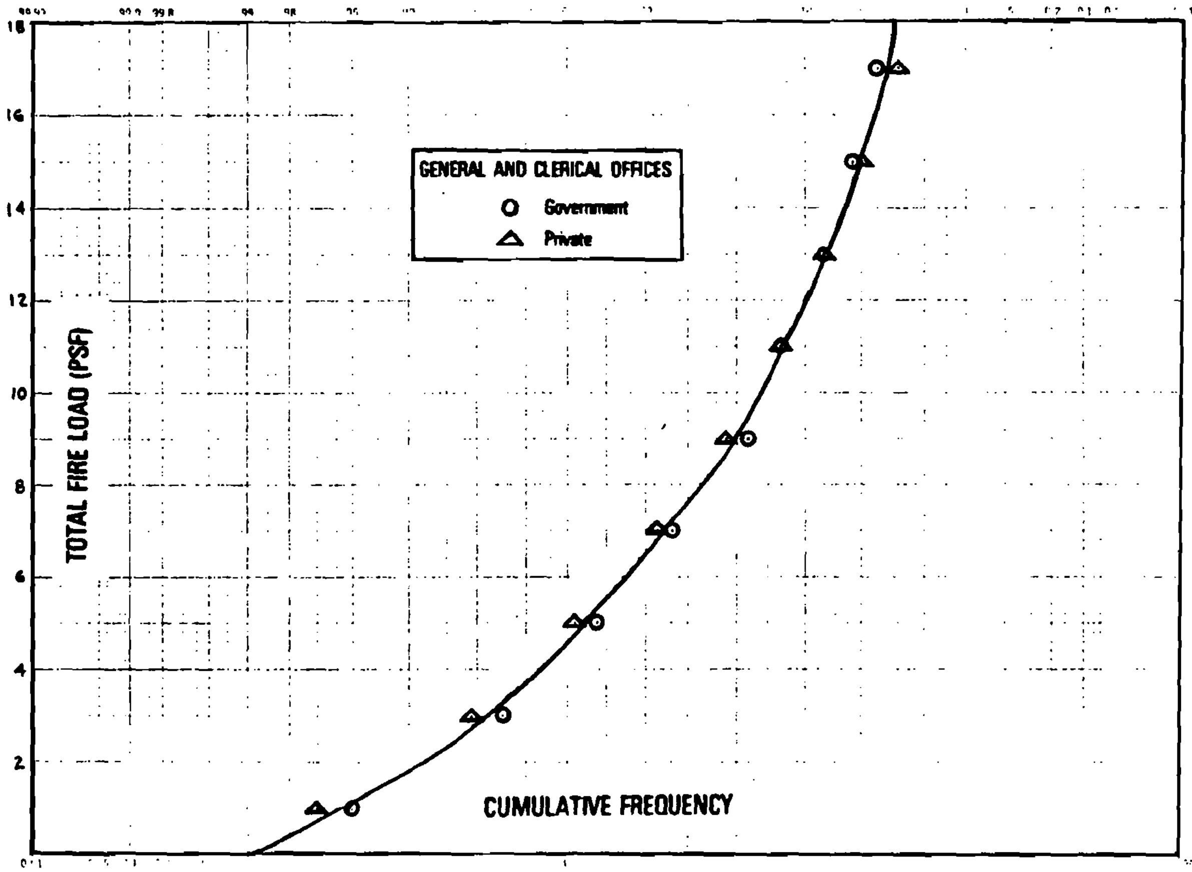


Figure 5. Normal Plot of Cumulative Fire Load Frequency

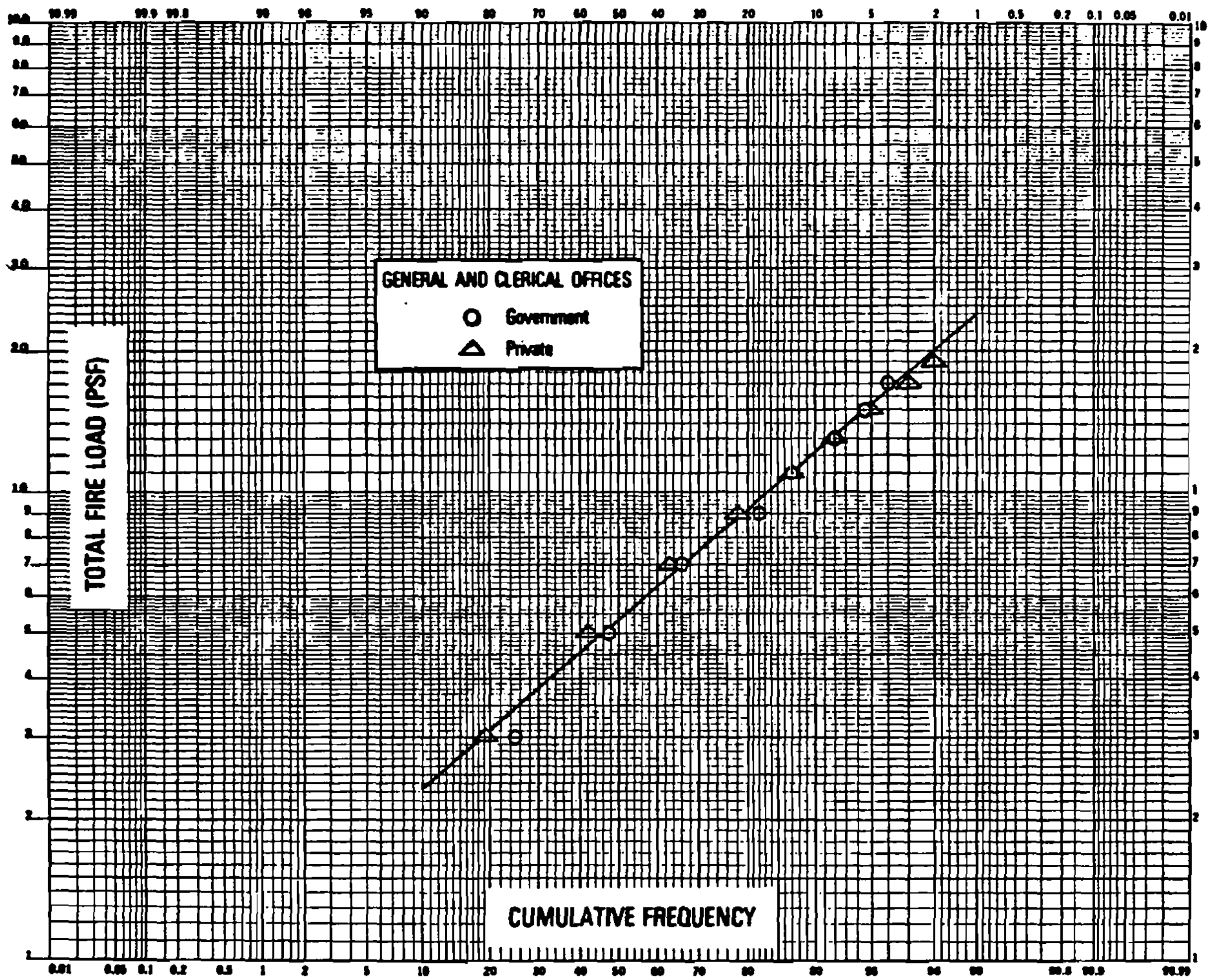
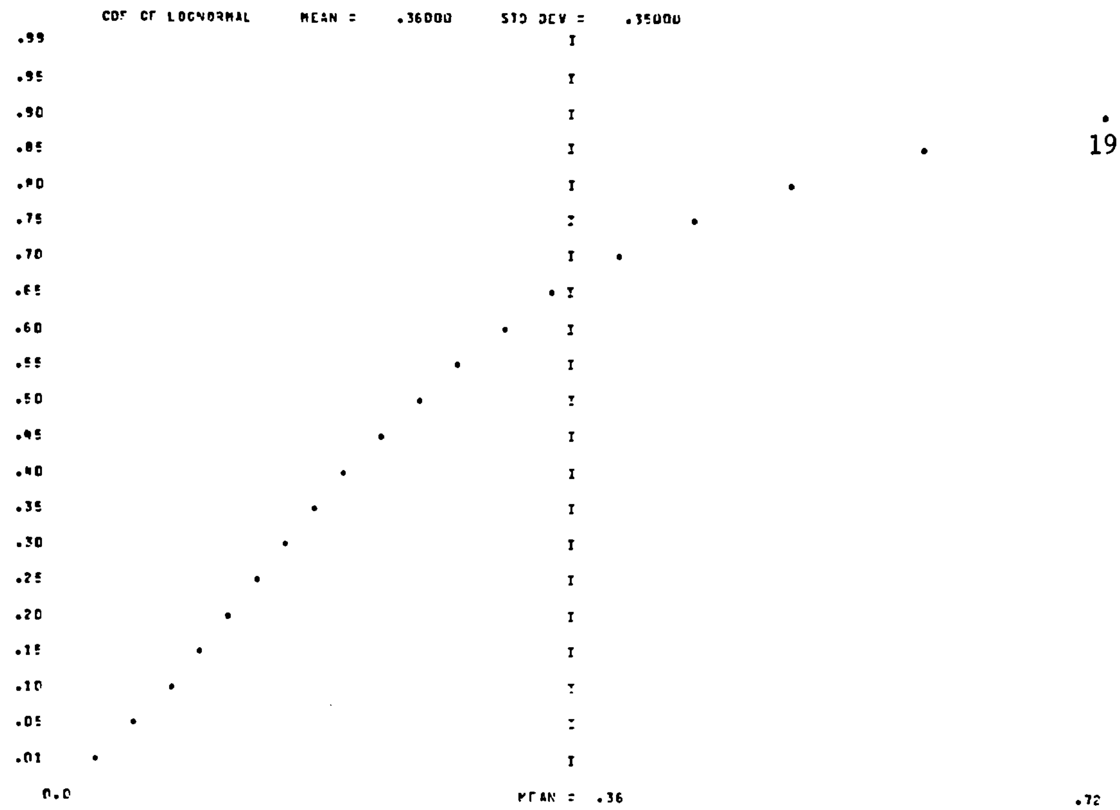
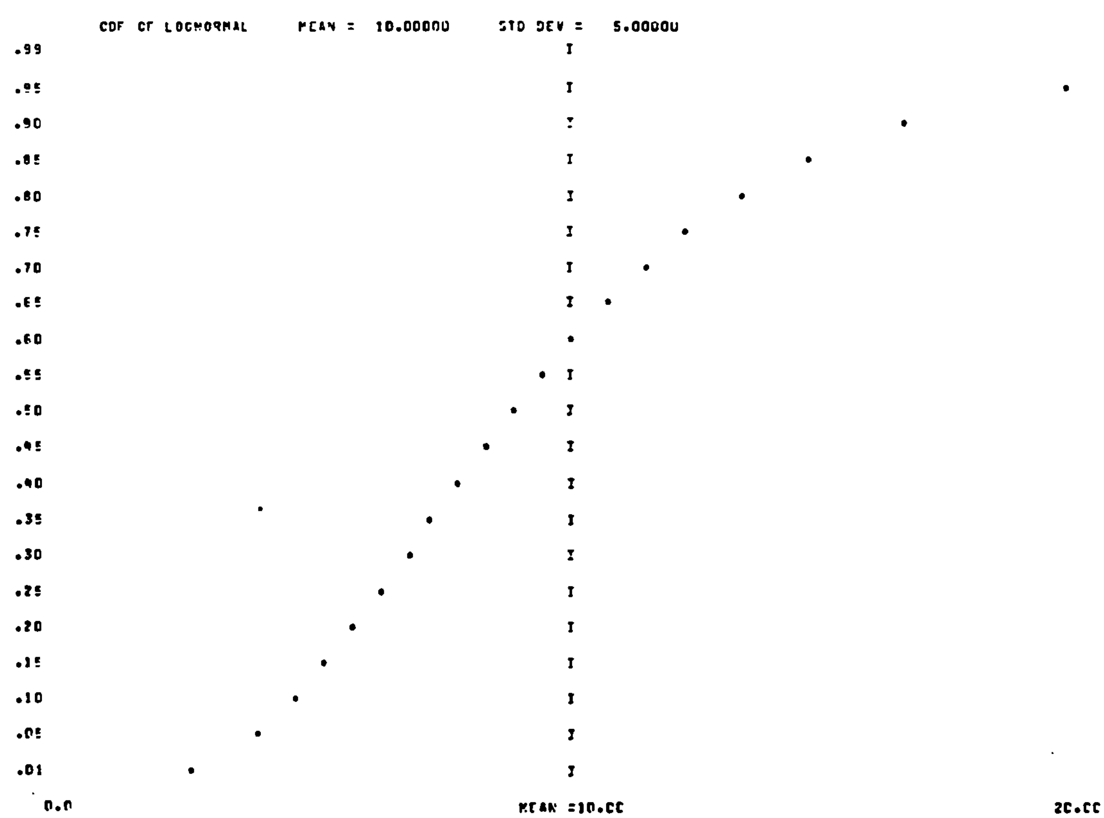


Figure 6. Lognormal Plot of Cumulative Fire Load Frequency

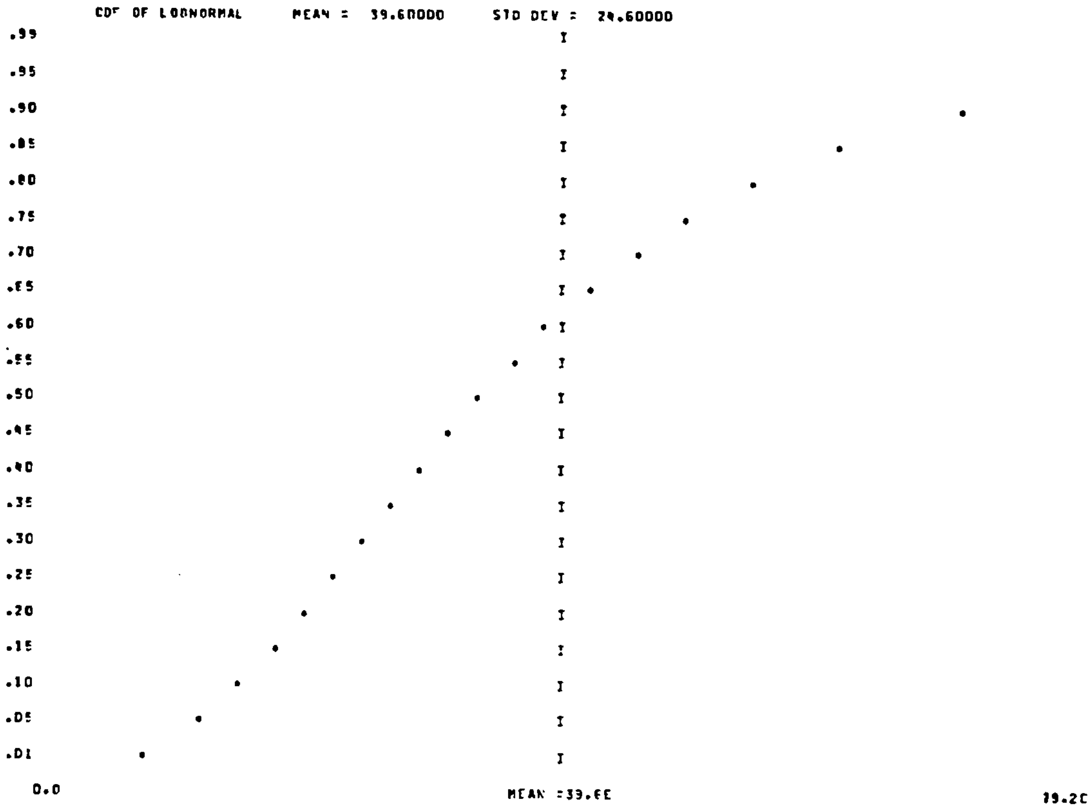
APPENDIX A4



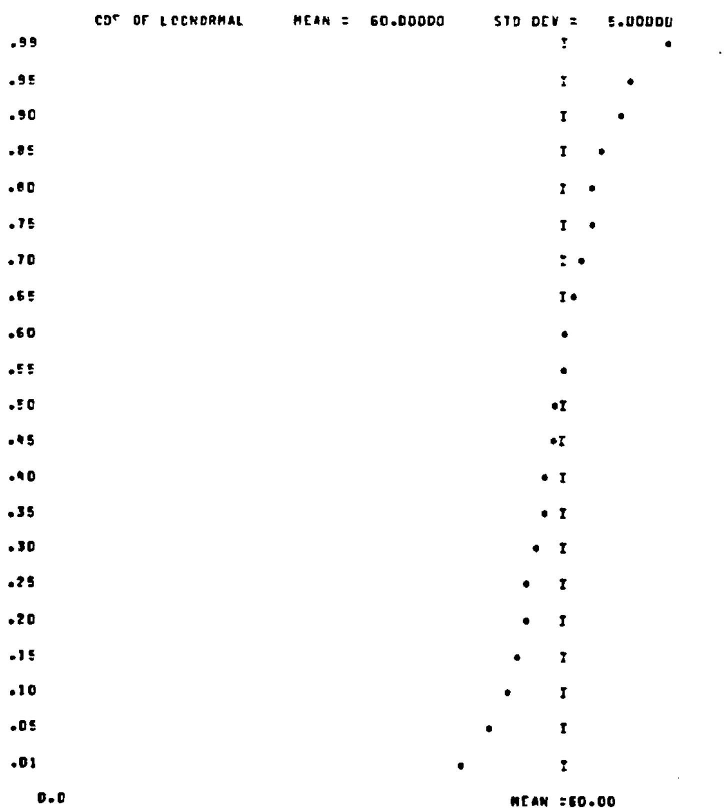
CDF of pre-flashover fire severity (μ = 0.36 MW, σ = 0.35 MW).



CDF of suppression capacity (μ = 10 MW, σ = 5 MW).



CDF of post-flashover fire severity (μ = 39.6 min, σ = 24.6 min).



CDF of barrier capacity (μ = 60 min, σ = 5 min).

```
C
C  FROGRAM FLOTS CDF OF LOGNORMAL DISTRIBUTION
C
      INTEGER IX(21)
      REAL M,MU,X(21),Z(21)
      DATA Z(1),Z(2),Z(3),Z(4),Z(5),Z(6),Z(7),Z(8),Z(9),Z(10),Z(11)/
     1 2.326,1.645,1.282,1.036,0.842,.674,.524,.385,.253,.126,0.0/
1     WRITE (6,5)
5     FORMAT (1H1/' INPUT MEAN AND STANDARD DEVIATION (2F5.2)'/)
      READ (5,10) MU,SIGMA
10    FORMAT (2F5.2)
C
C ECHO CHECK
C
      WRITE (6,20) MU,SIGMA
20    FORMAT (/10X'CDF OF LOGNORMAL'5X'MEAN ='F10.5,5X'STD DEV ='F10.5/)
C
C  TRANSFORM PARAMETERS TO NORMAL DISTRIBUTION
C
      V = ALOG((SIGMA/MU)**2.0 + 1.0)
      M = ALOG(MU) - 0.5*V
      S = V**0.5
C
C  CALCULATE VALUES OF THE CDF
C
      DO 25 I = 1,10
      J = 22-I
      Z(J) = -Z(I)
25    CONTINUE
      DO 30 I = 1,21
      X(I) = EXP(Z(I)*S + M)
      IX(I) = (X(I)/MU)*56.0
      IF (IX(I).GT.112) IX(I) = 112
30    CONTINUE
      CALL PLOT (IX,MU)
C
C  QUERY FOR ANOTHER DISTRIBUTION
C
      WRITE (6,50)
50    FORMAT (/' ANOTHER? TYPE Y IF YES, OTHERWISE RETURN')
      READ (5,60) ANS
60    FORMAT(A1)
      IF (ANS.EQ.'Y') GO TO 1
      END
```

```
      SUBROUTINE PLOT (IX,MU)
       INTEGER IX(21),IP (112)
      REAL MU,Y(21)
      Y(1) = 0.99
      DO 10 I = 2,20
      Y(I) = 1.05-I*0.05
10    CONTINUE
      Y(21) = 0.01
      DO 40 I = 1,21
      DO 30 J = 1,112
      IP(J) = 1H
      IP(56) = 1HI
30    CONTINUE
      J = IX(I)
      IP(J) = 1H*
      WRITE (6,50) Y(I),(IP(J),J=1,112)
40    CONTINUE
50    FORMAT (F4.2,112A1//)
      H = 2.0*MU
      WRITE (6,60) MU,H
60    FORMAT (4X,'0.0',47X,'MEAN ='F5.2,45X,F5.2)
      RETURN
      END
```

Errors in GOF Program*

Re: transformation of lognormal parameters, specifically, program statements A 980 and A 990.

1) The variable names do not correspond to previous statements.

2) The variance should not be squared in statement A 990.

3) Statement A 980 should follow statement A 1000 so as to utilize the transformed variance.

---

*Phillips, Don T., Applied Goodness of Fit Testing, AIIE, Atlanta (1972).

KOLMOGOROV - SMIRNOV TEST

CELLS	RANGE FROM	TO	OBSERVED	OBSERVED FREQUENCY	CUMULATIVE OBSERVED FREQUENCY	THEORETICAL FREQUENCY	CUMULATIVE THEORETICAL FREQUENCY	KOLMOGOROV - SMIRNOV STATISTIC
1	3.55948	3.78397	2.00000	.05556	.05556	.00710	.00710	.04846
2	3.78397	4.00846	.00000	.00000	.05556	.02153	.02863	.02693
3	4.00846	4.23294	.00000	.00000	.05556	.02335	.05198	.00358
4	4.23294	4.45743	.00000	.00000	.05556	.03642	.08840	.03284
5	4.45743	4.68191	5.00000	.13889	.19444	.05271	.14111	.05333
6	4.68191	4.90640	.00000	.00000	.19444	.07074	.21185	.01740
7	4.90640	5.13089	.00000	.00000	.19444	.08805	.29990	.10545
8	5.13089	5.35537	7.00000	.19444	.38889	.10164	.40154	.01265
9	5.35537	5.57986	5.00000	.13889	.52778	.10882	.51035	.01743
10	5.57986	5.80435	3.00000	.08333	.61111	.10805	.61840	.00729
11	5.80435	6.02883	4.00000	.11111	.72222	.09950	.71789	.00433
12	6.02883	6.25332	3.00000	.08333	.80556	.08458	.80287	.00268
13	6.25332	6.47780	1.00000	.02778	.83333	.06731	.87019	.03685
14	6.47780	6.70229	5.00000	.13889	.97222	.04945	.91963	.05259
15	6.70223	6.92678	1.00000	.02778	1.00000	.03369	.95332	.04668

THE KOLMOGOROV - SMIRNOV STATISTIC = .10545

DEGREES OF FREEDOM= 15

PARAMETERS OF THE LCNORM DISTRIBUTIONS

MUT= 361.803108215 SIGMAT2= 123583.982421875

Kolmogorov-Smirnoff Test of IITRI Heat Release Rate Data

APPENDIX A4.4

Program for Calculating the Probability of Limiting Fire Spread

This program is written for a Texas Instruments SR-52 programmable calculator. The main program, FIREPROB, and its principal subroutine, STDNRM, utilize 202 of the 224 program storage locations available. The programs have been recorded on a magnetic card which can be used to store the program and re-enter it into the calculator's memory.

A4.4.1 Program FIREPROB

FIREPROB follows the steps outlined in Chapter IV to calculate the probability that a fire will not spread beyond the room of origin. These steps are:

1. Enter parameters of the distribution of the post-flashover fire and the barrier.
2. Calculate the adequacy of the barrier (A_b) from the stress-strength relationship using subroutine STDNRM.
3. Calculate the barrier effectiveness (E_b) as the product of adequacy and reliability (R_b).
4. Enter parameters of the distribution of the pre-flashover fire and the suppression system.
5. Calculate the adequacy of the suppression system (A_s).
6. Calculate the effectiveness of the suppression system (E_s).
7. Enter the probability of self-termination of the fire (T).
8. Calculate the probability that the fire will not spread beyond the room of origin:

   $$P_1 = 1 - \left[(1 - E_b)(1 - E_s)(1 - T)\right]$$

SR-52 User Instructions

TITLE FIREPROB PAGE 1 OF 2

◄A► FIREPROB				

◄B► STDNRM				

STEP	PROCEDURE	ENTER	PRESS			DISPLAY
1	ENTER PROGRAM		CLR	2nd	read	
	insert card - side A		2nd	read		
	insert card - side B					
2	INITIALIZE		2nd	CMs		
			2nd	rset		
			RUN			
3	ENTER BARRIER DATA	μ_{post}	RUN			$1/(\mu_{post})^2$
		σ_{post}	RUN			EX_{post}
		μ_b	RUN			$1/(\mu_b)^2$
		σ_b	RUN			A_b
		R_b	RUN			$1-A_bR_b$
4	ENTER SUPPRESSION DATA	μ_{pre}	RUN			$1/(\mu_{pre})^2$
		σ_{pre}	RUN			EX_{pre}
	(if no suppression;	μ_s	RUN			$1/(\mu_s)^2$
	enter 0, press run	σ_s	RUN			A_s
	and procede to step 5)	R_s	RUN			1
5	ENTER P(SELF-TERM)	T	RUN			P_1

TITLE FIREPROB PAGE 2 OF 2
PROGRAMMER JW DATE 31. 1. 78

SR-52 Coding Form

LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS	LABELS
000 112	01	1			54	)			81	HLT		A 018
	75	−			42	STO			40	x^2		B 064
	51	SBR		040 152	00	0			85	+		C 058
	11	A			09	9			01	1		D 008
	65	×			00	0		080 192	54	)		E 113
005 117	51	SBR			42	STO			23	ln x		A' 121
	11	A			00	0			44	SUM		B' 149
	46	LBL		045 157	05	5			00	0		C'
	14	D			42	STO			05	5		D' 178
	65	×			00	0		085 197	55	÷		E' 097
010 122	53	(			08	8			02	2		REGISTERS
	01	1			42	STO			94	+/−		00 dsz
	75	−		050 162	00	0			85	+		01 μ
	81	HLT			07	7			43	RCL		02
	54	)			53	(		090 202	00	0		03
015 127	95	=			01	1			01	1		04 X
	81	HLT			75	−			23	ln x		05 $V_1 + V_2$
	46	LBL		055 167	41	GTO			54	)		06
	11	A			15	E			56	rtn		07 coeff.
	51	SBR			46	LBL		095 207	00	0		08 sum
020 132	12	B			13	C			46	LBL		09 z^*
	42	STO			65	×			10	E'		10
	00	0		060 172	81	HLT			01	1		11
	04	4			54	)			41	GTO		12
	53	(			56	rtn		100 212	14	D		13
025 137	53	(			46	LBL						14
	51	SBR			12	B						15
	12	B		065 177	53	(						16
	75	−			53	(						17
	43	RCL			81	HLT		105 217				18
030 142	00	0			90	if zro						19
	04	4			10	E'						FLAGS
	54	)		070 182	42	STO						0
	55	÷			00	0						1
	43	RCL			01	1		110 222				2
035 147	00	0			40	x^2						3
	05	5			20	1/x		TEXAS INSTRUMENTS INCORPORATED				4
	30	$\sqrt{x}$		075 187	65	×						

A4.4.2 Subroutine STDNRM

Subroutine STDNRM uses Simpson's rule to estimate values of the standard normal distribution:

$$f(z^*) = \frac{1}{\sqrt{2\pi}} \int_0^{z^*} e^{-\frac{z^2}{2}} \, dz.$$

Simpson's rule approximates the integral by summing areas under parabolas as estimates of intervals of the curve f(z*):

$$\int_{x - \Delta x}^{x + \Delta x} (ax^2 + bx + c) \, dx$$

$$= \frac{\Delta x}{3} \left[g(x_0) + 4g(x_1) + 2g(x_2) + 4g(x_3) + \ldots + 2g(x_{n-2}) + 4g(x_{n-1}) + g(x_n) \right]$$

where $x_i = (i \cdot z^*)$.

The current version of STDNRM uses four (4) intervals, thus the standard normal distribution is approximated by:

$$f(z^*) = \frac{1}{\sqrt{2\pi}} \frac{3^*/4}{3} \left[g(o) + 4g(z^*) + 2g(2z^*) + 4g(3z^*) + g(4z^*) \right]$$

where $g(x) = e^{-\frac{x^2}{2}}$.

Instructions are included for increasing the precision of the approximation by using eight (8) intervals with Simpson's rule.

SR-52 User Instructions

TITLE STDNRM PAGE 1 OF 2

◄A► FIREPROB				

◄B► STDNRM				

STEP	PROCEDURE	ENTER	PRESS			DISPLAY
	STDNRM is a subroutine					
	called by FIREPROB.					
	To use STDNRM alone to					
	generate values of the					
	standard normal					
	distribution:					
1	ENTER PROGRAM		CLR	2nd	read	
			HLT	2nd	read	
	insert card-side B					
2	INITIALIZE		2nd	CMs		
			GTO	112		
3	ENTER DATA	z^*	STO	0	9	z^*
4	RUN		RUN			$f(z^*)$
	To increase the precision					
	of STDNRM, change:					
	3 in LOC 114 to 7					
	32 in LOC 135 to 128					
	2 in LOC 173 to 4					
	12 in LOC 198 to 24					

TITLE STDNRM PAGE 2 OF 2 **SR-52 Coding Form**
PROGRAMMER JW DATE 31. 1. 78

LOC	CODE	KEY	COMMENTS
000 112	46	LBL	
	15	E	
	03	3	
	42	STO	
	0	0	
005 117	0	0	
	41	GTO	
	17	B′	
	46	LBL	
	16	A′	
010 122	53	(	
	53	(	
	53	(	
	43	RCL	
	00	0	
015 127	09	9	
	65	x	
	43	RCL	
	00	0	
	07	7	
020 132	54	)	
	40	x^2	
	55	÷	
	03	3	
	02	2	
025 137	54	)	
	94	+/-	
	22	INV	
	23	ln x	
	65	x	
030 142	02	2	
	54	)	
	44	SUM	
	00	0	
	08	8	
035 147	56	rtn	
	46	LBL	
	17	B′	

LOC	CODE	KEY	COMMENTS
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	44	SUM	
040 152	00	0	
	07	7	
	51	SBR	
	16	A′	
	58	dsz	
045 157	17	B′	
	01	1	
	44	SUM	
	00	0	
	08	8	
050 162	43	RCL	
	00	0	
	09	9	
	40	x^2	
	94	+/-	
055 167	22	INV	
	23	ln x	
	30	$\sqrt{x}$	
	44	SUM	
	00	0	
060 172	08	8	
	02	2	
	42	STO	
	00	0	
	00	0	
065 177	46	LBL	
	19	D′	
	51	SBR	
	16	A′	
	02	2	
070 182	94	+/-	
	44	SUM	
	00	0	
	07	7	
	58	dsz	
075 187	19	D′	

LOC	CODE	KEY	COMMENTS
	53	(	
	53	(	
	43	RCL	
	00	0	
080 192	08	8	
	65	x	
	43	RCL	
	00	0	
	09	9	
085 197	55	÷	
	01	1	
	02	2	
	54	)	
	55	÷	
090 202	53	(	
	02	2	
	65	x	
	59	π	
	54	)	
095 207	30	$\sqrt{x}$	
	85	+	
	93	.	
	05	5	
	54	)	
100 212	41	GTO	
	13	C	
105 217			
110 222			

LABELS	
A	018
B	064
C	058
D	008
E	113
A′	121
B′	149
C′	
D′	178
E′	097
REGISTERS	
00	dsz
01	μ
02	
03	
04	X
05	$V_1 + V_2$
06	
07	coeff.
08	sum
09	z^n
10	
11	
12	
13	
14	
15	
16	
17	
18	
19	
FLAGS	
0	
1	
2	
3	
4	

TEXAS INSTRUMENTS INCORPORATED

APPENDIX A5

A5.1 Data Sources

- A5.1.1 Post-Flashover Fire Severity
- A5.1.2 Partition X
- A5.1.3 Partition Y
- A5.1.4 Pre-Flashover Fire Severity
- A5.1.5 Suppression System

A5.2 Stress-Strength Sensititivy

- A5.2.1 Output
  - A5.2.1.1 Stress-Strength Probabilities
  - A5.2.1.2 Multiparameter Sensitivity
- A5.2.2 Programs
  - A5.2.2.1 SENS
  - A5.2.2.2 PROB
  - A5.2.2.3 SIMP
  - A5.2.2.4 MSENS

A5.3 Fire Spread Sensitivity

- A5.3.1 Output
  - A5.3.1.1 Example Probabilities
  - A5.3.1.2 Sensitivity Probabilities
- A5.3.2 Programs
  - A5.3.2.1 FIRESENS
  - A5.3.2.2 FPROB

A5.1.1 Post-Flashover Fire Severity

Data from GSA figures D-39.2 and D-38.5

Midpoint of increment	"dH"	Cumulative Probability
0.0625	0.04	0.04
0.1875	0.22	0.26
0.3125	0.31	0.57
0.4375	0.26	0.83
0.5625	0.10	0.93
0.6875	0.04	0.97
0.8125	--	--
0.9375	0.02	0.99
1.0625	0.004	0.994
1.1875	0.003	0.997
1.3125	0.002	0.999
1.4375	0.001	1.000

Parameter Calculation from Plot

$P_{10} = 0.14$ $P_{50} = 0.27$ $P_{90} = 0.53$

$\mu_y = \ln P_{50} = -1.31$

$\sigma_y = 0.39\ (\ln P_{90} - \ln P_{10}) = 0.519$

$\mu_x = \exp\ (\mu_y + 1/2\sigma_y^2) = 18.5$ min.

$\sigma_x = \mu_x \sqrt{\exp\ (\sigma_y^2) - 1} = 10.3$ min.

The values of P(T/H) and P(D/H) are determined by the total probability theorem. The total probability theorem consists of the summation of all the incremential probabilities of success. The incremential probabilities of success are determined in each increment by multiplying the probability of occurrence of that increment (dH) times the average probability of success in that increment for the structural element being evaluated. Where increments have been chosen so that the slope of plot for the evaluated element is essentially a straight line, the average probability of success is directly read at the mid-point of the increment. The results of each incremental success calculations are summed. The total obtained through this summation is the probability of success of the examined element given the potential fire exposure distribution described by the plot H.

The following is an example of the calculations used in the example case to determine the probability of success of lightweight partition (X) in preventing the passage of ignition energy through the partition, P(TX/H). The inputs are dH from figure D-38.5 and the plot of TX from figure D-38.4.

Increment	dH	TX	(TX)dH
0-1/8 hours	.04	.75	.03
1/8 - 1/4	.22	.45	.099
1/4 - 3/8	.31	.22	.068
3/8 - 1/2	.26	.12	.031
1/2 - 5/8	.10	.08	.008
5/8 - 3/4	.04	.05	.002
7/8 - 1	.02	.03	.0006
1 - 1 1/8	.004	.02	.00008
1 1/8 - 1 1/4	.003	.01	
1 1/4 - 1 3/8	.002		
1 3/8 - 1 1/2	.001		
Summations	1.00		0.23868 (0.24)

The values of the other fire severity conditional structural element probabilities needed for example cases are developed by the same process. The values of all of these are:

P(TX/H) = 0.24	Thermal capability of partion X.
P(DX/H) = 0.72	Structural capability of partion X.
P(TY/H) = 0.997	Thermal capability of partion Y.
P(DY/H) = 0.9997	Structural capability of partion Y.
P(TF/H) = 0.998	Thermal capability of the floor system.
P(DF/H)= 0.9986	Structural capability of the floor system.
P(DFr/H) = 0.99987	Structural capability of the building frame.

Figure D-39.2 Calculating Probability of Success of (Part 2 of 2) Compartmentation Elements

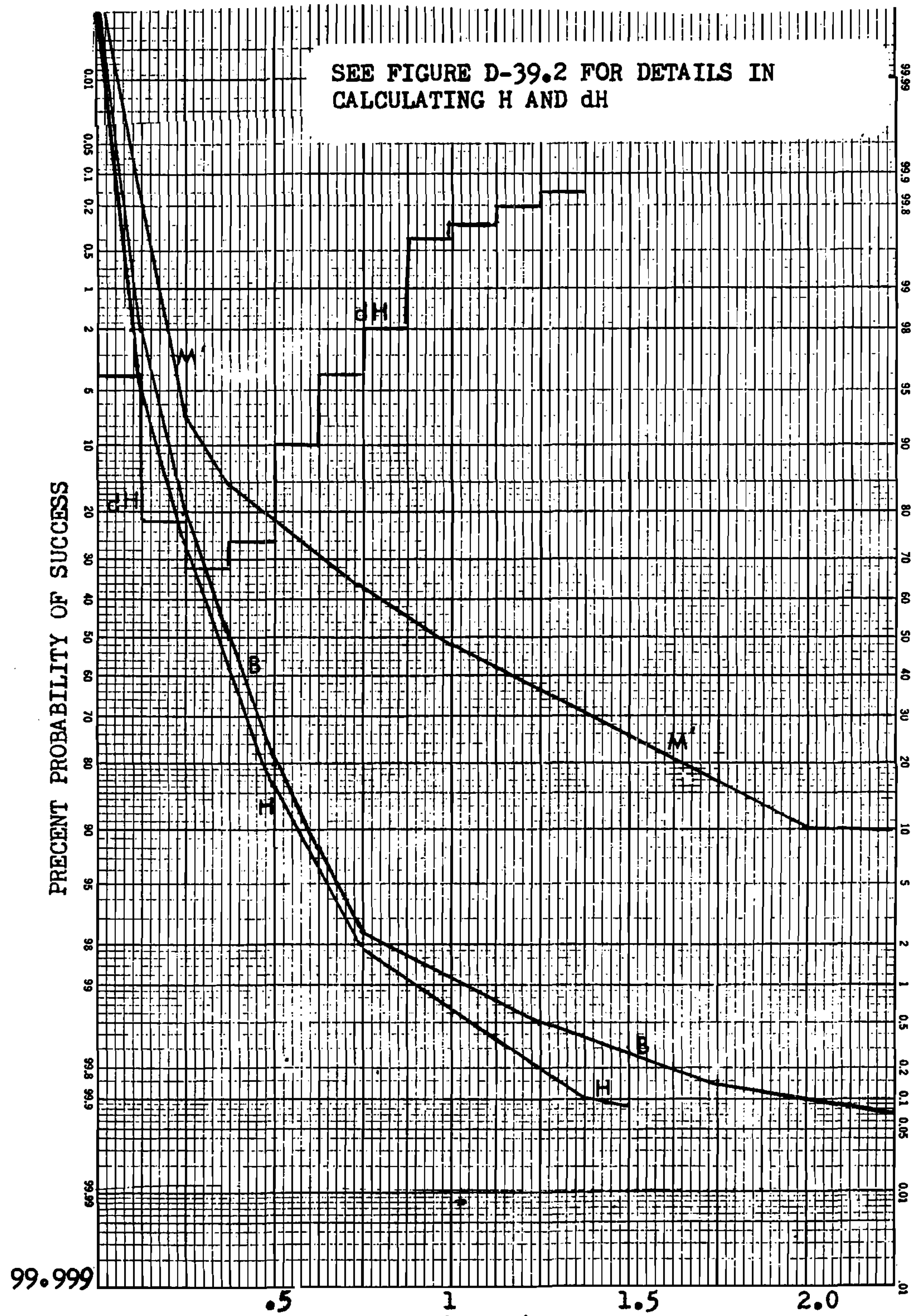
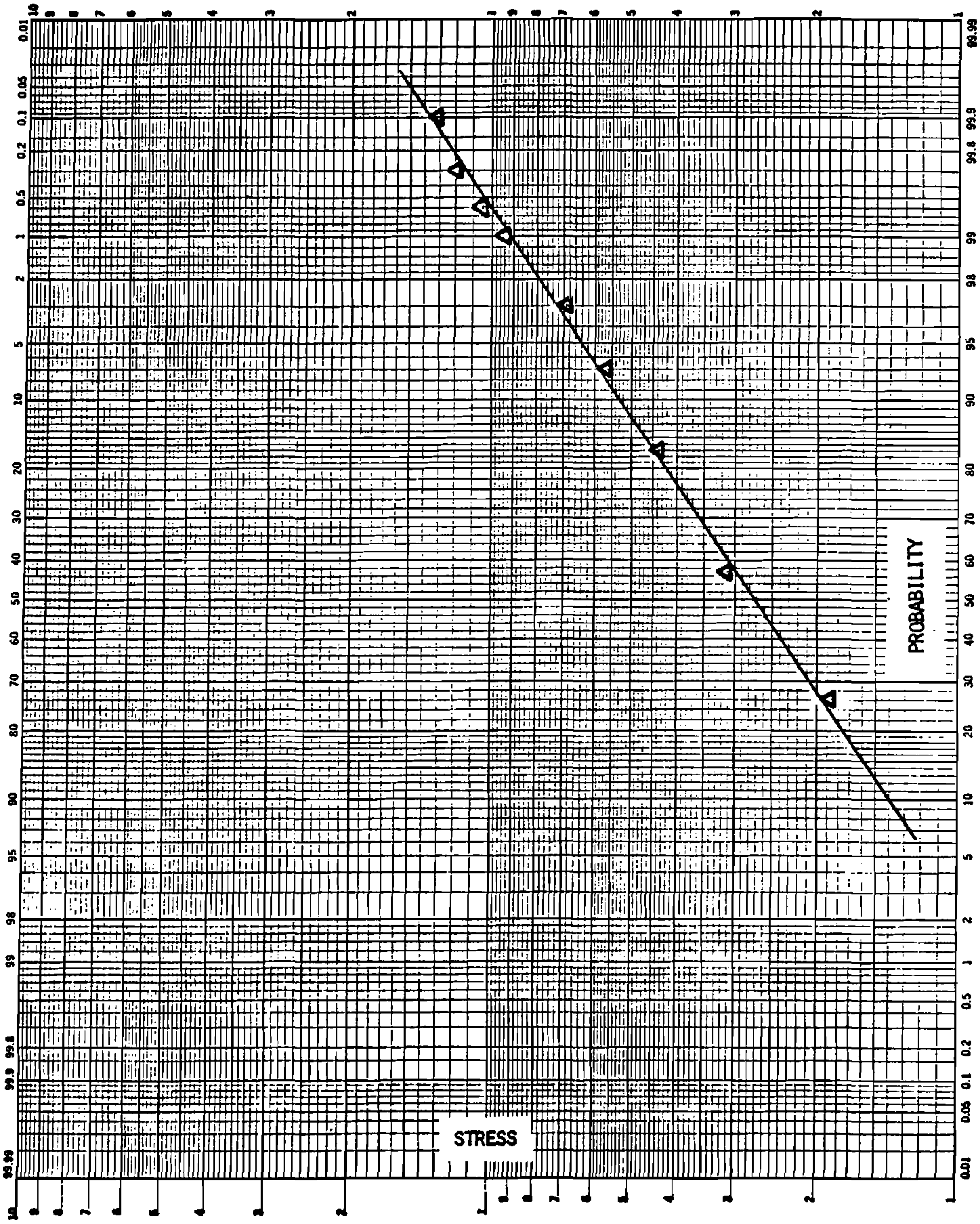


Figure D-38.5 Severity Determinations

A5.1.1 Post-Flashover Fire Severity



A5.1.2 Partition X Resistance

Data from GSA figure D-38.4

hours	T	D	T x D
0.125	0.56	0.993	0.556
0.25	0.28	0.915	0.256
0.375	0.15	0.69	0.104
0.5	0.08	0.50	0.040
0.625	0.04	0.35	0.014
0.75	0.02	0.25	0.005
0.875	0.01	0.15	0.0015
1.0	0.01	0.08	0.0008
1.125	0.005	0.04	0.0002

Parameter Calculation from Plot

$P_{10} = 0.33$ $P_{50} = 0.14$ $P_{90} = 0.06$

$\mu_y = \ln P_{50} = -1.966$

$\sigma_y = 0.39 (\ln P_{90} - \ln P_{10}) = -0.665$

$\mu_x = \exp (\mu_y + 1/2\sigma_y^2) = 10.5$ min.

$\sigma_x = \mu_x \sqrt{\exp(\sigma_y^2) - 1} = 7.8$ min.

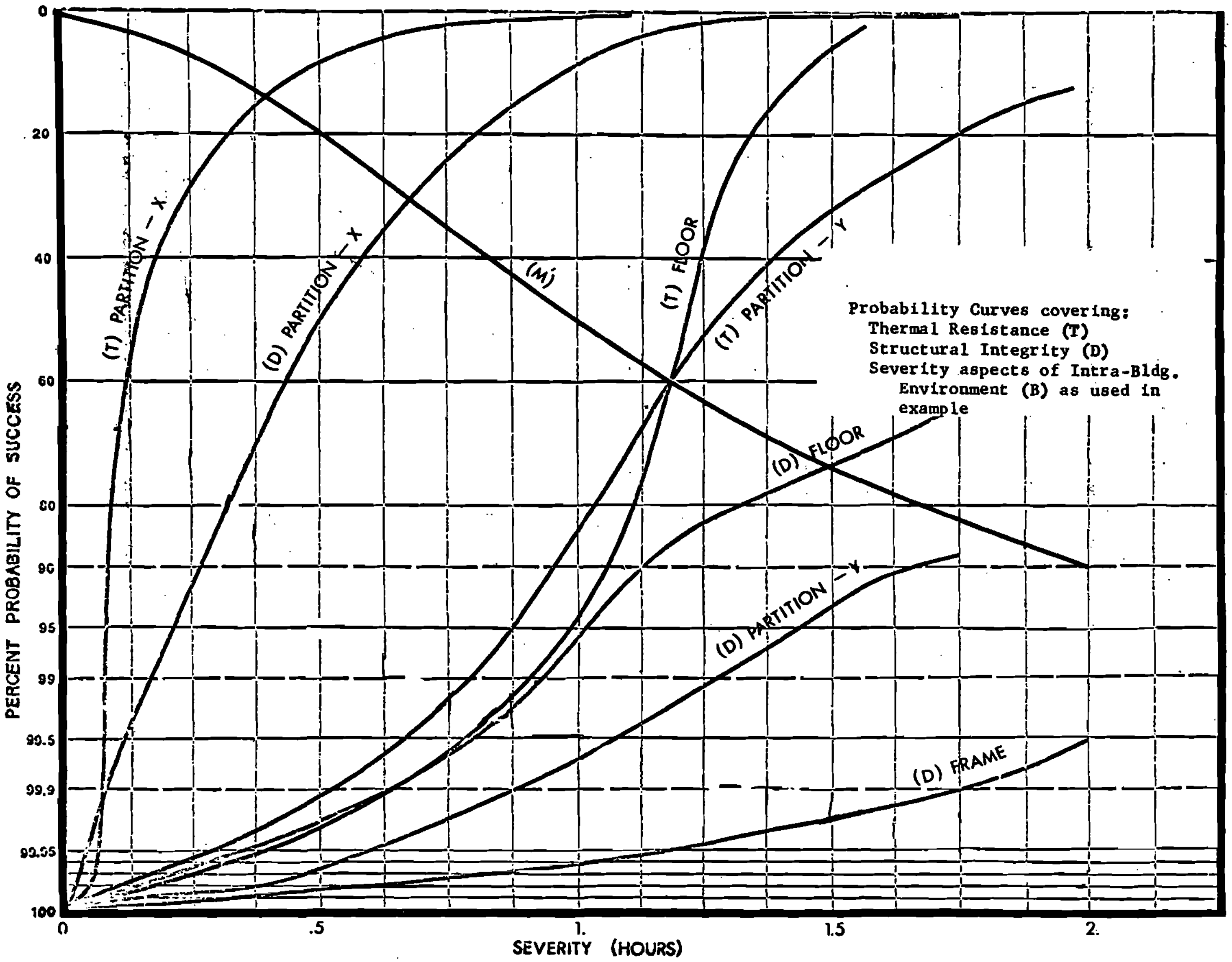
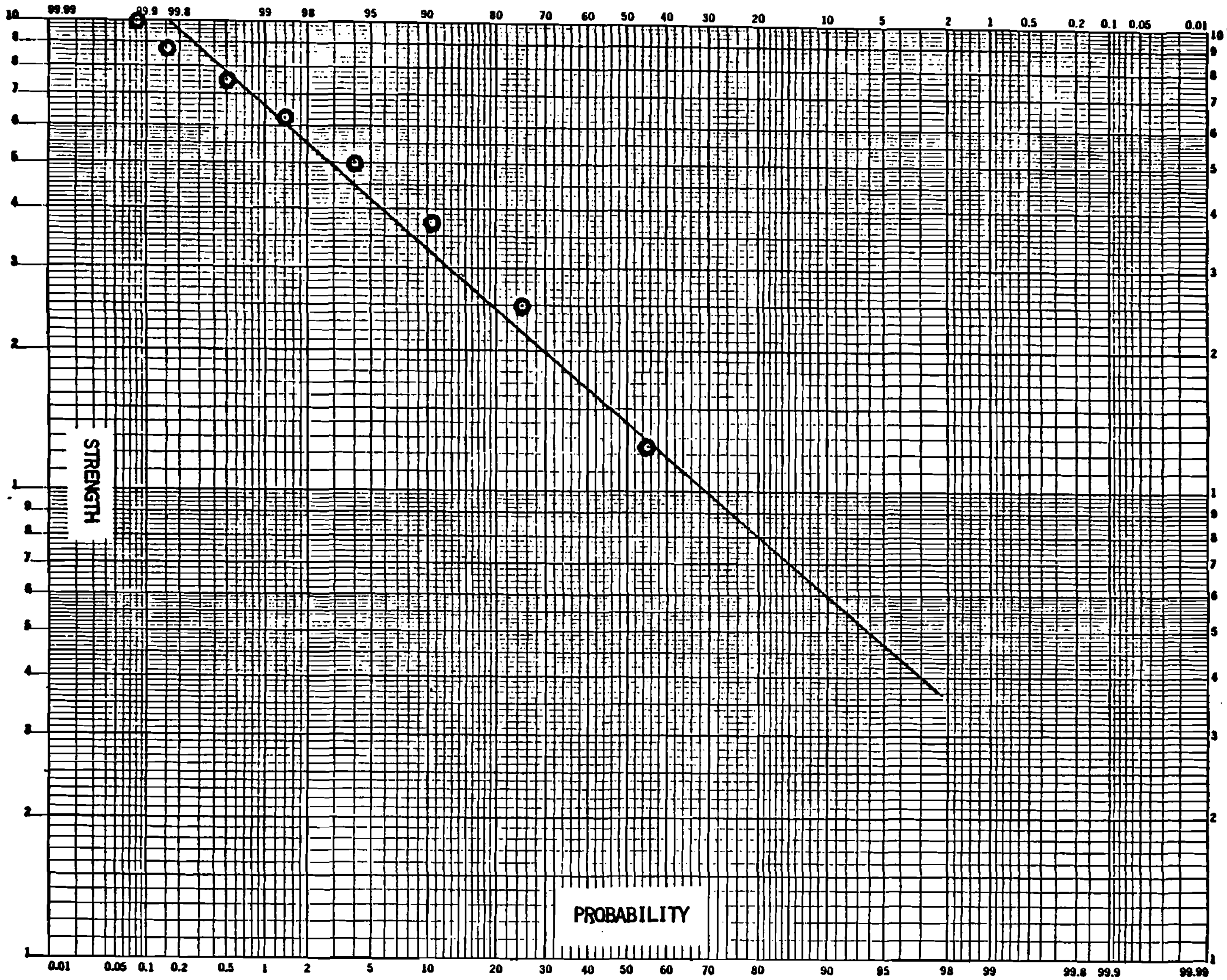


Figure D-38.4 Example Input Severity



A5.1.2 Partition X

A5.1.3 Partition X Resistance

Data from GSA figure D-38.4

hours	T	D	T x D
0.25	0.99955	0.99985	0.9994
0.375	0.9993	0.9998	0.9991
0.5	0.9991	0.99955	0.9986
0.625	0.996	0.9994	0.9954
0.75	0.991	0.9992	0.9902
0.875	0.95	0.999	0.949
1.0	0.84	0.997	0.837
1.125	0.67	0.994	0.666
1.25	0.52	0.991	0.515
1.375	0.41	0.975	0.396
1.5	0.32	0.93	0.298
1.625	0.26	0.905	0.235
1.75	0.20	0.88	0.176

Parameter Calculation from Plot

$P_{10} = 2.0$ $P_{50} = 1.3$ $P_{90} = 0.84$

$\mu_y = \ln P_{50} = 0.26$

$\sigma_y = 0.39 (\ln P_{90} - \ln P_{10}) = -0.338$

$\mu_x = \exp (\mu_y + 1/2\sigma_y^2) = 82.6$ min.

$\sigma_x = \mu_x \sqrt{\exp (\sigma_y^2) -1} = 28.8$ min.

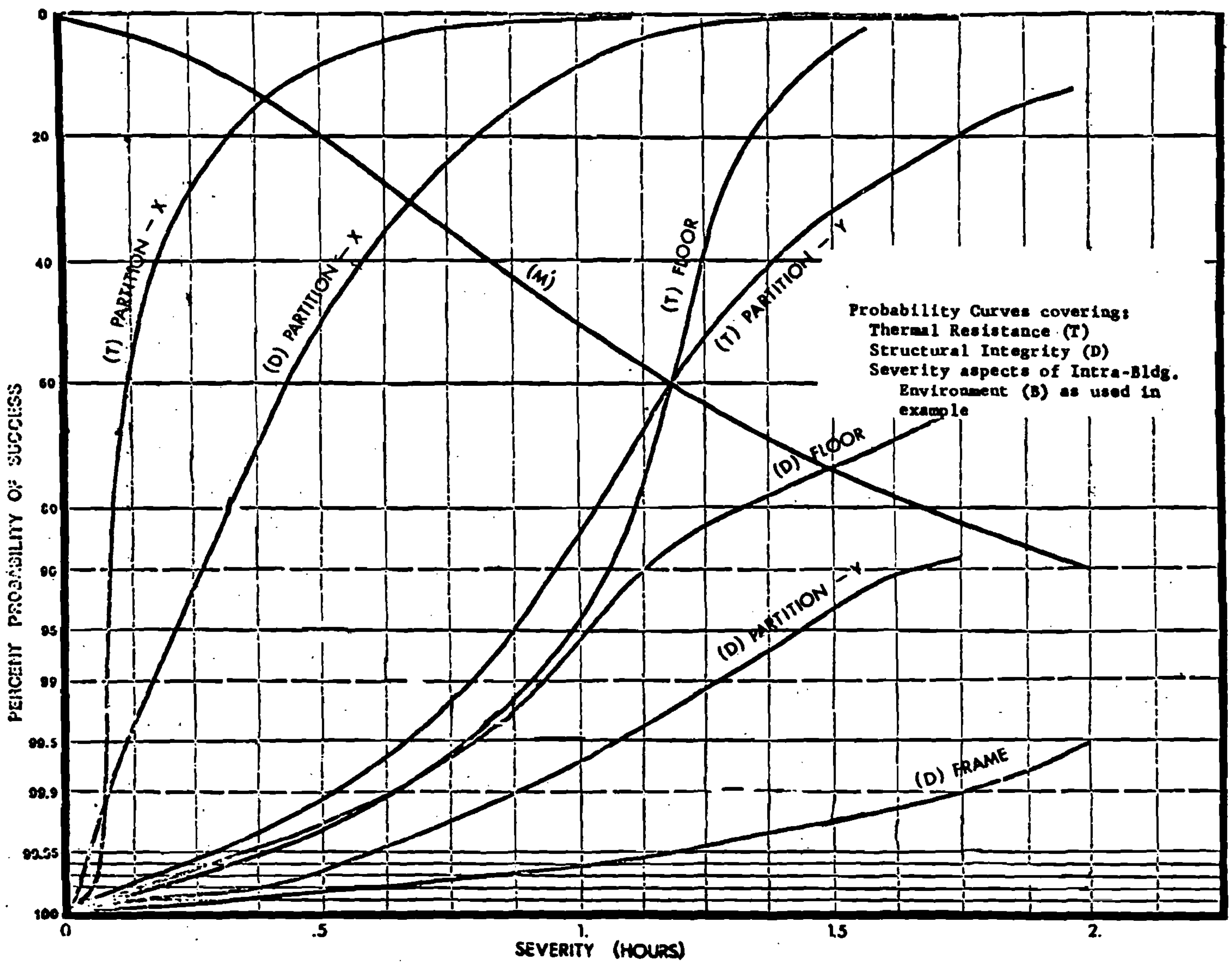
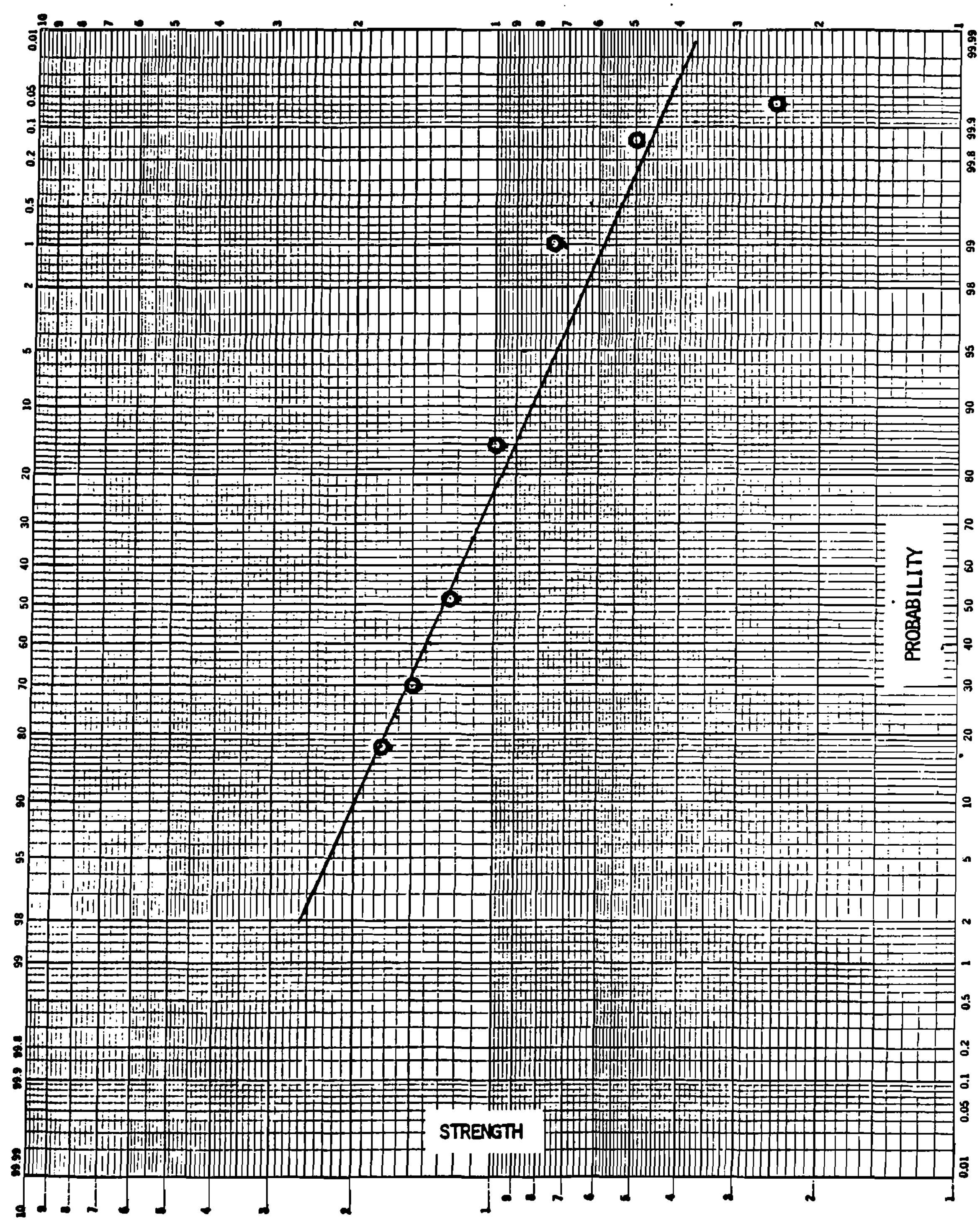


Figure D-38.4 Example Input Severity

A5.1.3 Partition Y



A5.1.4 Pre-Flashover Fire Severity

Data from GSA figure D-19.1

Density	Control (o)	Extinguish (Δ)
0.075	0.80	0.75
0.1	0.95	0.80
0.2	0.99	0.97

Parameter Calculation from Plot

$P_{10} = 0.015$ $P_{50} = 0.04$ $P_{90} = 0.11$

$\mu_y = \ln P_{50} = -3.22$

$\sigma_y = 0.39\ (\ln P_{90} - \ln P_{10}) = 0.78$

$\mu_x = \exp\ (\mu_y + 1/2\sigma_y^2) = 0.054$

$\sigma_x = \mu_x \sqrt{\exp(\sigma_y^2) - 1} = 0.049$

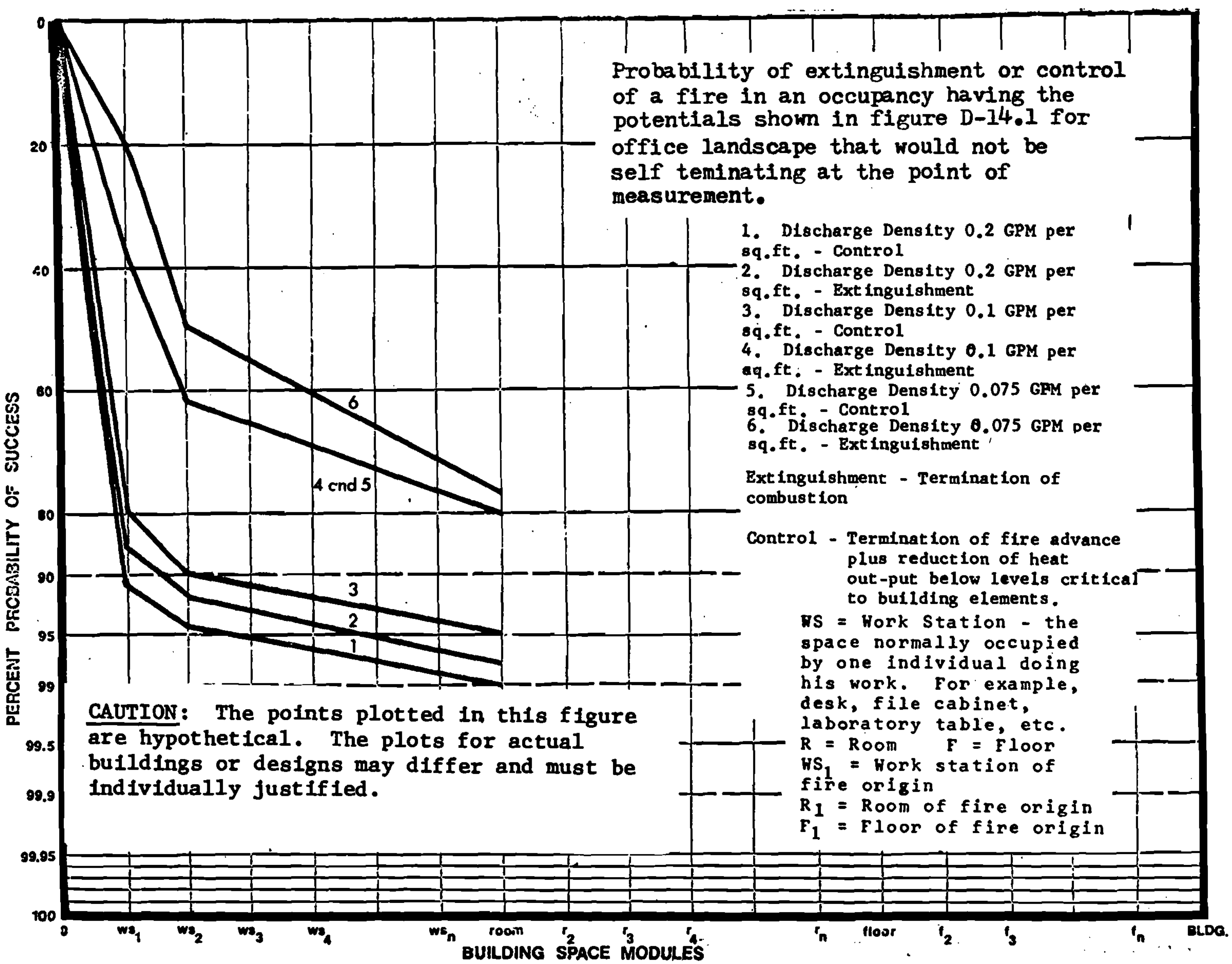
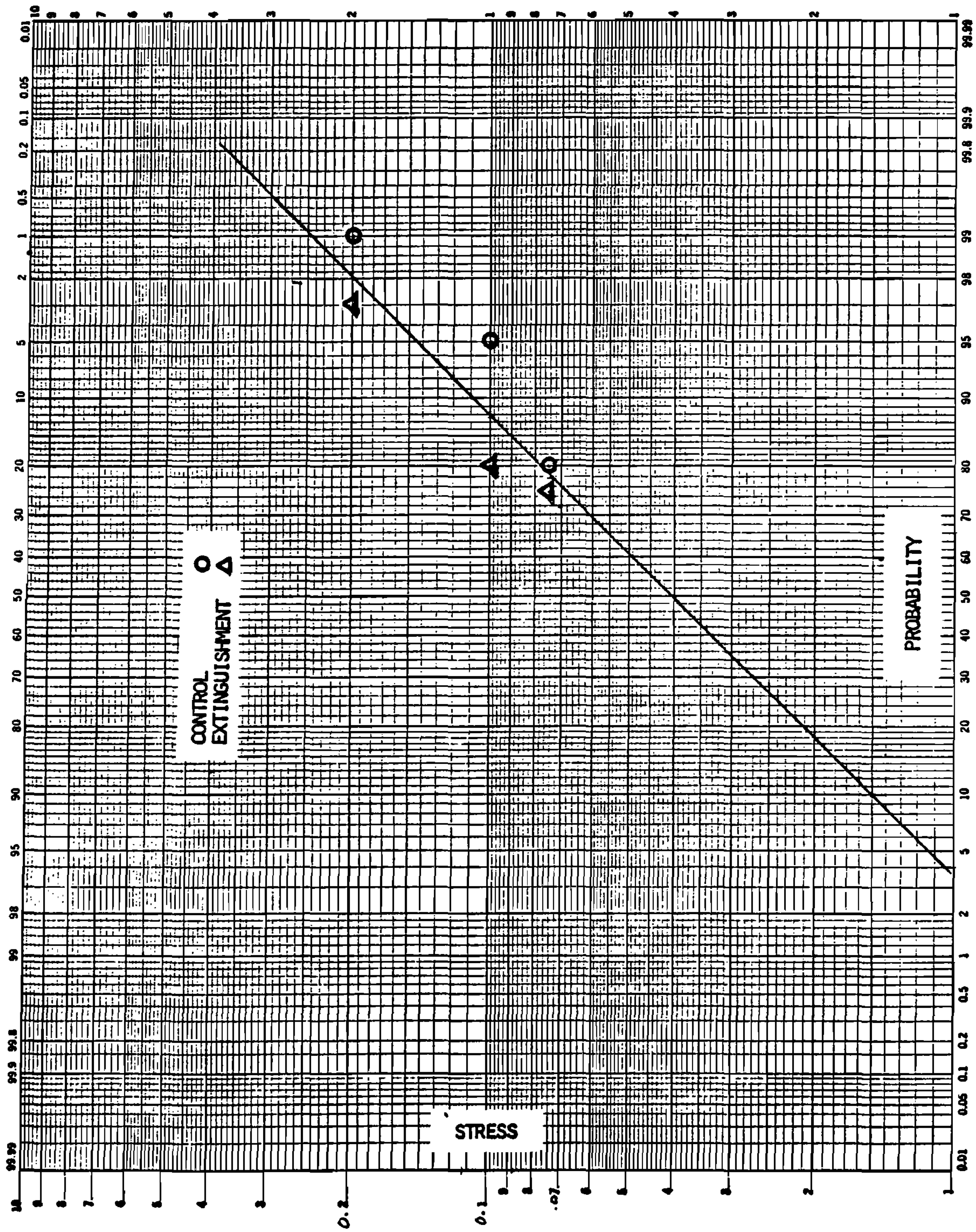


Figure D-19.1 Automatic Sprinklers Success Probability - Various Discharge Rates

A5.1.4 Pre-Flashover Fire Severity



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A5.1.5 Suppression System

Data from GSA figure D-19.1

0.075 gpm/ft^2 Probability of control = 0.80

0.1 gpm/ft^2 Probability of extinguishment = 0.80

Therefore, assume the difference between extinguishment and control is 0.025 gpm/ft^2

Design density for examples is assumed to be 0.1 gpm/ft^2
(Curve A of GSA figure D-38.2 corresponds to office landscape curve of GSA figure D-19.2 which represents a sustained discharge of 0.1 gpm/ft^2)

Find distribution between control and extinguishment about 0.1 gpm/ft^2 density:

Probability of control = 0.95, control density = 0.1 - 0.025/2 = 0.0875

Probability of extinguishment = 0.80, extinguishment density = 0.1 + 0.025/2 = 0.1125

Parameter Calculation from Plot

$P_{10} = 0.215$ $P_{50} = 0.145$ $P_{90} = 0.098$

$\mu_y = \ln P_{50} = -1.93$

$\sigma_y = 0.39 (\ln P_{90} - \ln P_{10}) = 0.306$

$\mu_x = \exp (\mu_y + 1/2\sigma_y^2) = 0.152$

$\sigma_x = \mu_x \sqrt{\exp (\sigma_y^2) - 1} = 0.048$

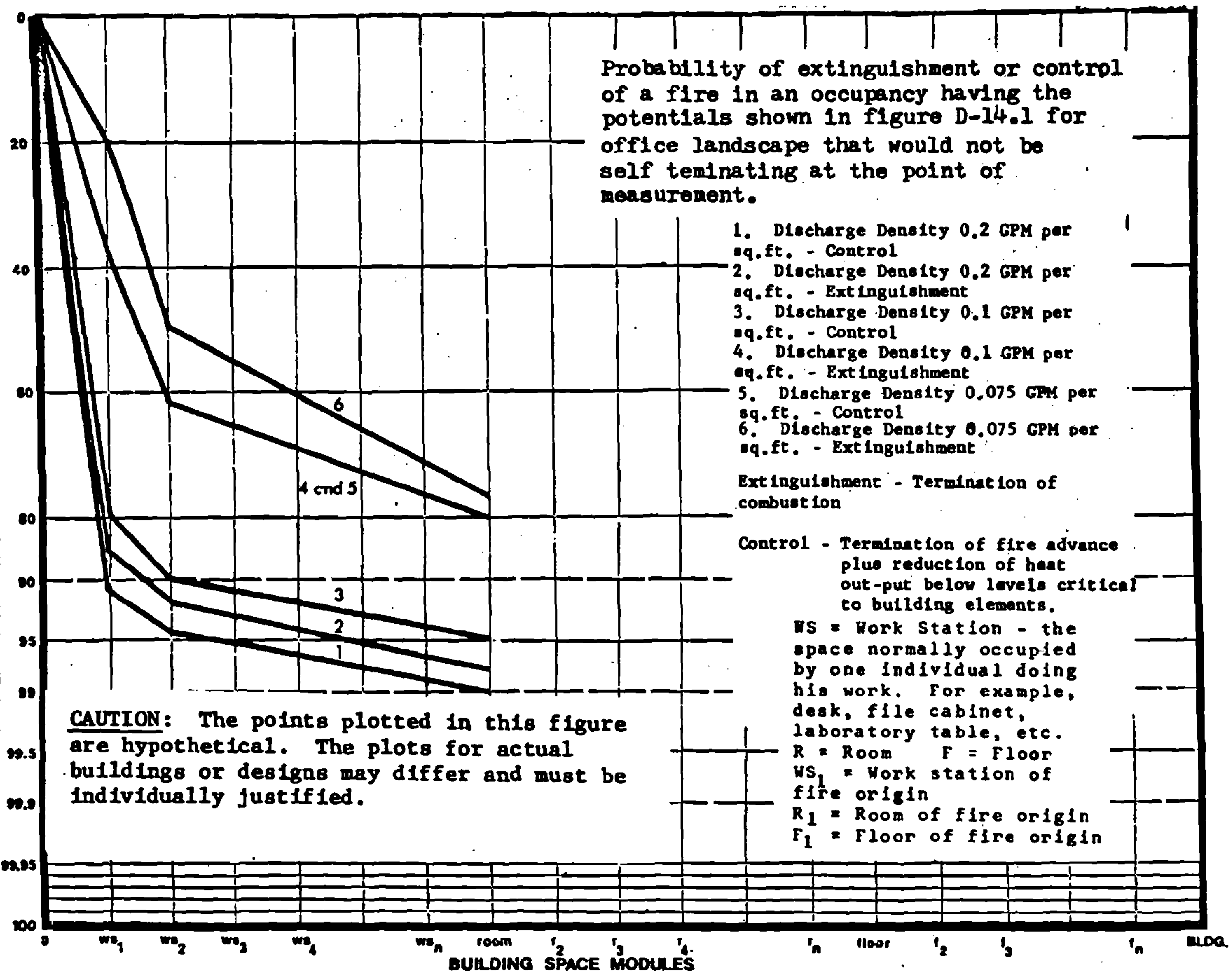


Figure D-19.1 Automatic Sprinklers Success Probability - Various Discharge Rates

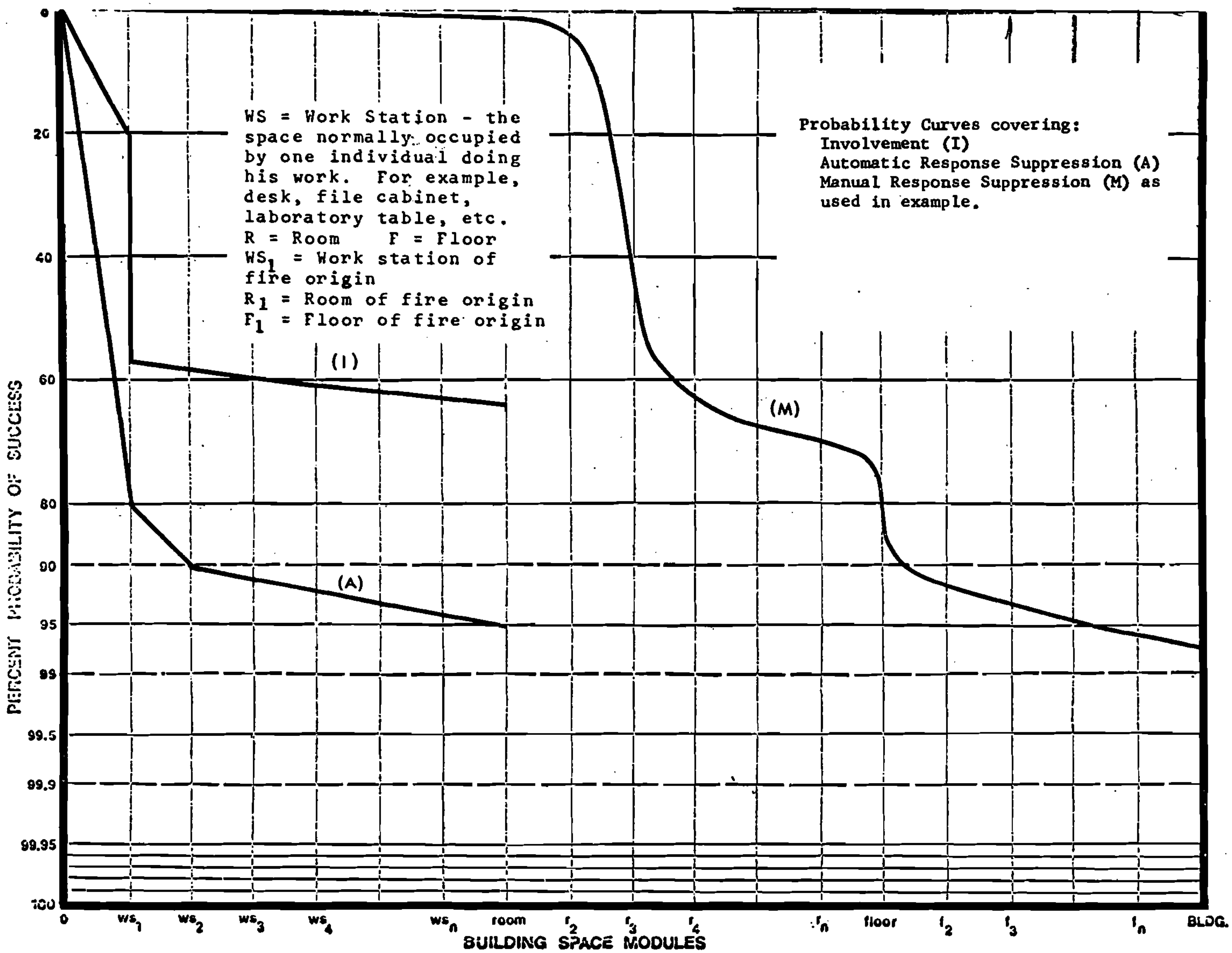


Figure D-38.2 Example Input Space Modules

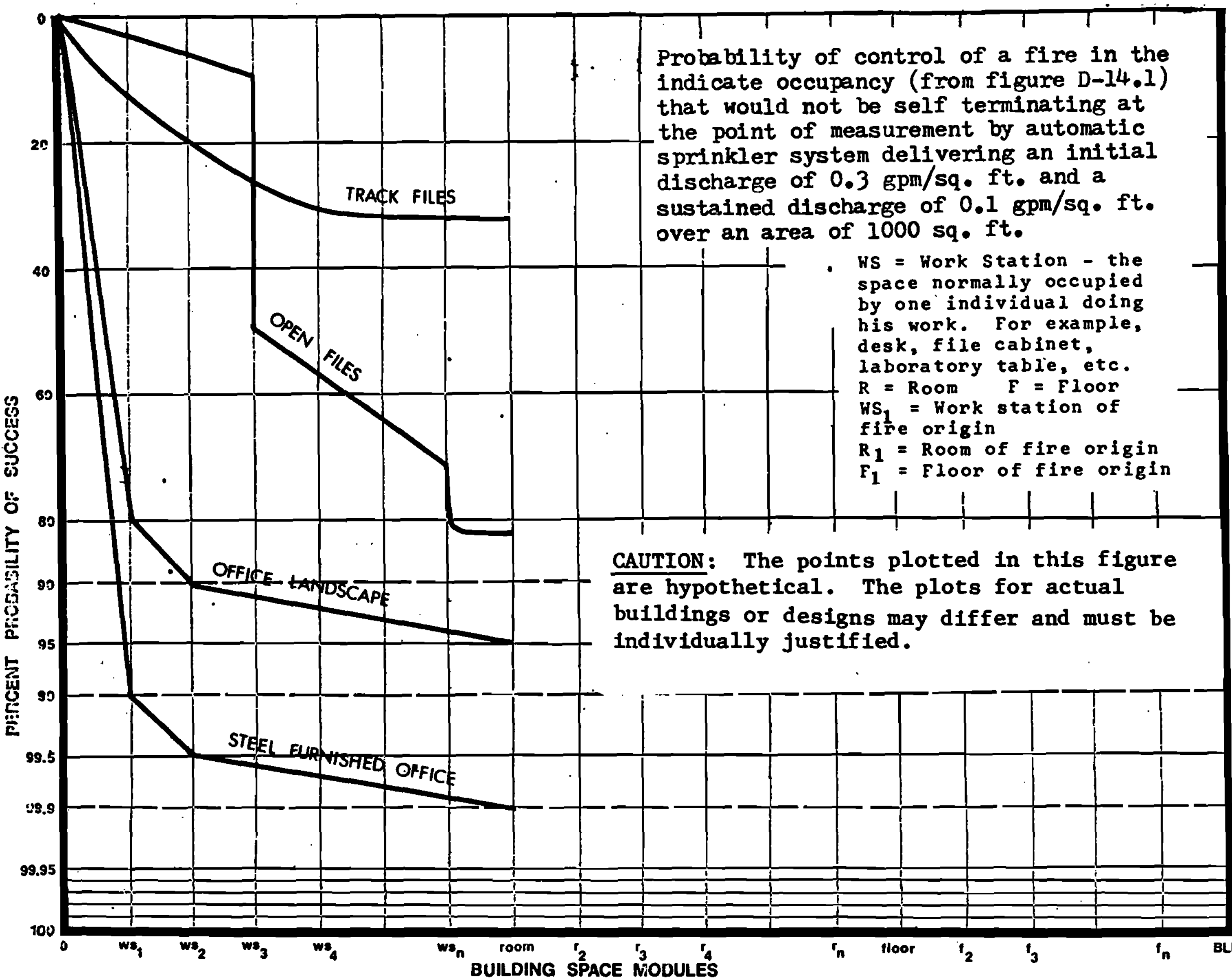
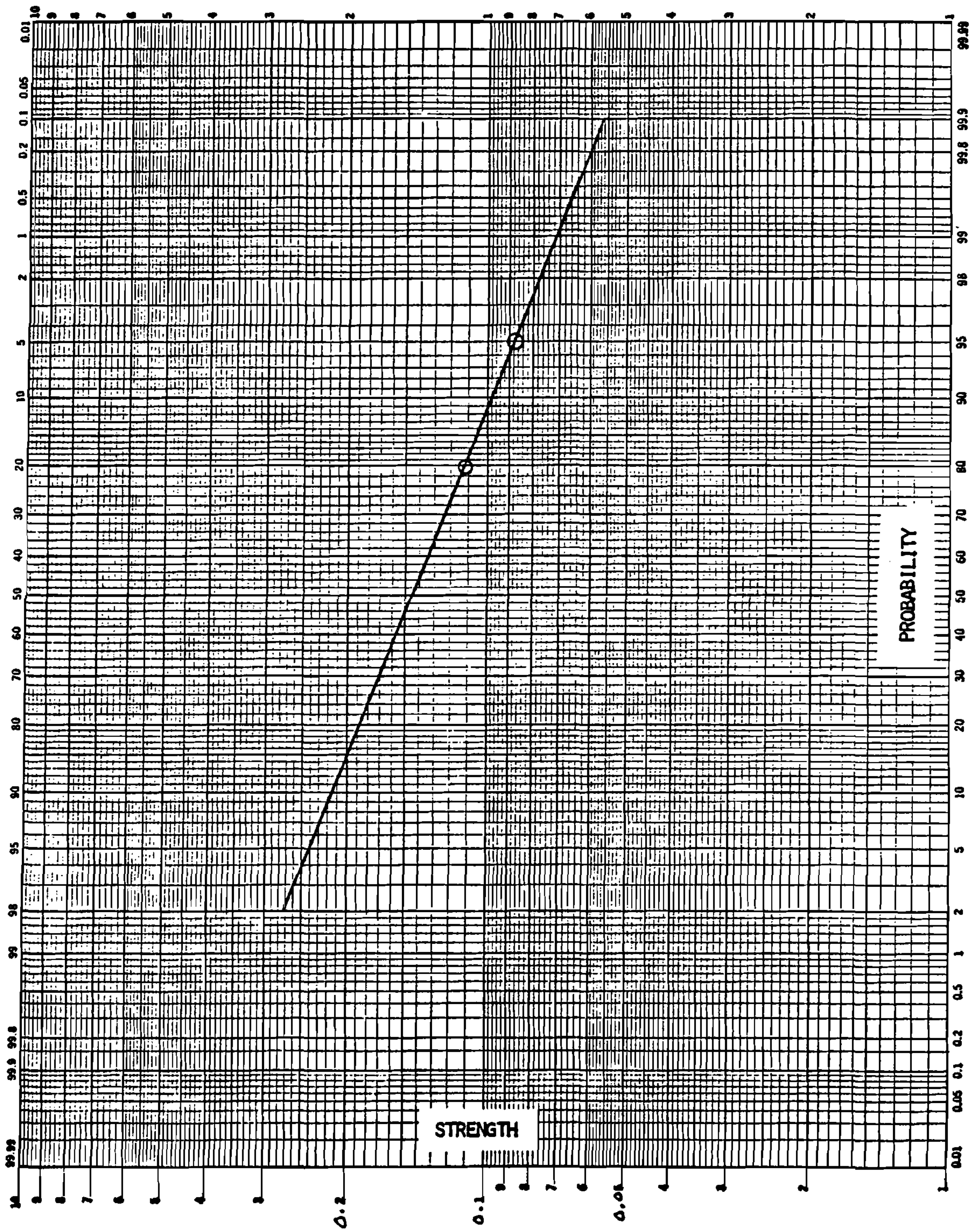


Figure D-19.2 Automatic Sprinklers Success Probability - Various Fuel Loads

A5.1.5 Suppression System



STRESS-STRENGTH PROBABILITIES FOR LOGNORMAL DISTRIBUTIONS

DIST 1: X, S		DIST 2: X, S		MEAN	SIGMA	PROB	PERCENT
18.500	10.300	10.500	7.800	-.65111	.84229	.21975	
1.850	10.300	10.500	7.800	3.24930	1.97613	.94994	332.28
3.700	10.300	10.500	7.800	1.90782	1.61506	.88125	301.02
5.550	10.300	10.500	7.800	1.16366	1.38962	.79891	263.50
7.400	10.300	10.500	7.800	.66893	1.23165	.70648	221.49
9.250	10.300	10.500	7.800	.31025	1.11619	.60948	177.35
11.100	10.300	10.500	7.800	.03528	1.02984	.51366	133.75
12.950	10.300	10.500	7.800	-.19435	.96417	.42418	93.03
14.800	10.300	10.500	7.800	-.36549	.91346	.34454	56.78
16.650	10.300	10.500	7.900	-.51874	.87377	.27636	25.76
18.500	10.300	10.500	7.800	-.65111	.84229	.21975	.00
20.350	10.300	10.500	7.800	-.76739	.81702	.17390	-20.91
22.200	10.300	10.500	7.800	-.87096	.79649	.13709	-37.62
24.050	10.300	10.500	7.800	-.96428	.77965	.10908	-50.82
25.900	10.300	10.500	7.800	-1.04917	.76568	.08530	-61.16
27.750	10.300	10.500	7.800	-1.12705	.75399	.06749	-69.29
29.600	10.300	10.500	7.900	-1.19897	.74413	.05356	-75.63
31.450	10.300	10.500	7.800	-1.26580	.73575	.04268	-80.58
33.300	10.300	10.500	7.800	-1.32822	.72857	.03415	-84.46
35.150	10.300	10.500	7.800	-1.39678	.72237	.02745	-87.51
37.000	10.300	10.500	7.800	-1.44194	.71699	.02216	-89.92
18.500	10.300	1.050	7.800	-4.74829	2.07332	.01101	-94.99
18.500	10.300	2.100	7.800	-3.38800	1.72173	.02455	-88.83
18.500	10.300	3.150	7.800	-2.61763	1.45484	.03996	-81.81
18.500	10.300	4.200	7.800	-2.09402	1.32766	.05737	-73.89
18.500	10.300	5.250	7.800	-1.70726	1.15810	.07708	-64.92
18.500	10.300	6.300	7.800	-1.40689	1.09516	.09946	-54.74
18.500	10.300	7.350	7.800	-1.16523	1.01210	.12480	-43.21
18.500	10.300	8.400	7.800	-.96543	.94435	.15331	-30.23
18.500	10.300	9.450	7.800	-.79653	.88858	.18502	-15.81
18.500	10.300	10.500	7.800	-.65111	.84229	.21975	.00
18.500	10.300	11.550	7.800	-.52395	.80358	.25720	17.04
18.500	10.300	12.600	7.800	-.41128	.77099	.29686	35.09
18.500	10.300	13.650	7.800	-.31031	.74336	.33818	53.89
18.500	10.300	14.700	7.800	-.21895	.71978	.38049	73.14
18.500	10.300	15.750	7.800	-.13560	.69954	.42315	92.56
18.500	10.300	16.800	7.800	-.05899	.68207	.46554	111.85
18.500	10.300	17.850	7.800	.01186	.66690	.50710	130.76
18.500	10.300	18.900	7.800	.07776	.65367	.54734	149.07
18.500	10.300	19.950	7.800	.13934	.64207	.58590	166.62
18.500	10.300	21.000	7.800	.19714	.63186	.62248	183.26
18.500	1.030	10.500	7.900	-.78457	.66523	.11912	-45.79
18.500	2.060	10.500	7.800	-.77995	.67213	.12294	-44.06
18.500	3.090	10.500	7.800	-.77236	.68334	.12918	-41.22
18.500	4.120	10.500	7.800	-.76191	.69846	.13767	-37.35
18.500	5.150	10.500	7.800	-.74880	.71659	.14816	-32.58
18.500	6.180	10.500	7.800	-.73322	.73840	.16036	-27.03
18.500	7.210	10.500	7.800	-.71541	.76213	.17394	-20.85
18.500	8.240	10.500	7.800	-.69563	.78766	.18858	-14.19
18.500	9.270	10.500	7.800	-.67411	.81452	.20394	-7.19
18.500	10.300	10.500	7.800	-.65111	.84229	.21975	.00
18.500	11.330	10.500	7.800	-.62686	.87060	.23575	7.28
18.500	12.360	10.500	7.800	-.60159	.89916	.25173	14.55
18.500	13.390	10.500	7.800	-.57549	.92773	.26752	21.74
18.500	14.420	10.500	7.800	-.54876	.95611	.28300	28.78
18.500	15.450	10.500	7.800	-.52155	.98416	.29807	35.64
18.500	16.480	10.500	7.800	-.49402	1.01175	.31267	42.28
18.500	17.510	10.500	7.800	-.46628	1.03880	.32676	48.69
18.500	18.540	10.500	7.800	-.43846	1.06525	.34031	54.86
18.500	19.570	10.500	7.800	-.41064	1.09105	.35332	60.78
18.500	20.600	10.500	7.800	-.38290	1.11619	.36578	66.45
18.500	10.300	10.500	.780	-.43414	.52489	.20409	-7.13
18.500	10.300	10.500	1.560	-.44231	.54023	.20647	-6.05
18.500	10.300	10.500	2.340	-.45563	.56434	.20973	-4.56
18.500	10.300	10.500	3.120	-.47370	.59550	.21317	-2.99
18.500	10.300	10.500	3.900	-.49601	.63186	.21623	-1.60
18.500	10.300	10.500	4.680	-.52199	.67173	.21855	-.55
18.500	10.300	10.500	5.460	-.55106	.71368	.22002	.12
18.500	10.300	10.500	6.240	-.58262	.75661	.22064	.40
18.500	10.300	10.500	7.020	-.61613	.79968	.22051	.34
18.500	10.300	10.500	7.800	-.65111	.84229	.21975	.00
18.500	10.300	10.500	8.580	-.68712	.88401	.21850	-.57
18.500	10.300	10.500	9.360	-.72379	.92456	.21686	-1.32
18.500	10.300	10.500	10.140	-.76082	.96378	.21493	-2.19
18.500	10.300	10.500	10.920	-.79796	1.00157	.21281	-3.16
18.500	10.300	10.500	11.700	-.83499	1.03789	.21055	-4.19
18.500	10.300	10.500	12.480	-.87176	1.07273	.20821	-5.25
18.500	10.300	10.500	13.260	-.90815	1.10613	.20582	-6.34
18.500	10.300	10.500	14.040	-.94404	1.13812	.20342	-7.43
18.500	10.300	10.500	14.820	-.97938	1.16876	.20102	-8.52
18.500	10.300	10.500	15.600	-1.01411	1.19810	.19866	-9.60

STRESS-STRENGTH PROBABILITIES FOR LOGNORMAL DISTRIBUTIONS

DIST 1: X, S		DIST 2: X, S		MEAN	SIGMA	PROB	PERCENT
18.500	10.300	82.600	28.800	1.57388	.62027	.99442	
1.850	10.300	82.600	28.800	5.47429	1.89219	.99809	.37
3.700	10.300	82.600	28.800	4.13281	1.51120	.99688	.25
5.550	10.300	82.600	28.800	3.38865	1.26741	.99625	.18
7.400	10.300	82.600	28.800	2.89392	1.09190	.99598	.16
9.250	10.300	82.600	28.800	2.53524	.95977	.99587	.15
11.100	10.300	82.600	28.800	2.26027	.85783	.99579	.14
12.950	10.300	82.600	28.800	2.04064	.77776	.99565	.12
14.800	10.300	82.600	28.800	1.85950	.71393	.99540	.10
16.650	10.300	82.600	28.800	1.70625	.66239	.99500	.06
18.500	10.300	82.600	28.800	1.57388	.62027	.99442	.00
20.350	10.300	82.600	28.800	1.45760	.58550	.99360	-.08
22.200	10.300	82.600	28.800	1.35403	.55650	.99252	-.19
24.050	10.300	82.600	28.800	1.26071	.53211	.99109	-.33
25.900	10.300	82.600	28.800	1.17582	.51142	.98925	-.52
27.750	10.300	82.600	28.800	1.09794	.49376	.98691	-.75
29.600	10.300	82.600	28.800	1.02602	.47857	.98398	-1.05
31.450	10.300	82.600	28.800	.95919	.46542	.98034	-1.42
33.300	10.300	82.600	28.800	.89677	.45398	.97588	-1.86
35.150	10.300	82.600	28.800	.83821	.44397	.97049	-2.41
37.000	10.300	82.600	28.800	.78305	.43516	.96402	-3.06
18.500	10.300	8.260	28.800	-1.95982	1.68729	.12272	-87.66
18.500	10.300	16.520	28.800	-.67622	1.25076	.30018	-69.81
18.500	10.300	24.780	28.800	-.00010	1.06054	.49996	-49.72
18.500	10.300	33.040	28.800	.43235	.91350	.68192	-31.42
18.500	10.300	41.300	28.800	.73996	.81626	.81767	-17.77
18.500	10.300	49.560	28.800	.97495	.74897	.90349	-9.14
18.500	10.300	57.820	28.800	1.16376	.70117	.95152	-4.31
18.500	10.300	66.080	28.800	1.32114	.66628	.97631	-1.82
18.500	10.300	74.340	28.800	1.45597	.64019	.98852	-.59
18.500	10.300	82.600	28.800	1.57388	.62027	.99442	.00
18.500	10.300	90.860	28.800	1.67869	.60477	.99725	.28
18.500	10.300	99.120	28.800	1.77304	.59250	.99862	.42
18.500	10.300	107.380	28.800	1.85888	.58265	.99929	.49
18.500	10.300	115.640	28.800	1.93763	.57462	.99963	.52
18.500	10.300	123.900	28.800	2.01040	.56801	.99980	.54
18.500	10.300	132.160	28.800	2.07805	.56250	.99989	.55
18.500	10.300	140.420	28.800	2.14127	.55787	.99994	.56
18.500	10.300	148.680	28.800	2.20061	.55394	.99996	.56
18.500	10.300	156.940	28.800	2.25654	.55057	.99998	.56
18.500	10.300	165.200	28.800	2.30942	.54768	.99999	.56
18.500	1.030	82.600	28.800	1.44042	.34326	.99999	.56
18.500	2.060	82.600	28.800	1.44504	.35644	.99997	.56
18.500	3.090	82.600	28.800	1.45263	.37715	.99994	.56
18.500	4.120	82.600	28.800	1.46308	.40350	.99985	.55
18.500	5.150	82.600	28.800	1.47619	.43516	.99965	.53
18.500	6.180	82.600	28.800	1.49177	.46960	.99925	.49
18.500	7.210	82.600	28.800	1.50958	.50610	.99857	.42
18.500	8.240	82.600	28.800	1.52936	.54379	.99754	.31
18.500	9.270	82.600	28.800	1.55088	.58201	.99615	.17
18.500	10.300	82.600	28.800	1.57388	.62027	.99442	.00
18.500	11.330	82.600	28.800	1.59813	.65821	.99241	-.20
18.500	12.360	82.600	28.800	1.62340	.69555	.99020	-.42
18.500	13.390	82.600	28.800	1.64950	.73210	.98787	-.66
18.500	14.420	82.600	28.800	1.67623	.76775	.98549	-.90
18.500	15.450	82.600	28.800	1.70344	.80241	.98312	-1.14
18.500	16.480	82.600	28.800	1.73097	.83602	.98080	-1.37
18.500	17.510	82.600	28.800	1.75870	.86856	.97856	-1.59
18.500	18.540	82.600	28.800	1.78653	.90002	.97642	-1.81
18.500	19.570	82.600	28.800	1.81435	.93042	.97441	-2.01
18.500	20.600	82.600	28.800	1.84209	.95977	.97253	-2.20
18.500	10.300	82.600	2.880	1.63064	.52075	.99913	.47
18.500	10.300	82.600	5.760	1.62882	.52427	.99905	.47
18.500	10.300	82.600	8.640	1.62580	.52999	.99892	.45
18.500	10.300	82.600	11.520	1.62161	.53784	.99871	.43
18.500	10.300	82.600	14.400	1.61627	.54768	.99842	.40
18.500	10.300	82.600	17.280	1.60983	.55933	.99800	.36
18.500	10.300	82.600	20.160	1.60231	.57260	.99743	.30
18.500	10.300	82.600	23.040	1.59378	.58731	.99667	.23
18.500	10.300	82.600	25.920	1.59428	.60327	.99568	.13
18.500	10.300	82.600	28.800	1.57388	.62027	.99442	.00
18.500	10.300	82.600	31.680	1.56263	.63816	.99283	-.16
18.500	10.300	82.600	34.560	1.55058	.65676	.99089	-.35
18.500	10.300	82.600	37.440	1.53782	.67592	.98855	-.59
18.500	10.300	82.600	40.320	1.52438	.69551	.98580	-.87
18.500	10.300	82.600	43.200	1.51035	.71540	.98262	-1.19
18.500	10.300	82.600	46.080	1.49577	.73550	.97901	-1.55
18.500	10.300	82.600	48.960	1.48070	.75571	.97496	-1.96
18.500	10.300	82.600	51.840	1.46520	.77595	.97050	-2.40
18.500	10.300	82.600	54.720	1.44932	.79616	.96565	-2.89
18.500	10.300	82.600	57.600	1.43311	.81626	.96043	-3.42

STRESS-STRENGTH PROBABILITIES FOR LOGNORMAL DISTRIBUTIONS

DIST 1: X	S	DIST 2: X	S	MEAN	SIGMA	PROB	PERCENT
.054	.049	.152	.048	1.28772	.83412	.93868	
.005	.049	.152	.048	5.50141	2.12555	.99518	6.02
.011	.049	.152	.048	4.13280	1.77962	.98989	5.46
.016	.049	.152	.048	3.35002	1.55315	.98449	4.88
.022	.049	.152	.048	2.81157	1.38235	.97902	4.30
.027	.049	.152	.048	2.40907	1.24586	.97342	3.70
.032	.049	.152	.048	2.09321	1.13362	.96759	3.08
.038	.049	.152	.048	1.83702	1.03972	.96137	2.42
.043	.049	.152	.048	1.62403	.96026	.95460	1.70
.049	.049	.152	.048	1.44342	.89243	.94710	.90
.054	.049	.152	.048	1.28772	.83412	.93868	.00
.059	.049	.152	.048	1.15160	.78367	.92915	-1.02
.065	.049	.152	.048	1.03116	.73978	.91832	-2.17
.070	.049	.152	.048	.92345	.70140	.90601	-3.48
.076	.049	.152	.048	.82626	.66767	.89205	-4.97
.081	.049	.152	.048	.73783	.63789	.87630	-6.65
.086	.049	.152	.048	.65680	.61150	.85861	-8.53
.092	.049	.152	.048	.58208	.58800	.83890	-10.63
.097	.049	.152	.048	.51280	.56701	.81711	-12.95
.103	.049	.152	.048	.44824	.54815	.79323	-15.50
.108	.049	.152	.048	.38781	.53126	.76730	-18.26
.054	.049	.015	.048	-2.16503	1.73092	.10550	-88.76
.054	.049	.030	.048	-.89958	1.36069	.25427	-72.91
.054	.049	.046	.048	-.24161	1.16037	.41753	-55.52
.054	.049	.061	.048	.17673	1.04170	.56736	-39.56
.054	.049	.076	.048	.47426	.96767	.68797	-26.71
.054	.049	.091	.048	.70216	.91936	.77749	-17.17
.054	.049	.106	.048	.88595	.88653	.84118	-10.39
.054	.049	.122	.048	1.03970	.86343	.88574	-5.64
.054	.049	.137	.048	1.17183	.84664	.91684	-2.33
.054	.049	.152	.048	1.28772	.83412	.93868	.00
.054	.049	.167	.048	1.39096	.82456	.95419	1.65
.054	.049	.182	.048	1.48409	.81710	.96534	2.84
.054	.049	.198	.048	1.56894	.81119	.97345	3.70
.054	.049	.213	.048	1.64690	.80643	.97944	4.34
.054	.049	.228	.048	1.71903	.80254	.98390	4.82
.054	.049	.243	.048	1.78614	.79932	.98728	5.18
.054	.049	.258	.048	1.84891	.79663	.98985	5.45
.054	.049	.274	.048	1.90787	.79436	.99184	5.66
.054	.049	.289	.048	1.96347	.79243	.99339	5.83
.054	.049	.304	.048	2.01608	.79077	.99461	5.96
.054	.005	.152	.048	.99147	.32134	.99898	6.42
.054	.010	.152	.048	1.00357	.35702	.99753	6.27
.054	.015	.152	.048	1.02311	.40810	.99391	5.88
.054	.020	.152	.048	1.04925	.46778	.98755	5.21
.054	.024	.152	.048	1.08096	.53126	.97906	4.30
.054	.029	.152	.048	1.11717	.59554	.96966	3.30
.054	.034	.152	.048	1.15684	.65879	.96046	2.32
.054	.039	.152	.048	1.19901	.71996	.95208	1.43
.054	.044	.152	.048	1.24286	.77849	.94481	.65
.054	.049	.152	.048	1.28772	.83412	.93868	.00
.054	.054	.152	.048	1.33301	.88677	.93363	-.54
.054	.059	.152	.048	1.37833	.93647	.92947	-.98
.054	.064	.152	.048	1.42333	.98336	.92611	-1.34
.054	.069	.152	.048	1.46778	1.02756	.92341	-1.63
.054	.073	.152	.048	1.51149	1.06925	.92126	-1.86
.054	.078	.152	.048	1.55434	1.10860	.91955	-2.04
.054	.083	.152	.048	1.59624	1.14578	.91821	-2.18
.054	.088	.152	.048	1.63716	1.18095	.91717	-2.29
.054	.093	.152	.048	1.67706	1.21426	.91638	-2.38
.054	.098	.152	.048	1.71592	1.24586	.91579	-2.44
.054	.049	.152	.005	1.33475	.77565	.95735	1.99
.054	.049	.152	.010	1.33325	.77761	.95679	1.93
.054	.049	.152	.014	1.33078	.78079	.95585	1.83
.054	.049	.152	.019	1.32733	.78519	.95453	1.69
.054	.049	.152	.024	1.32293	.79077	.95283	1.51
.054	.049	.152	.029	1.31761	.79748	.95076	1.29
.054	.049	.152	.034	1.31139	.80524	.94830	1.02
.054	.049	.152	.038	1.30431	.81398	.94547	.72
.054	.049	.152	.043	1.29641	.82364	.94226	.38
.054	.049	.152	.048	1.28772	.83412	.93868	.00
.054	.049	.152	.053	1.27828	.84535	.93476	-.42
.054	.049	.152	.058	1.26815	.85725	.93047	-.87
.054	.049	.152	.062	1.25737	.86974	.92587	-1.37
.054	.049	.152	.067	1.24598	.88274	.92095	-1.89
.054	.049	.152	.072	1.23403	.89617	.91574	-2.44
.054	.049	.152	.077	1.22156	.90998	.91027	-3.03
.054	.049	.152	.082	1.20862	.92409	.90455	-3.64
.054	.049	.152	.086	1.19526	.93844	.89861	-4.27
.054	.049	.152	.091	1.18150	.95299	.89247	-4.92
.054	.049	.152	.096	1.16740	.96767	.88617	-5.59

STRESS-STRENGTH PROBABILITIES FOR LOGNORMAL DISTRIBUTIONS

DIST 1; X, S		DIST 2; X, S		MEAN	SIGMA	PROB	PERCENT
18.500	10.300	10.500	7.800	-.65111	.84229	.21975	
9.250	5.150	15.750	3.900	.63747	.57404	.86661	294.35
10.175	5.665	15.225	4.290	.49991	.58857	.80211	265.01
11.100	6.180	14.700	4.680	.36764	.60544	.72815	231.35
12.025	6.695	14.175	5.070	.23931	.62432	.64914	195.40
12.950	7.210	13.650	5.460	.11344	.64636	.56960	159.20
13.875	7.725	13.125	5.850	-.01117	.67173	.49337	124.51
14.800	8.240	12.600	6.240	-.13560	.69354	.42316	92.56
15.725	8.755	12.075	6.630	-.26096	.73042	.36049	64.04
16.650	9.270	11.550	7.020	-.38791	.76445	.30592	39.21
17.575	9.785	11.025	7.410	-.51768	.80173	.25923	17.97
18.500	10.300	10.500	7.800	-.65111	.84229	.21975	.00
19.425	10.815	9.975	8.190	-.78912	.88617	.18660	-15.09
20.350	11.330	9.450	8.580	-.93267	.93340	.15884	-27.72
21.275	11.845	8.925	8.970	-1.08277	.98397	.13558	-38.30
22.200	12.360	8.400	9.360	-1.24046	1.03789	.11601	-47.21
23.125	12.875	7.875	9.750	-1.40689	1.09516	.09946	-54.74
24.050	13.390	7.350	10.140	-1.58335	1.15579	.08535	-61.16
24.975	13.905	6.825	10.530	-1.77128	1.21994	.07324	-66.67
25.900	14.420	6.300	10.920	-1.97239	1.28741	.06274	-71.45
26.825	14.935	5.775	11.310	-2.18878	1.35867	.05359	-75.61
27.750	15.450	5.250	11.700	-2.42303	1.43334	.04553	-79.28

STRESS-STRENGTH PROBABILITIES FOR LOGNORMAL DISTRIBUTIONS

DIST 1; X, S		DIST 2; X, S		MEAN	SIGMA	PROB	PERCENT
18.500	10.300	82.600	28.800	1.57388	.62027	.99442	
9.250	5.150	123.900	14.400	2.72315	.53239	1.00000	.56
10.175	5.665	119.770	15.840	2.59197	.53605	1.00000	.56
11.100	6.180	115.640	17.280	2.46750	.54046	1.00000	.56
12.025	6.695	111.510	18.720	2.34824	.54571	.99999	.56
12.950	7.210	107.380	20.160	2.23296	.55135	.99997	.56
13.875	7.725	103.250	21.600	2.12065	.55933	.99992	.55
14.800	8.240	99.120	23.040	2.01040	.56801	.99980	.54
15.725	8.755	94.990	24.480	1.90137	.57920	.99950	.51
16.650	9.270	90.860	25.920	1.79290	.59013	.99881	.44
17.575	9.785	86.730	27.360	1.68389	.60405	.99734	.29
18.500	10.300	82.600	28.800	1.57389	.62027	.99442	-.00
19.425	10.815	78.470	30.240	1.46193	.63312	.98891	-.55
20.350	11.330	74.340	31.680	1.34714	.66097	.97923	-1.53
21.275	11.845	70.210	33.120	1.22850	.68624	.96329	-3.13
22.200	12.360	66.080	34.560	1.10488	.71540	.93876	-5.60
23.125	12.875	61.950	36.000	.97495	.74897	.90349	-9.14
24.050	13.390	57.820	37.440	.83713	.78751	.85611	-13.91
24.975	13.905	53.690	38.880	.68956	.83163	.79649	-19.90
25.900	14.420	49.560	40.320	.52937	.88202	.72603	-26.99
26.825	14.935	45.430	41.760	.35562	.93940	.64749	-34.99
27.750	15.450	41.300	43.200	.16306	1.00456	.56447	-43.24

STRESS-STRENGTH PROBABILITIES FOR LOGNORMAL DISTRIBUTIONS

DIST 1; X, S		DIST 2; X, S		MEAN	SIGMA	PROB	PERCENT
.054	.049	.152	.048	1.28772	.83412	.93868	
.027	.025	.228	.024	2.42835	.78212	.99905	6.43
.030	.027	.220	.026	2.29752	.78418	.99830	6.35
.032	.029	.213	.029	2.17347	.78667	.99713	6.23
.035	.032	.205	.031	2.05470	.78965	.99537	6.04
.038	.034	.198	.034	1.94003	.79322	.99277	5.76
.040	.037	.190	.036	1.82843	.79748	.98907	5.37
.043	.039	.182	.038	1.71903	.80254	.98390	4.82
.046	.042	.175	.041	1.61100	.80854	.97634	4.06
.049	.044	.167	.043	1.50360	.81567	.96736	3.06
.051	.047	.160	.046	1.39609	.82412	.95487	1.72
.054	.049	.152	.048	1.29772	.83412	.93868	.00
.057	.051	.144	.050	1.17768	.84596	.91806	-2.20
.059	.054	.137	.053	1.06514	.85998	.89225	-4.95
.062	.056	.129	.055	.94913	.87656	.86055	-8.32
.065	.059	.122	.058	.82856	.89617	.82240	-12.39
.067	.061	.114	.060	.70216	.91936	.77749	-17.17
.070	.064	.106	.062	.56840	.94673	.72597	-22.67
.073	.066	.099	.065	.42546	.97902	.66807	-28.83
.076	.069	.091	.067	.27110	1.01705	.60510	-35.54
.078	.071	.094	.070	.10256	1.06173	.53848	-42.63
.081	.073	.076	.072	-.09364	1.11411	.47008	-49.92

```
C
C   SENSITIVITY ANALYSIS OF STRESS-STRENGTH MODEL
C
        WRITE (6,1)
1       FORMAT(1H1'STRESS-STRENGTH PROBABILITIES FOR LOGNORMAL DISTRIBUTIO
       1NS'/)
        WRITE (6,2)
2       FORMAT (5X,12HDIST 1: X, S,6X,12HDIST 2: X, S,7X,
       14HMEAN,8X,5HSIGMA,7X,4HPROB,3X,7HPERCENT)
        REAL X(2),S(2)
        READ (5,10) (X(I),S(I), I=1,2)
10      FORMAT (2F5.2)
C
C  STRESS-STRENGTH PROBABILITY
C
        WRITE (6,99)
        CALL PROB (X,S,F)
        WRITE (6,99)
        FRO = F
C
C EFFECT OF VARIATION OF MEANS
C
        DO 30 I = 1,2
        A = X(I)
        DO 20 J = 1,20
        X(I) = J*A/10.0
        CALL PROB (X,S,F)
        PER = 100.0*(F-FRO)/FRO
        WRITE (6,60) PER
20      CONTINUE
        WRITE (6,99)
        X(I) = A
30      CONTINUE
C
C EFFECT OF VARIATION OF STANDARD DEVIATIONS
C
        DO 50 I = 1,2
        B = S(I)
        DO 40 J = 1,20
        S(I) = J*B/10.0
        CALL PROB (X,S,F)
        PER = 100.0*(F-FRO)/FRO
        WRITE (6,60) PER
40      CONTINUE
        WRITE (6,99)
        S(I) = B
50      CONTINUE
60      FORMAT (1H+,72X,F6.2)
99      FORMAT (1H )
        END
```

A5.2.2.2 PROB

```
      SUBROUTINE PROB (X,S,F)
C
C FROB
C
      REAL X(2),Y(2),S(2),V(2),MEAN
C
C INPUTS ARE THE MEANS (X) AND THE STANDARD DEVIATIONS (S) OF TWO
C          LOGNORMAL DISTRIBUTIONS.
C
C ECHO CHECK
C
      WRITE (6,20) (X(I),S(I), I=1,2)
20    FORMAT (4(2X,F7.3))
C
C TRANSFORM PARAMETERS TO NORMAL DISTRIBUTIONS
C
      DO 30 I = 1,2
      V(I) = S(I)**2.C
      V(I) = ALOG(V(I)/X(I)**2.0 + 1.0)
      Y(I) = ALOG  (X(I)) - C.5*V(I)
30    CONTINUE
C
C CALCULATE PARAMETERS OF DISTRIBUTION OF THE DIFFERENCE
C
      MEAN = Y(2)-Y(1)
      SIGMA = (V(1) + V(2))**C.5
      WRITE (6,99)  MEAN,SIGMA
99    FORMAT (1H+,36X,2(2X,F10.5))
C
C CALCULATE VALUE OF STANDARD NORMAL
C
      Z = MEAN/SIGMA
C
C FIND PROBABILITY
C
      CALL SIMP  (Z,F)
      WRITE (6,10C) F
100   FORMAT (1H+,63X,F7.5)
      RETURN
       END
```

A5.2.2.3 SIMP

```
      SUBROUTINE SIMP (B,P)
C
C   SIMPSONS RULE
C   INPUT
C
      A = 0.0
      IERR = 4
      NMAX =20
      ERROR = 1.0/10.0**IERR
C
C   START
C
      A1 = 0.0
      N = 2
40    H = (B - A)/N
      S = 0.0
      A2 = A1
      X = A
      DO 50 I = 1,N,2
      Y0 = EXP ((X**2)/(-2.0))
      Y1 = EXP (((X+H)**2)/(-2.0))
      X = X+(2*H)
      Y2 = EXP((X**2)/(-2.0))
      S = S+ Y0+4*Y1+Y2
50    CONTINUE
      A1 = S*H/3
      IF (ABS((A1-A2)/A1).LE.ERROR) GO TO 80
      N = 2*N
      IF (N.LE.NMAX) GO TO 40
      WRITE (6,60)
60    FORMAT (' NO CONVERGENCE')
      WRITE (6,20)  A,B
20    FORMAT ('  A =',F10.5,/,'  B =',F10.5)
      WRITE (6,30)  ERROR,NMAX
30    FORMAT ('  ERROR= ',F10.5,/,'  MAX N =',I3/)
      WRITE (6,70) N,A1,A2
70    FORMAT ('  N= 'I3,/' A1 ='F10.5/' A2 ='F10.5)
      STOP
80    P = A1/(2.0*3.14159265)**0.5 + 0.5
90
      RETURN
      END
```

A5.2.2.4 MSENS

```
C
C MULTIPARAMETER SENSITIVITY ANALYSIS
C
      WRITE (6,1)
1     FORMAT(1H1'STRESS-STRENGTH PROBABILITIES FOR LOGNORMAL DISTRIBUTIO
     1NS'/)
      WRITE (6,2)
2     FORMAT (5X,12HDIST 1; X, S,6X,12HDIST 2; X, S,7X,
     14HMEAN,8X,5HSIGMA,7X,4HPROB,3X,7HPERCENT)
      REAL X(2),S(2)
      READ (5,10) (X(I),S(I), I=1,2)
10    FORMAT (2F5.2)
C
C STRESS-STRENGTH PROBABILITY
C
      WRITE (6,99)
      CALL PROB (X,S,F)
      WRITE (6,99)
      PRO = F
C
C EFFECT OF VARIATION
C
      A =X(1)
      B = X(2)
      C = S(1)
      D = S(2)
      DO 20 J = 0,20
      X(1) = A/2.0 + J*A/20.0
      X(2) = 1.5*B - J*B/20.0
      S(1) = C/2.0 + J*C/20.0
      S(2) = D/2.0 + J*D/20.0
      CALL PROB (X,S,F)
      PER = 100.0*(F-PRO)/PRO
      WRITE (6,60) PER
20    CONTINUE
60    FORMAT (1H+,72X,F6.2)
99    FORMAT (1H )
      END
```

A5.3.1.1 Example Probabilities

EXAMPLE - 1

FIRE SPREAD PROBABILITY

BAR-ADQ	SUF-ADQ	BAR-REL	SUF-REL	S-TERM	BAR-EFF	SUF-EFF	ROOM-1	ROOM-2	ROOM-3
.2200	.0000	.7500	.0000	.6600	.1650	.0000	.7161	.9194	.9771

EXAMPLE - 2

FIRE SPREAD PROBABILITY

BAR-ADQ	SUF-ADQ	BAR-REL	SUF-REL	S-TERM	BAR-EFF	SUF-EFF	ROOM-1	ROOM-2	ROOM-3
.9940	.0000	.9970	.0000	.6600	.9910	.0000	.9969	1.0000	1.0000

EXAMPLE - 3

FIRE SPREAD PROBABILITY

BAR-ADQ	SUF-ADQ	BAR-REL	SUF-REL	S-TERM	BAR-EFF	SUF-EFF	ROOM-1	ROOM-2	ROOM-3
.2200	.9390	.7500	1.0000	.6600	.1650	.3330	.9827	.9951	.9986

EXAMPLE - 4

FIRE SPREAD PROBABILITY

BAR-ADQ	SUF-ADQ	BAR-REL	SUF-REL	S-TERM	BAR-EFF	SUF-EFF	ROOM-1	ROOM-2	ROOM-3
.9940	.9390	.9970	1.0000	.6600	.9910	.9390	.9998	1.0000	1.0000

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A5.3.1.2 Sensitivity Probabilities

EXAMPLE - 1

FIRE SPREAD PROBABILITY

BAR-ADD	SUF-ADD	BAR-REL	SUF-REL	S-TERM	BAR-EFF	SLF-EFF	ROOM-1	ROOM-2	ROOM-3
.0000	.0000	.7500	.0000	.6600	.0000	.0000	.6600	.8844	.9607
.0500	.0000	.7500	.0000	.6600	.0375	.0000	.6727	.8929	.9650
.1000	.0000	.7500	.0000	.6600	.0750	.0000	.6855	.9011	.9693
.1500	.0000	.7500	.0000	.6600	.1125	.0000	.6983	.9089	.9725
.2000	.0000	.7500	.0000	.6600	.1500	.0000	.7110	.9165	.9759
.2500	.0000	.7500	.0000	.6600	.1875	.0000	.7237	.9237	.9789
.3000	.0000	.7500	.0000	.6600	.2250	.0000	.7365	.9306	.9817
.3500	.0000	.7500	.0000	.6600	.2625	.0000	.7492	.9371	.9842
.4000	.0000	.7500	.0000	.6600	.3000	.0000	.7620	.9434	.9865
.4500	.0000	.7500	.0000	.6600	.3375	.0000	.7748	.9493	.9886
.5000	.0000	.7500	.0000	.6600	.3750	.0000	.7875	.9549	.9904
.5500	.0000	.7500	.0000	.6600	.4125	.0000	.8003	.9601	.9920
.6000	.0000	.7500	.0000	.6600	.4500	.0000	.8130	.9650	.9935
.6500	.0000	.7500	.0000	.6600	.4875	.0000	.8257	.9696	.9947
.7000	.0000	.7500	.0000	.6600	.5250	.0000	.8385	.9739	.9958
.7500	.0000	.7500	.0000	.6600	.5625	.0000	.8513	.9779	.9967
.8000	.0000	.7500	.0000	.6600	.6000	.0000	.8640	.9815	.9975
.8500	.0000	.7500	.0000	.6600	.6375	.0000	.8768	.9848	.9981
.9000	.0000	.7500	.0000	.6600	.6750	.0000	.8895	.9878	.9987
.9500	.0000	.7500	.0000	.6600	.7125	.0000	.9023	.9904	.9991
1.0000	.0000	.7500	.0000	.6600	.7500	.0000	.9150	.9928	.9994

BAR-ADD	SUF-ADD	BAR-REL	SUF-REL	S-TERM	BAR-EFF	SLF-EFF	ROOM-1	ROOM-2	ROOM-3
.2200	.0000	.7500	.0000	.0000	.1650	.0000	.1650	.3028	.4178
.2200	.0000	.7500	.0000	.0500	.1650	.0000	.2067	.3708	.5009
.2200	.0000	.7500	.0000	.1000	.1650	.0000	.2485	.4352	.5756
.2200	.0000	.7500	.0000	.1500	.1650	.0000	.2902	.4963	.6425
.2200	.0000	.7500	.0000	.2000	.1650	.0000	.3320	.5538	.7019
.2200	.0000	.7500	.0000	.2500	.1650	.0000	.3737	.6078	.7544
.2200	.0000	.7500	.0000	.3000	.1650	.0000	.4155	.6584	.8003
.2200	.0000	.7500	.0000	.3500	.1650	.0000	.4572	.7054	.8401
.2200	.0000	.7500	.0000	.4000	.1650	.0000	.4990	.7490	.8742
.2200	.0000	.7500	.0000	.4500	.1650	.0000	.5407	.7891	.9031
.2200	.0000	.7500	.0000	.5000	.1650	.0000	.5825	.8257	.9272
.2200	.0000	.7500	.0000	.5500	.1650	.0000	.6242	.8588	.9469
.2200	.0000	.7500	.0000	.6000	.1650	.0000	.6660	.8884	.9627
.2200	.0000	.7500	.0000	.6500	.1650	.0000	.7077	.9146	.9750
.2200	.0000	.7500	.0000	.7000	.1650	.0000	.7495	.9372	.9843
.2200	.0000	.7500	.0000	.7500	.1650	.0000	.7912	.9564	.9909
.2200	.0000	.7500	.0000	.8000	.1650	.0000	.8330	.9721	.9953
.2200	.0000	.7500	.0000	.8500	.1650	.0000	.8748	.9843	.9980
.2200	.0000	.7500	.0000	.9000	.1650	.0000	.9165	.9930	.9994
.2200	.0000	.7500	.0000	.9500	.1650	.0000	.9583	.9983	.9999
.2200	.0000	.7500	.0000	1.0000	.1650	.0000	1.0000	1.0000	1.0000

BAR-ADD	SUF-ADD	BAR-REL	SUF-REL	S-TERM	BAR-EFF	SLF-EFF	ROOM-1	ROOM-2	ROOM-3
.2200	.0000	.0000	.0000	.6600	.0000	.0000	.6600	.8844	.9607
.2200	.0000	.0500	.0000	.6600	.0110	.0000	.6637	.8869	.9620
.2200	.0000	.1000	.0000	.6600	.0220	.0000	.6675	.8894	.9632
.2200	.0000	.1500	.0000	.6600	.0330	.0000	.6712	.8919	.9645
.2200	.0000	.2000	.0000	.6600	.0440	.0000	.6750	.8943	.9657
.2200	.0000	.2500	.0000	.6600	.0550	.0000	.6787	.8968	.9668
.2200	.0000	.3000	.0000	.6600	.0660	.0000	.6824	.8992	.9680
.2200	.0000	.3500	.0000	.6600	.0770	.0000	.6862	.9015	.9691
.2200	.0000	.4000	.0000	.6600	.0880	.0000	.6899	.9039	.9702
.2200	.0000	.4500	.0000	.6600	.0990	.0000	.6937	.9062	.9713
.2200	.0000	.5000	.0000	.6600	.1100	.0000	.6974	.9084	.9723
.2200	.0000	.5500	.0000	.6600	.1210	.0000	.7011	.9107	.9733
.2200	.0000	.6000	.0000	.6600	.1320	.0000	.7049	.9129	.9743
.2200	.0000	.6500	.0000	.6600	.1430	.0000	.7086	.9151	.9753
.2200	.0000	.7000	.0000	.6600	.1540	.0000	.7124	.9173	.9762
.2200	.0000	.7500	.0000	.6600	.1650	.0000	.7161	.9194	.9771
.2200	.0000	.8000	.0000	.6600	.1760	.0000	.7198	.9215	.9780
.2200	.0000	.8500	.0000	.6600	.1870	.0000	.7236	.9236	.9789
.2200	.0000	.9000	.0000	.6600	.1980	.0000	.7273	.9256	.9797
.2200	.0000	.9500	.0000	.6600	.2090	.0000	.7311	.9277	.9805
.2200	.0000	1.0000	.0000	.6600	.2200	.0000	.7348	.9297	.9813

EXAMPLE - 2

FIRE SPREAD PROBABILITY

BAR-ADQ	SUF-ADQ	BAR-REL	SUF-REL	S-TERM	BAR-EFF	SUF-EFF	ROOM-1	ROOM-2	ROOM-3
.0000	.0000	.9970	.0000	.6600	.0000	.0000	.6600	.8844	.9607
.0500	.0000	.9970	.0000	.6600	.0498	.0000	.6769	.8956	.9663
.1000	.0000	.9970	.0000	.6600	.0997	.0000	.6939	.9063	.9713
.1500	.0000	.9970	.0000	.6600	.1495	.0000	.7108	.9164	.9758
.2000	.0000	.9970	.0000	.6600	.1994	.0000	.7278	.9259	.9798
.2500	.0000	.9970	.0000	.6600	.2492	.0000	.7447	.9348	.9834
.3000	.0000	.9970	.0000	.6600	.2991	.0000	.7617	.9432	.9865
.3500	.0000	.9970	.0000	.6600	.3489	.0000	.7786	.9510	.9892
.4000	.0000	.9970	.0000	.6600	.3988	.0000	.7956	.9582	.9915
.4500	.0000	.9970	.0000	.6600	.4486	.0000	.8125	.9649	.9934
.5000	.0000	.9970	.0000	.6600	.4985	.0000	.8295	.9709	.9950
.5500	.0000	.9970	.0000	.6600	.5483	.0000	.8464	.9764	.9964
.6000	.0000	.9970	.0000	.6600	.5982	.0000	.8634	.9813	.9975
.6500	.0000	.9970	.0000	.6600	.6480	.0000	.8803	.9857	.9983
.7000	.0000	.9970	.0000	.6600	.6979	.0000	.8973	.9894	.9989
.7500	.0000	.9970	.0000	.6600	.7477	.0000	.9142	.9926	.9994
.8000	.0000	.9970	.0000	.6600	.7976	.0000	.9312	.9953	.9997
.8500	.0000	.9970	.0000	.6600	.8474	.0000	.9481	.9973	.9999
.9000	.0000	.9970	.0000	.6600	.8973	.0000	.9651	.9988	1.0000
.9500	.0000	.9970	.0000	.6600	.9471	.0000	.9820	.9997	1.0000
1.0000	.0000	.9970	.0000	.6600	.9970	.0000	.9990	1.0000	1.0000

BAR-ADQ	SUF-ADQ	BAR-REL	SUF-REL	S-TERM	BAR-EFF	SUF-EFF	ROOM-1	ROOM-2	ROOM-3
.9940	.0000	.0000	.0000	.6600	.0000	.0000	.6600	.8844	.9607
.9940	.0000	.0500	.0000	.6600	.0497	.0000	.6769	.8955	.9663
.9940	.0000	.1000	.0000	.6600	.0994	.0000	.6938	.9062	.9713
.9940	.0000	.1500	.0000	.6600	.1491	.0000	.7107	.9163	.9758
.9940	.0000	.2000	.0000	.6600	.1988	.0000	.7276	.9258	.9798
.9940	.0000	.2500	.0000	.6600	.2485	.0000	.7445	.9347	.9833
.9940	.0000	.3000	.0000	.6600	.2982	.0000	.7614	.9431	.9864
.9940	.0000	.3500	.0000	.6600	.3479	.0000	.7783	.9508	.9891
.9940	.0000	.4000	.0000	.6600	.3976	.0000	.7952	.9581	.9914
.9940	.0000	.4500	.0000	.6600	.4473	.0000	.8121	.9647	.9934
.9940	.0000	.5000	.0000	.6600	.4970	.0000	.8290	.9708	.9950
.9940	.0000	.5500	.0000	.6600	.5467	.0000	.8459	.9762	.9963
.9940	.0000	.6000	.0000	.6600	.5964	.0000	.8628	.9812	.9974
.9940	.0000	.6500	.0000	.6600	.6461	.0000	.8797	.9855	.9983
.9940	.0000	.7000	.0000	.6600	.6958	.0000	.8966	.9893	.9989
.9940	.0000	.7500	.0000	.6600	.7455	.0000	.9135	.9925	.9994
.9940	.0000	.8000	.0000	.6600	.7952	.0000	.9304	.9952	.9997
.9940	.0000	.8500	.0000	.6600	.8449	.0000	.9473	.9972	.9999
.9940	.0000	.9000	.0000	.6600	.8946	.0000	.9642	.9987	1.0000
.9940	.0000	.9500	.0000	.6600	.9443	.0000	.9811	.9996	1.0000
.9940	.0000	1.0000	.0000	.6600	.9940	.0000	.9980	1.0000	1.0000

BAR-ADQ	SUF-ADQ	BAR-REL	SUF-REL	S-TERM	BAR-EFF	SUF-EFF	ROOM-1	ROOM-2	ROOM-3
.9940	.0000	.9970	.0000	.0000	.9910	.0000	.9910	.9999	1.0000
.9940	.0000	.9970	.0000	.0500	.9910	.0000	.9915	.9999	1.0000
.9940	.0000	.9970	.0000	.1000	.9910	.0000	.9919	.9999	1.0000
.9940	.0000	.9970	.0000	.1500	.9910	.0000	.9924	.9999	1.0000
.9940	.0000	.9970	.0000	.2000	.9910	.0000	.9923	.9999	1.0000
.9940	.0000	.9970	.0000	.2500	.9910	.0000	.9933	1.0000	1.0000
.9940	.0000	.9970	.0000	.3000	.9910	.0000	.9937	1.0000	1.0000
.9940	.0000	.9970	.0000	.3500	.9910	.0000	.9942	1.0000	1.0000
.9940	.0000	.9970	.0000	.4000	.9910	.0000	.9946	1.0000	1.0000
.9940	.0000	.9970	.0000	.4500	.9910	.0000	.9951	1.0000	1.0000
.9940	.0000	.9970	.0000	.5000	.9910	.0000	.9955	1.0000	1.0000
.9940	.0000	.9970	.0000	.5500	.9910	.0000	.9960	1.0000	1.0000
.9940	.0000	.9970	.0000	.6000	.9910	.0000	.9964	1.0000	1.0000
.9940	.0000	.9970	.0000	.6500	.9910	.0000	.9969	1.0000	1.0000
.9940	.0000	.9970	.0000	.7000	.9910	.0000	.9973	1.0000	1.0000
.9940	.0000	.9970	.0000	.7500	.9910	.0000	.9978	1.0000	1.0000
.9940	.0000	.9970	.0000	.8000	.9910	.0000	.9982	1.0000	1.0000
.9940	.0000	.9970	.0000	.8500	.9910	.0000	.9987	1.0000	1.0000
.9940	.0000	.9970	.0000	.9000	.9910	.0000	.9991	1.0000	1.0000
.9940	.0000	.9970	.0000	.9500	.9910	.0000	.9996	1.0000	1.0000
.9940	.0000	.9970	.0000	1.0000	.9910	.0000	1.0000	1.0000	1.0000

3.

EXAMPLE - 3

PIPE SPREAD PROBABILITY

BAR-ADQ	SUF-ADQ	BAR-REL	SUF-REL	S-TERM	BAR-EFF	SUP-EFF	ROOM-1	ROOM-2	ROOM-3
.0000	.9390	.7500	1.0000	.6600	.0000	.9390	.9793	.9929	.9976
.0500	.9390	.7500	1.0000	.6600	.0375	.9390	.9800	.9935	.9979
.1000	.9390	.7500	1.0000	.6600	.0750	.9390	.9808	.9940	.9981
.1500	.9390	.7500	1.0000	.6600	.1125	.9390	.9816	.9944	.9983
.2000	.9390	.7500	1.0000	.6600	.1500	.9390	.9824	.9949	.9985
.2500	.9390	.7500	1.0000	.6600	.1875	.9390	.9831	.9953	.9987
.3000	.9390	.7500	1.0000	.6600	.2250	.9390	.9839	.9958	.9989
.3500	.9390	.7500	1.0000	.6600	.2625	.9390	.9847	.9962	.9990
.4000	.9390	.7500	1.0000	.6600	.3000	.9390	.9855	.9965	.9992
.4500	.9390	.7500	1.0000	.6600	.3375	.9390	.9863	.9969	.9993
.5000	.9390	.7500	1.0000	.6600	.3750	.9390	.9870	.9972	.9994
.5500	.9390	.7500	1.0000	.6600	.4125	.9390	.9878	.9976	.9995
.6000	.9390	.7500	1.0000	.6600	.4500	.9390	.9886	.9979	.9996
.6500	.9390	.7500	1.0000	.6600	.4875	.9390	.9894	.9981	.9997
.7000	.9390	.7500	1.0000	.6600	.5250	.9390	.9901	.9984	.9997
.7500	.9390	.7500	1.0000	.6600	.5625	.9390	.9909	.9987	.9998
.8000	.9390	.7500	1.0000	.6600	.6000	.9390	.9917	.9989	.9998
.8500	.9390	.7500	1.0000	.6600	.6375	.9390	.9925	.9991	.9999
.9000	.9390	.7500	1.0000	.6600	.6750	.9390	.9933	.9993	.9999
.9500	.9390	.7500	1.0000	.6600	.7125	.9390	.9940	.9994	.9999
1.0000	.9390	.7500	1.0000	.6600	.7500	.9390	.9948	.9996	1.0000

BAR-ADQ	SUF-ADQ	BAR-REL	SUF-REL	S-TERM	BAR-EFF	SUP-EFF	ROOM-1	ROOM-2	ROOM-3
.2200	.9390	.0000	1.0000	.6600	.0000	.9390	.9793	.9929	.9976
.2200	.9390	.0500	1.0000	.6600	.0110	.9390	.9795	.9931	.9977
.2200	.9390	.1000	1.0000	.6600	.0220	.9390	.9797	.9933	.9978
.2200	.9390	.1500	1.0000	.6600	.0330	.9390	.9799	.9934	.9978
.2200	.9390	.2000	1.0000	.6600	.0440	.9390	.9802	.9936	.9979
.2200	.9390	.2500	1.0000	.6600	.0550	.9390	.9804	.9937	.9980
.2200	.9390	.3000	1.0000	.6600	.0660	.9390	.9806	.9938	.9980
.2200	.9390	.3500	1.0000	.6600	.0770	.9390	.9809	.9940	.9981
.2200	.9390	.4000	1.0000	.6600	.0880	.9390	.9811	.9941	.9982
.2200	.9390	.4500	1.0000	.6600	.0990	.9390	.9813	.9943	.9982
.2200	.9390	.5000	1.0000	.6600	.1100	.9390	.9815	.9944	.9983
.2200	.9390	.5500	1.0000	.6600	.1210	.9390	.9818	.9946	.9984
.2200	.9390	.6000	1.0000	.6600	.1320	.9390	.9820	.9947	.9984
.2200	.9390	.6500	1.0000	.6600	.1430	.9390	.9822	.9948	.9985
.2200	.9390	.7000	1.0000	.6600	.1540	.9390	.9825	.9950	.9985
.2200	.9390	.7500	1.0000	.6600	.1650	.9390	.9827	.9951	.9986
.2200	.9390	.8000	1.0000	.6600	.1760	.9390	.9829	.9952	.9987
.2200	.9390	.8500	1.0000	.6600	.1870	.9390	.9831	.9953	.9987
.2200	.9390	.9000	1.0000	.6600	.1980	.9390	.9834	.9955	.9988
.2200	.9390	.9500	1.0000	.6600	.2090	.9390	.9836	.9956	.9988
.2200	.9390	1.0000	1.0000	.6600	.2200	.9390	.9838	.9957	.9989

BAR-ADQ	SUF-ADQ	BAR-REL	SUF-REL	S-TERM	BAR-EFF	SUP-EFF	ROOM-1	ROOM-2	ROOM-3
.2200	.9390	.7500	1.0000	.0000	.1650	.9390	.9491	.9575	.9645
.2200	.9390	.7500	1.0000	.0500	.1650	.9390	.9516	.9616	.9696
.2200	.9390	.7500	1.0000	.1000	.1650	.9390	.9542	.9656	.9741
.2200	.9390	.7500	1.0000	.1500	.1650	.9390	.9567	.9693	.9782
.2200	.9390	.7500	1.0000	.2000	.1650	.9390	.9593	.9728	.9818
.2200	.9390	.7500	1.0000	.2500	.1650	.9390	.9618	.9761	.9850
.2200	.9390	.7500	1.0000	.3000	.1650	.9390	.9643	.9792	.9878
.2200	.9390	.7500	1.0000	.3500	.1650	.9390	.9669	.9820	.9902
.2200	.9390	.7500	1.0000	.4000	.1650	.9390	.9694	.9847	.9923
.2200	.9390	.7500	1.0000	.4500	.1650	.9390	.9720	.9871	.9941
.2200	.9390	.7500	1.0000	.5000	.1650	.9390	.9745	.9894	.9956
.2200	.9390	.7500	1.0000	.5500	.1650	.9390	.9771	.9914	.9968
.2200	.9390	.7500	1.0000	.6000	.1650	.9390	.9796	.9932	.9977
.2200	.9390	.7500	1.0000	.6500	.1650	.9390	.9822	.9949	.9985
.2200	.9390	.7500	1.0000	.7000	.1650	.9390	.9847	.9962	.9990
.2200	.9390	.7500	1.0000	.7500	.1650	.9390	.9873	.9973	.9994
.2200	.9390	.7500	1.0000	.8000	.1650	.9390	.9898	.9983	.9997
.2200	.9390	.7500	1.0000	.8500	.1650	.9390	.9924	.9990	.9999
.2200	.9390	.7500	1.0000	.9000	.1650	.9390	.9949	.9995	1.0000
.2200	.9390	.7500	1.0000	.9500	.1650	.9390	.9975	.9999	1.0000
.2200	.9390	.7500	1.0000	1.0000	.1650	.9390	1.0000	1.0000	1.0000

FIRE SPREAD PROBABILITY

BAR-ADD	SUF-ADD	BAR-REL	SUF-REL	S-TERM	BAR-EFF	SUF-EFF	ROOM-1	ROOM-2	ROOM-3
.2200	.0000	.7500	1.0000	.6600	.1650	.0000	.7161	.9194	.9771
.2200	.0500	.7500	1.0000	.6600	.1650	.0500	.7303	.9234	.9783
.2200	.1000	.7500	1.0000	.6600	.1650	.1000	.7445	.9275	.9794
.2200	.1500	.7500	1.0000	.6600	.1650	.1500	.7587	.9315	.9806
.2200	.2000	.7500	1.0000	.6600	.1650	.2000	.7729	.9355	.9817
.2200	.2500	.7500	1.0000	.6600	.1650	.2500	.7871	.9396	.9828
.2200	.3000	.7500	1.0000	.6600	.1650	.3000	.8013	.9436	.9840
.2200	.3500	.7500	1.0000	.6600	.1650	.3500	.8155	.9476	.9851
.2200	.4000	.7500	1.0000	.6600	.1650	.4000	.8297	.9516	.9863
.2200	.4500	.7500	1.0000	.6600	.1650	.4500	.8439	.9557	.9874
.2200	.5000	.7500	1.0000	.6600	.1650	.5000	.8581	.9597	.9886
.2200	.5500	.7500	1.0000	.6600	.1650	.5500	.8722	.9637	.9897
.2200	.6000	.7500	1.0000	.6600	.1650	.6000	.8864	.9678	.9908
.2200	.6500	.7500	1.0000	.6600	.1650	.6500	.9006	.9718	.9920
.2200	.7000	.7500	1.0000	.6600	.1650	.7000	.9148	.9758	.9931
.2200	.7500	.7500	1.0000	.6600	.1650	.7500	.9290	.9799	.9943
.2200	.8000	.7500	1.0000	.6600	.1650	.8000	.9432	.9839	.9954
.2200	.8500	.7500	1.0000	.6600	.1650	.8500	.9574	.9879	.9966
.2200	.9000	.7500	1.0000	.6600	.1650	.9000	.9716	.9919	.9977
.2200	.9500	.7500	1.0000	.6600	.1650	.9500	.9858	.9960	.9989
.2200	1.0000	.7500	1.0000	.6600	.1650	1.0000	1.0000	1.0000	1.0000

BAR-ADD	SUF-ADD	BAR-REL	SUF-REL	S-TERM	BAR-EFF	SUF-EFF	ROOM-1	ROOM-2	ROOM-3
.2200	.9390	.7500	.0000	.6600	.1650	.0000	.7161	.9194	.9771
.2200	.9390	.7500	.0500	.6600	.1650	.0469	.7294	.9232	.9782
.2200	.9390	.7500	.1000	.6600	.1650	.0939	.7428	.9270	.9793
.2200	.9390	.7500	.1500	.6600	.1650	.1408	.7561	.9308	.9803
.2200	.9390	.7500	.2000	.6600	.1650	.1878	.7694	.9345	.9814
.2200	.9390	.7500	.2500	.6600	.1650	.2347	.7827	.9383	.9825
.2200	.9390	.7500	.3000	.6600	.1650	.2817	.7961	.9421	.9836
.2200	.9390	.7500	.3500	.6600	.1650	.3286	.8094	.9459	.9846
.2200	.9390	.7500	.4000	.6600	.1650	.3756	.8227	.9497	.9857
.2200	.9390	.7500	.4500	.6600	.1650	.4225	.8361	.9535	.9868
.2200	.9390	.7500	.5000	.6600	.1650	.4695	.8494	.9572	.9879
.2200	.9390	.7500	.5500	.6600	.1650	.5164	.8627	.9610	.9889
.2200	.9390	.7500	.6000	.6600	.1650	.5634	.8760	.9648	.9900
.2200	.9390	.7500	.6500	.6600	.1650	.6103	.8894	.9686	.9911
.2200	.9390	.7500	.7000	.6600	.1650	.6573	.9027	.9724	.9922
.2200	.9390	.7500	.7500	.6600	.1650	.7042	.9160	.9762	.9932
.2200	.9390	.7500	.8000	.6600	.1650	.7512	.9294	.9799	.9943
.2200	.9390	.7500	.8500	.6600	.1650	.7981	.9427	.9837	.9954
.2200	.9390	.7500	.9000	.6600	.1650	.8451	.9560	.9875	.9965
.2200	.9390	.7500	.9500	.6600	.1650	.8920	.9694	.9913	.9975
.2200	.9390	.7500	1.0000	.6600	.1650	.9390	.9827	.9951	.9986

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EXAMPLE - 4

FIRE SPREAD PROBABILITY

BAR-ADQ	SUP-ADQ	BAR-REL	SUP-REL	S-TERM	BAR-EFF	SUP-EFF	ROOM-1	ROOM-2	ROOM-3
.0000	.9390	.9970	1.0000	.6600	.0000	.9390	.9793	.9929	.9976
.0500	.9390	.9970	1.0000	.6600	.0498	.9390	.9803	.9936	.9979
.1000	.9390	.9970	1.0000	.6600	.0997	.9390	.9813	.9943	.9983
.1500	.9390	.9970	1.0000	.6600	.1495	.9390	.9824	.9949	.9985
.2000	.9390	.9970	1.0000	.6600	.1994	.9390	.9834	.9955	.9988
.2500	.9390	.9970	1.0000	.6600	.2492	.9390	.9844	.9960	.9990
.3000	.9390	.9970	1.0000	.6600	.2991	.9390	.9855	.9965	.9992
.3500	.9390	.9970	1.0000	.6600	.3489	.9390	.9865	.9970	.9993
.4000	.9390	.9970	1.0000	.6600	.3988	.9390	.9875	.9975	.9995
.4500	.9390	.9970	1.0000	.6600	.4486	.9390	.9886	.9979	.9996
.5000	.9390	.9970	1.0000	.6600	.4985	.9390	.9896	.9982	.9997
.5500	.9390	.9970	1.0000	.6600	.5483	.9390	.9906	.9986	.9998
.6000	.9390	.9970	1.0000	.6600	.5982	.9390	.9917	.9989	.9998
.6500	.9390	.9970	1.0000	.6600	.6480	.9390	.9927	.9991	.9999
.7000	.9390	.9970	1.0000	.6600	.6979	.9390	.9937	.9994	.9999
.7500	.9390	.9970	1.0000	.6600	.7477	.9390	.9948	.9996	1.0000
.8000	.9390	.9970	1.0000	.6600	.7976	.9390	.9958	.9997	1.0000
.8500	.9390	.9970	1.0000	.6600	.8474	.9390	.9968	.9998	1.0000
.9000	.9390	.9970	1.0000	.6600	.8973	.9390	.9979	.9999	1.0000
.9500	.9390	.9970	1.0000	.6600	.9471	.9390	.9989	1.0000	1.0000
1.0000	.9390	.9970	1.0000	.6600	.9970	.9390	.9999	1.0000	1.0000

BAR-ADQ	SUP-ADQ	BAR-REL	SUP-REL	S-TERM	BAR-EFF	SUP-EFF	ROOM-1	ROOM-2	ROOM-3
.9940	.9390	.0000	1.0000	.6600	.0000	.9390	.9793	.9929	.9976
.9940	.9390	.0500	1.0000	.6600	.0497	.9390	.9803	.9936	.9979
.9940	.9390	.1000	1.0000	.6600	.0994	.9390	.9813	.9943	.9982
.9940	.9390	.1500	1.0000	.6600	.1491	.9390	.9824	.9949	.9985
.9940	.9390	.2000	1.0000	.6600	.1988	.9390	.9834	.9955	.9988
.9940	.9390	.2500	1.0000	.6600	.2485	.9390	.9844	.9960	.9990
.9940	.9390	.3000	1.0000	.6600	.2982	.9390	.9854	.9965	.9992
.9940	.9390	.3500	1.0000	.6600	.3479	.9390	.9865	.9970	.9993
.9940	.9390	.4000	1.0000	.6600	.3976	.9390	.9875	.9974	.9995
.9940	.9390	.4500	1.0000	.6600	.4473	.9390	.9895	.9978	.9996
.9940	.9390	.5000	1.0000	.6600	.4970	.9390	.9896	.9982	.9997
.9940	.9390	.5500	1.0000	.6600	.5467	.9390	.9906	.9986	.9998
.9940	.9390	.6000	1.0000	.6600	.5964	.9390	.9916	.9989	.9998
.9940	.9390	.6500	1.0000	.6600	.6461	.9390	.9927	.9991	.9999
.9940	.9390	.7000	1.0000	.6600	.6958	.9390	.9937	.9993	.9999
.9940	.9390	.7500	1.0000	.6600	.7455	.9390	.9947	.9995	1.0000
.9940	.9390	.8000	1.0000	.6600	.7952	.9390	.9959	.9997	1.0000
.9940	.9390	.8500	1.0000	.6600	.8449	.9390	.9968	.9998	1.0000
.9940	.9390	.9000	1.0000	.6600	.8946	.9390	.9978	.9999	1.0000
.9940	.9390	.9500	1.0000	.6600	.9443	.9390	.9988	1.0000	1.0000
.9940	.9390	1.0000	1.0000	.6600	.9940	.9390	.9999	1.0000	1.0000

BAR-ADQ	SUP-ADQ	BAR-REL	SUP-REL	S-TERM	BAR-EFF	SUP-EFF	ROOM-1	ROOM-2	ROOM-3
.9940	.9390	.9970	1.0000	.0000	.9910	.9390	.9995	1.0000	1.0000
.9940	.9390	.9970	1.0000	.0500	.9910	.9390	.9995	1.0000	1.0000
.9940	.9390	.9970	1.0000	.1000	.9910	.9390	.9995	1.0000	1.0000
.9940	.9390	.9970	1.0000	.1500	.9910	.9390	.9995	1.0000	1.0000
.9940	.9390	.9970	1.0000	.2000	.9910	.9390	.9996	1.0000	1.0000
.9940	.9390	.9970	1.0000	.2500	.9910	.9390	.9996	1.0000	1.0000
.9940	.9390	.9970	1.0000	.3000	.9910	.9390	.9996	1.0000	1.0000
.9940	.9390	.9970	1.0000	.3500	.9910	.9390	.9996	1.0000	1.0000
.9940	.9390	.9970	1.0000	.4000	.9910	.9390	.9997	1.0000	1.0000
.9940	.9390	.9970	1.0000	.4500	.9910	.9390	.9997	1.0000	1.0000
.9940	.9390	.9970	1.0000	.5000	.9910	.9390	.9997	1.0000	1.0000
.9940	.9390	.9970	1.0000	.5500	.9910	.9390	.9998	1.0000	1.0000
.9940	.9390	.9970	1.0000	.6000	.9910	.9390	.9998	1.0000	1.0000
.9940	.9390	.9970	1.0000	.6500	.9910	.9390	.9998	1.0000	1.0000
.9940	.9390	.9970	1.0000	.7000	.9910	.9390	.9998	1.0000	1.0000
.9940	.9390	.9970	1.0000	.7500	.9910	.9390	.9999	1.0000	1.0000
.9940	.9390	.9970	1.0000	.8000	.9910	.9390	.9999	1.0000	1.0000
.9940	.9390	.9970	1.0000	.8500	.9910	.9390	.9999	1.0000	1.0000
.9940	.9390	.9970	1.0000	.9000	.9910	.9390	.9999	1.0000	1.0000
.9940	.9390	.9970	1.0000	.9500	.9910	.9390	1.0000	1.0000	1.0000
.9940	.9390	.9970	1.0000	1.0000	.9910	.9390	1.0000	1.0000	1.0000

FIRE SPREAD PROBABILITY

BAR-ADQ	SUF-ADQ	BAR-REL	SUF-REL	S-TERM	BAR-EFF	SLP-EFF	ROOM-1	ROOM-2	ROOM-3
.9940	.0000	.9970	1.0000	.6600	.9910	.0000	.9969	1.0000	1.0000
.9940	.0500	.9970	1.0000	.6600	.9910	.0500	.9971	1.0000	1.0000
.9940	.1000	.9970	1.0000	.6600	.9910	.1000	.9973	1.0000	1.0000
.9940	.1500	.9970	1.0000	.6600	.9910	.1500	.9974	1.0000	1.0000
.9940	.2000	.9970	1.0000	.6600	.9910	.2000	.9976	1.0000	1.0000
.9940	.2500	.9970	1.0000	.6600	.9910	.2500	.9977	1.0000	1.0000
.9940	.3000	.9970	1.0000	.6600	.9910	.3000	.9979	1.0000	1.0000
.9940	.3500	.9970	1.0000	.6600	.9910	.3500	.9980	1.0000	1.0000
.9940	.4000	.9970	1.0000	.6600	.9910	.4000	.9982	1.0000	1.0000
.9940	.4500	.9970	1.0000	.6600	.9910	.4500	.9983	1.0000	1.0000
.9940	.5000	.9970	1.0000	.6600	.9910	.5000	.9985	1.0000	1.0000
.9940	.5500	.9970	1.0000	.6600	.9910	.5500	.9986	1.0000	1.0000
.9940	.6000	.9970	1.0000	.6600	.9910	.6000	.9988	1.0000	1.0000
.9940	.6500	.9970	1.0000	.6600	.9910	.6500	.9989	1.0000	1.0000
.9940	.7000	.9970	1.0000	.6600	.9910	.7000	.9991	1.0000	1.0000
.9940	.7500	.9970	1.0000	.6600	.9910	.7500	.9992	1.0000	1.0000
.9940	.8000	.9970	1.0000	.6600	.9910	.8000	.9994	1.0000	1.0000
.9940	.8500	.9970	1.0000	.6600	.9910	.8500	.9995	1.0000	1.0000
.9940	.9000	.9970	1.0000	.6600	.9910	.9000	.9997	1.0000	1.0000
.9940	.9500	.9970	1.0000	.6600	.9910	.9500	.9998	1.0000	1.0000
.9940	1.0000	.9970	1.0000	.6600	.9910	1.0000	1.0000	1.0000	1.0000

BAR-ADQ	SUF-ADQ	BAR-REL	SUF-REL	S-TERM	BAR-EFF	SLP-EFF	ROOM-1	ROOM-2	ROOM-3
.9940	.9930	.9970	.0000	.6600	.9910	.0000	.9969	1.0000	1.0000
.9940	.9930	.9970	.0500	.6600	.9910	.0465	.9971	1.0000	1.0000
.9940	.9930	.9970	.1000	.6600	.9910	.0939	.9972	1.0000	1.0000
.9940	.9930	.9970	.1500	.6600	.9910	.1408	.9974	1.0000	1.0000
.9940	.9930	.9970	.2000	.6600	.9910	.1878	.9975	1.0000	1.0000
.9940	.9930	.9970	.2500	.6600	.9910	.2347	.9977	1.0000	1.0000
.9940	.9930	.9970	.3000	.6600	.9910	.2817	.9978	1.0000	1.0000
.9940	.9930	.9970	.3500	.6600	.9910	.3286	.9979	1.0000	1.0000
.9940	.9930	.9970	.4000	.6600	.9910	.3756	.9981	1.0000	1.0000
.9940	.9930	.9970	.4500	.6600	.9910	.4225	.9982	1.0000	1.0000
.9940	.9930	.9970	.5000	.6600	.9910	.4695	.9984	1.0000	1.0000
.9940	.9930	.9970	.5500	.6600	.9910	.5164	.9985	1.0000	1.0000
.9940	.9930	.9970	.6000	.6600	.9910	.5634	.9987	1.0000	1.0000
.9940	.9930	.9970	.6500	.6600	.9910	.6103	.9988	1.0000	1.0000
.9940	.9930	.9970	.7000	.6600	.9910	.6573	.9990	1.0000	1.0000
.9940	.9930	.9970	.7500	.6600	.9910	.7042	.9991	1.0000	1.0000
.9940	.9930	.9970	.8000	.6600	.9910	.7512	.9992	1.0000	1.0000
.9940	.9930	.9970	.8500	.6600	.9910	.7981	.9994	1.0000	1.0000
.9940	.9930	.9970	.9000	.6600	.9910	.8451	.9995	1.0000	1.0000
.9940	.9930	.9970	.9500	.6600	.9910	.8920	.9997	1.0000	1.0000
.9940	.9930	.9970	1.0000	.6600	.9910	.9390	.9998	1.0000	1.0000

A5.3.2.1 FIRESENS


```
C
C FIRE SPREAD MODEL SENSITIVITY ANALYSIS
C
      REAL F(5)
      WRITE (6,10)
10    FORMAT (1H1,10X,'FIRE SPREAD PROBABILITY'/)
C
C INPUT 5 MODEL PARAMETERS
C
      READ (5,20) (F(I),I=1,5)
20    FORMAT (5F5.3)
C
C INITIAL FIRE SPREAD PROBABILITY
C
      WRITE (6,30)
30    FORMAT (5X,46HBAR-ADQ   SUP-ADQ   BAR-REL   SUP-REL   S-TERM,
     14X,47HBAR-EFF   SUP-EFF    ROOM-1    ROOM-2    ROOM-3/)
      CALL FPROB (F)
C
C EFFECT OF VARIATION OF PARAMETERS
C
      DO 60 I = 1,5
      WRITE (6,10)
      WRITE (6,30)
      X = F(I)
      DO 50 J = 0,20
      F(I) = J*0.05
      CALL FPROB (F)
50    CONTINUE
      F(I) = X
60    CONTINUE
      END
```

A5.3.2.2 FPROB

```
      SUBROUTINE FPROB (F)
      REAL F(5)
C
C CALCULATE EFFECTIVENESS FACTORS
C
      EB = F(1)*F(3)
      ES = F(2)*F(4)
C
C COMPLEMENTS
C
      ESC = 1.0 - ES
      EBC = 1.0 - EB
       TC = 1.0 - F(5)
C
C COMPUTE PROBABILITIES
C
      P1 = 1.0 - ESC*EBC*TC
      P2 = 1.0 - (EBC*TC)*(1.0 - P1)
      P3 = 1.0 -(EBC*TC)*(1.0 - P2)
C
C PRINT RESULTS
C
      WRITE (6,10) (F(I),I=1,5),EB,ES,P1,P2,P3
10    FORMAT (5X,10(F6.4,4X))
      END
      RETURN
```

APPENDIX A6

User's Guide to the Goal-Oriented Systems Approach

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A6.1 Synopsis

The essence of the revised Goal-Oriented Systems Approach to Building Fire Safety is in the concepts of containability and suppressibility of a fire in a compartment. Each of these is estimated by a stress-strength relationship of the severity of a fire versus the resistance of a barrier or of an automatic extinguishing system.

For the case of the barrier, the severity of the fire and resistance of the barrier are modeled as lognormal distributions of the same dimension e.g. hours of duration. The stress-strength relationship then identifies the adequacy of the barrier to contain the fire. The ulitmate effectiveness of the barrier also includes a factor of reliability, estimated as the expectation that the barrier is not immediately penetrable via openings or defective assembly.

The suppressibility of both the fire and the automatic extinguishing system are similarly modeled as lognormal distributions with a consistant dimension e.g. heat release/absorption. The stress-strength relationship predicts the adequacy of the suppression system and the expected reliability is estimated. The product of adequacy and reliability yields a measure of the effectiveness of the automatic extinguishing system.

A third concept, self-termination of the fire is also estimated as an expected value.

The probability of limiting the extent of a fire to the room of origin is then the Boolean sum of these three factors: The effectiveness of the barrier, the effectiveness of suppression and the expected value of the self-termination.

The probability of limiting the fire to within successive barriers is found by assuming a simple Markov process of fire spread whereby the probability of success of fire limitation at a given barrier is the intersection of the probability of failure of the previous barrier and the probability of the effectiveness of the present barrier.

A6.2 Procedure for calculating the probability of limiting fire spread to the compartment of origin.

Step 1. Input mean and standard deviation of lognormal distribution of post-flashover fire severity: $LN(\mu_{post}, \sigma_{post})$.

Step 2. Input mean and standard deviation of lognormal distribution of barrier capacity: $LN(\mu_b, \sigma_b)$.

Step 3. Calculate the probability that the barrier is adequate, $P(A_b)$, by the stress-strength relationship (A6.2.1).

Step 4. Input the barrier reliability: $P(R_b)$.

Step 5. Calculate the effectiveness of the barrier:

$$P(E_b) = P(A_b)\, P(R_b)$$

Step 6. If there is <u>no</u> suppression system $P(E_s) = 0$, proceed to Step 12.

Step 7. Input mean and standard deviation of lognormal distribution of pre-flashover fire severity: $LN(\mu_{pre}, \sigma_{pre})$.

Step 8. Input mean and standard deviation of lognormal distribution of capacity of the suppression system: $LN(\mu_s, \sigma_s)$.

Step 9. Calculate the probability that the suppression system is adequate, $P(A_s)$, by the stress-strength relationship (A6.2.1).

Step 10. Input the suppression system reliability: $P(R_s)$.

Step 11. Calculate the effectiveness of the suppression system:

$$P(E_s) = P(A_s)\, P(R_s)$$

Step 12. Input the probability of self-termination of the fire: P(T).

Step 13. Calculate the probability of limiting fire spread to the compartment of origin:

$$\rho_1 = 1 - [1 - P\ (T)]\ [1 - P\ (E_s)]\ [1 - P\ (E_b)]$$

Step 14. If the scenario includes more than one barrier proceed to A6.2.2.

A6.2.1 Procedure for calculating probabilities of the adequacy of fire control alternatives (barriers and suppression system) by the stress-strenth relationship.

Step 1. Transform the parameters (mean and standard deviation) of the lognormal distributions of the stress and strength to parameters of the normal distributions, $Y_i = \ln X_i$:

$$\mu_y = \ln \mu_x - (\sigma_y^2 /2)$$

$$\sigma_y = \ln [(\sigma_x / \mu_x)^2 + 1]$$

Step 2. Calculate the parameters of the normally distributed difference between the stress and strength distributions, $W = \ln X_1 - \ln X_2$:

$$\mu_w = \mu_{y1} - \mu_{y2}$$

$$\sigma_w = \sqrt{(\sigma_{y1}^2 + \sigma_{y2}^2)}$$

Step 3. Find the standard normal variate corresponding to the condition of adequacy, $P \{ W \geq 0 \}$:

$$z = \frac{\mu_w}{\sigma_w}$$

Identify the probability $P \{Z \geq z\}$ from standard tables or by numerical methods e.g. as in Appendix A4.4.2 Subrowtine STDNRM.

This is the probability that the particular fire control measure in question is adequate.

A6.2.2 Procedure for calculating the probability of limiting fire spread to successive compartments.

Step 1. Calculate the probability of limiting fire spread to the compartment of origin (ρ_1). (see A6.2)

Step 2. For each successive compartment, $P(E_S) = 0$.

Step 3. Calculate the probability of limiting fire spread to each successive compartment as if it were the compartment of origin (ρ_i, $i = 2, 3, \ldots n$).

Step 4. Calculate the probability of limiting the spread of fire to any successive compartment (n):

$$P_n = 1 - \prod_{i=1}^{n} (1-\rho_i)$$

A6.2.3 Notation

μ - mean (severity, resistance)

σ - standard deviation (severity, resistance)

b - Barrier

s - Suppression system

Pre - Pre-flashover fire

Post - Post-flashover fire

A - Adequacy

R - Reliability

E - Effectiveness

T - Self-termination

ρ_i - Probability of fire limitation within compartment i

P_n - Probability that the fire does not spread beyond compartment n

A6.3 Application of the revised approach to the Atlanta Federal Building

One of the first applications of the GSA Goal Oriented Systems Approach was the Richard B. Russell Federal Courthouse and Office Building in Atlanta, Georgia. This structure, referred to as the Atlanta Federal Building, is twenty-four stories high and contains over one million square feet of floor area. The lobby floor of the building is essentially unoccupied, the second through fourteenth floors are office space, the fifteenth and twenty-fourth floors are mechanical equipment spaces, the sixteenth houses the U.S. Marshal's Offices, the seventeenth through twenty-third floors contain two-level courtrooms and auxiliary activities. Two sub-levels contain parking, maintenance shops, storage and similar support functions.

The entire building is fitted with a hydraulically calculated, fully supervised automatic sprinkler system.

On floors two through fourteen, the general office space, there is a central core area which is separated from the remainder of the building as an area of refuge from fire. The separating walls are non-bearing, concrete masonry unit partitions.

Two critical events were identified for examination by the revised Goal-Oriented Approach: the limitation of fire spread within the general office space and the prevention of fire spread to the central core area of the structure.

Data necessary for the application of the revised approach was extracted from available reports [1, 2, 3] and the GSA document [4]. The input parameters are summarized in Table A6.1

Distribution of Post-flashover Severity: LN (28.0, 24.7)
Distribution of Barrier Resistance: LN (82.6, 28.8)
Probability of Barrier Reliability: $P(R_b) = 0.9995$
Distribution of Pre-flashover Severity: LN (0.054, 0.049)
Distribution of Suppression Resistance: LN (0.152, 0.048)
Probability of Suppression Reliability: $P(R_s) = 0.99$
Probability of Self-termination: P(T) = .983

Table A6.1 Input data for application of revised approach to Atlanta Federal Building.

The probabilities of the critical events for both the original GSA approach and the revised Goal-Oriented approach are presented in Table A6.2.

	Original	Revised
Limit to Office Area	0.9996	0.9988
Prevent Spread to Core	0.99999	0.99993

Table A6.2. Probabilities of fire limitation in the Atlanta Federal Building by original and revised approaches.

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The "L - Curve" for the office floors developed by the designing fire protection engineers is shown in Figure A6.1. Probabilities of limiting fire spread to within the office area for both the original GSA approach and the revised approach are identified. The revised approach produces a more conservative value, which is still within the goal level set by GSA. The probabilities of preventing fire spread to the central core for the two approaches are essentially coincident near the abscissa of Figure A6.1.

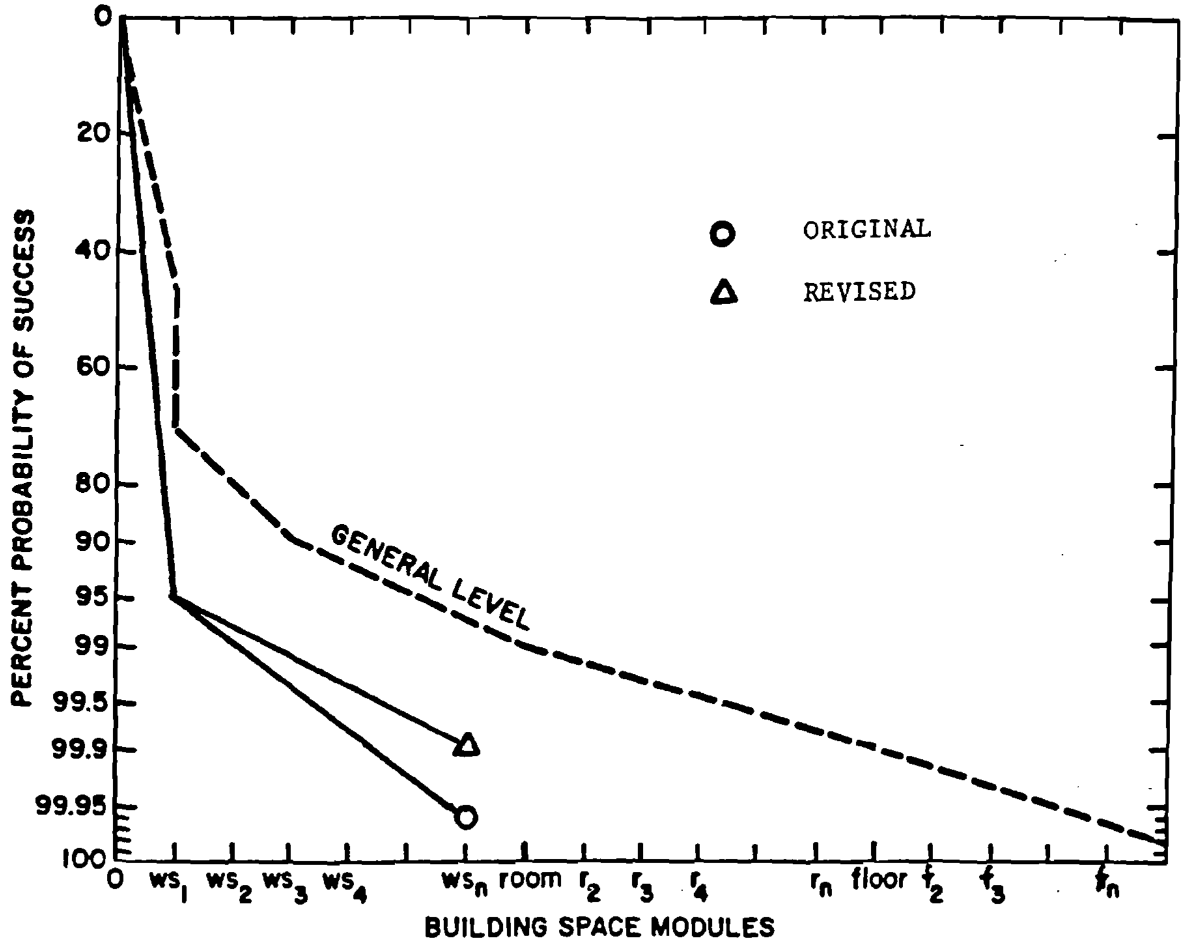
References

1. Ferguson, John B., Slifka, Michael J., Jensen, Rolf H. and Strull, Leslie, "The Application of the GSA Goal Oriented Systems Approach to Building Fire Safety to the Atlanta Federal Building", Presented to the NRC/NFPA Ottawa Life Safety Systems Conference (July 24, 1974).

2. Fire Safety Systems - Richard B. Russell Courthouse and Federal Office Building, Atlanta, Georgia, General Services Administration, Washington, D.C. (1974).

3. Jensen, Rolf H. and Strull, Leslie, "The Application of the GSA Goal Oriented Systems Approach to Building Fire Safety to the Atlanta Federal Building", Presented to Public Service International Conference on Fire Safety in High-Rise Buildings, Seattle, Washington (November 18, 1974).

4. Watts, J., The Goal Oriented Systems Approach, NBS-GCR-77-103, National Bureau of Standards, Washington, D.C. (July 12, 1977).



Richard B. Russell Courthouse

and

Federal Office Building, Atlanta, Georgia

L-CURVE. WS = Work Station, r = room, f = floor.

Figure A6.1