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REPORT FROM THE 1987 WORKSHOP ON
ANALYTICAL METHODS FOR DESIGNING BUILDINGS FOR FIRE SAFETY

Committee on Analytical Methods of Designing Buildings for Fire Safety
Building Research Board
Commission on Engineering and Technical Systems
National Research Council

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NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competencies and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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This report was prepared as part of the technical program of the Federal Construction Council (FCC). The FCC is a continuing activity of the Building Research Board, which is a unit of the Commission on Engineering and Technical Systems of the National Research Council. The purpose of the FCC is to promote cooperation among federal construction agencies and between such agencies and other elements of the building community in addressing technical issues of mutual concern. The FCC program is supported by 14 federal agencies: the Department of the Air Force, the Department of the Army, the Department of Commerce, the Department of Energy, the Department of the Navy, the Department of State, the General Services Administration, the National Aeronautics and Space Administration, the National Endowment for the Arts, the National Science Foundation, the U.S. Postal Service, the U.S. Public Health Service, the Smithsonian Institution, and the Veterans Administration.

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REPORT SUMMARY

This report represents the work of 75 persons assembled by the Building Research Board of the National Research Council to address the state of the art of analytical methods for fire safety in buildings. The group, widely representative of the research, design, regulatory and manufacturing sectors of the U.S. building community, was asked to evaluate three types of analytical methods for potential use in the design of buildings. It was the organizing committee's hypothesis that it should be potentially possible to base fire hazard and fire risk evaluation on scientific analysis, rather than on intuitive judgment or prescriptive building codes. Workshop participants were not asked to address funding issues nor were they expected to discuss organizational issues associated with fire research.

The seven papers presented at the workshop (reproduced in Appendix 1) address three analytical methods for improved fire safety design: (1) numeric methods that are on a point system intended to grade a building for fire safety and that are simple to use and provide explicit results, (2) deterministic methods that predict results based on known physical variables, and (3) probabilistic methods related to the potential for experiencing a fire hazard given the nature of the fire load.

Participants agreed that despite the important advances made in fire research over the last decade, there continues to be a need for a better understanding of the science of basic fire processes. While the analytical approaches presented show that progress is being made, it is necessary to continue development of engineering forumlas and mechanisms for technology transfer, support this with valid data measurements, and move toward more accurate predictions by all models. Better communications and improved educational programs, both for professionals in practice and for university students, were identified as important.

There was a consensus that better and more accurate quantitative fire safety design information, coupled with effective fire models, would raise public confidence in and use of fire protection engineering. Another recommendation calls for developing a rating system to determine the level of a fire hazard relative to an "acceptable" level through the use of analytical models. In their concluding deliberations, workshop participants called for a national committee to establish information and data needs, and to coordinate information delivery and conferences.

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INTRODUCTION

Responding to a request from federal construction agencies that the building community be provided with a forum to evaluate modern analytical methods for the design of fire safety in buildings, the National Research Council's (NRC) Building Research Board (BRB) established in January, 1987 a committee to organize such a forum. The planning committee was requested by BRB's Federal Construction Council (FCC), a consortium of 14 federal construction agencies.

This report addresses the state of the art of analytical methods for fire safety and their application to building design and public safety as reviewed and discussed at a three-day workshop held on October 14-16, 1987 at the National Academy of Sciences in Washington, D.C.

Seventy-five experts from a broad cross section of the U.S. building community participated in the workshop. Many of the participants were users of analytical procedures; others were concerned primarily with the validity of the computational procedures proposed for implementation. The workshop participants heard presentations on three of the leading analytical fire safety design methods and held discussions on the following topics:

- The status of modern fire safety design methods;
- Ways to help users evaluate these methods (both available and in development);
- Building community user needs of the methods; and
- Educational needs and delivery methods for their application.

Presented here are the summary and conclusions of the workshop, conference recommendations for action by the building community, and seven papers presented at the workshop that address three of these analytical methods for improved fire safety design.

In general, analytical fire methods consist of numerically-based models for evaluating fire safety performance of a building or a building component. In the workshop, three approaches were used to represent the scope of analytical methods in use or under consideration. The approaches are: (1) numeric grading systems which consist of guidelines based on a point system that are used to grade a building for fire safety (e.g., the Fire Safety Evaluation System - FSES); (2) deterministic methods that predict results based on known physical variables; and (3) probabilistic methods that assess the probability of experiencing a fire risk given a fire load.

The first day of the workshop consisted of presentations by three teams of leading experts consisting of a researcher and a practitioner. The presentations were organized around the three approaches, and the seven papers that were presented are included in this report in Appendix 1. The papers are:

Numerical Grading Systems

1. "Overview: Numerical Grading Systems," by Harold E. Nelson, National Bureau of Standards.
2. "Field Application of Fire Safety Evaluation Systems," by Jonas L. Morehart, National Institutes of Health.
3. "A User's Perspective of a Fire Safety Analytical Method: The Fire Safety Evaluation System (FSES)," by Kenneth Faulstich, Veterans Administration.

Deterministic Methods

4. "Analytical Methods for Fire Safety," by James Quintiere, National Bureau of Standards.
5. "Fire Protection Engineering Applications of Deterministic Models," by Russell P. Fleming, National Fire Sprinkler Association.

Probabilistic Methods

6. "Fire Risk Assessment Programs," by Frederic B. Clarke, Benjamin/Clarke Associates.
7. "An Integration Method for Translating Research into Engineering Practice," by Robert W. Fitzgerald, Worcester Polytechnic Institute.

The workshop's second day featured concurrent sessions consisting of six working groups: (1) fire protection engineers; (2) building and fire code officials; (3) owners, users, developers, insurance, and testing laboratories; (4) architects and engineers; (5) educators and researchers; and (6) product manufacturers. The third day was devoted to developing conclusions and recommendations.

It is the committee's hope that implementation of these recommendations will, through improved building design practices, reduce the number and magnitude of incidents of fire deaths and losses in the United States.

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SUMMARY OF THE WORKSHOP

Howard Emmons, a leader in the science of fire modeling, chaired the three-day workshop. His summary of the meeting, which was applauded by the participants, follows.

IMPROVE THE MODELS

Analytical methods are becoming more accepted by the leaders in the fire community. Many beneficial uses of these methods have already been made. Like all analytical methods, those presented during the workshop have limitations because there are limited techniques available today to validate fully all essential fire phenomena.

Researchers validate their analytical models using available data and professional judgment. Present modeling efforts incorporate many, but not all, of the aspects of fire phenomena. Models need to be adequately documented so that others can understand their limitations, assumptions and technical content. Validations must be based on their correctness and completeness, and their ability to accurately predict experimental results.

Organizations have developed eloquent fluid mechanics procedures to evaluate turbulence models. These organizations identify problems, certify good quality data, then invite modelers to submit their predictions for peer review. The intent is to move toward more accurate predictions by all models. Fire modelers should consider emulating this approach.

Models, especially deterministic models, require very specific data for materials or products undergoing combustion. The form of these data is becoming common to most models. The availability of the data is limited and not standardized. Work must be done to improve the availability of appropriate data and to improve the ability of models to deal with combustion processes. For example, rather than test five different manufacturers' chairs, the designer, using only handbook information about chairs, should be able to arrive at a satisfactory prediction of the chair's performance.

COMMUNICATION

Communication and education about the use of analytical fire methods need to be undertaken and addressed to all segments of the building community. Communication tools are needed to:

- Educate present and future fire protection engineers, architects, and general engineers using both degree-granting and mid-career methods, including those provided by university courses and conferences, and
- Give users the information necessary to select the appropriate analytical model based on the model's capabilities. Such information includes written documents, reference manuals, and descriptions about what available computer models can and can not do.

USE

The workshop literature describes currently available technologies that are beginning to form a base for the building community's use of analytical models. Advancing current technologies may be achieved by the following actions:

- Supplement present techniques with a new generation of scientifically-based Fire Safety Evaluation System (FSES) or other evaluation systems that can gradually increase the use of fire science and decrease the need for intuition.
- Aim for performance-based building fire codes. Building code officials base risk judgment on the prescriptive requirements contained in today's building codes. In order to ultimately use the various analytical systems, performance objectives must be defined and adopted into the codes, upon which the results of the analytical analyses may be judged for compliance. Currently, only a few fire-related problems that can potentially be solved by computer analytical analysis have adequate precision to allow computer design without separate professional analyses. It is time that additional steps be taken, beyond the early testing that has been done, to adopt a performance code for sprinkler system design.
- Develop a rating system to determine the level of a fire hazard relative to an "acceptable" level. For example, fire safety design for residences might be based on a rating scheme. Above a threshold rating, the building or the area within the building would be classified a fire hazard. Below the threshold, the area would be acceptably safe. Ratings for residences or interior areas might be based on an additive function of the rating of individual components that make up the interior of buildings (furniture, appliances, other contents). Thus, the homeowner could rate his own home and its contents.
- Develop methods to evaluate analytical fire models and select the best ones.

- Create a national committee to establish information needs and to coordinate information delivery. Additional quantitative information is needed to back up the knowledge base and to define in quantifiable terms the performance objectives of current building fire models and code regulations. When quantitative fire safety design information becomes available, it will raise the confidence in, and use of, fire protection engineering. The ultimate goal is to base fire hazard and fire risk evaluation on scientific analysis, rather than intuitive judgment.

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CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The workshop provided an excellent forum to learn about available analytical fire methods and to study in detail three modern analytical approaches to improving fire safety design. The practitioners at the workshop learned about the structure of available analytical methods and how to select the ones best suited for their particular use. The researchers learned about concerns and needs of practitioners that must be incorporated into the analytical methods.

The workshop consensus showed that analytical methods are available, applicable, and used by the fire design community. While these methods are still in their development stages, much work is being done to improve the accuracy of their predictive capabilities. Much more work remains to develop fully acceptable methods that accurately predict all aspects of the fire safety of buildings.

Many analytical fire models have been developed. Some of these are available to practitioners. Some analytical models are based on physics and chemistry. Others are derived from empirical correlations of tests and other data; while others are based on professional judgment. Fire models have not yet reached the state of development of other engineering practices such as structural engineering. Formulas are not as well developed, data are not as well organized, and applications are not as well used or accepted.

Structural engineers usually size structural elements using well-developed formulas based on the science of mechanics and from well-characterized properties of materials. Currently, the fire professional generally has only limited amounts of similar information available to make sound judgments about selecting appropriate materials for fire safety. However, as more research is performed, the data base will increase. Workshop participants recognized that many fire property tests include contradictory factors. For the most part, the reasons for such contradictory factors have their roots in tradition and opinion rather than scientific fact. The problem is lessening as worldwide acceptance of emerging fire science occurs. It will continue until a fully adequate scientific understanding of ignition, fire development, fire spread, and fire products is completed and broadly accepted.

Workshop participants agreed that despite the important advances made in fire science over the last decade, there continues to be a need to understand better basic fire processes and their scientific basis. It was recognized that the important groundwork set over the last decade is just now beginning to bear fruit. The analytical approaches presented during this workshop show the progress that has been made. If this progress is to continue to fulfill its potential, it will be necessary to continue development of engineering formulas and mechanisms for technology transfer, support this with valid data measurements, and increase the scientific investigations of the phenomena of fire.

Measurements need to be developed by various organizations to better quantify the fire phenomena in terms of the inputs needed by the various analytical methods; e.g., how materials burn, their chemical properties, the flow of gases, the hazards to humans from high temperatures and toxic materials, and the human reactions to fire. Also, evaluations of existing methods, as used by the fire professionals, will significantly augment the future iterative process necessary to develop better analytical methods.

The participants agreed that these analytical methods are professional tools, and the fire protection profession must take the lead to develop and implement these tools. The research and development segment of the fire protection profession must be sensitive to understanding the needs of users of fire models and responding to the need for a concentrated effort to transfer new fire methods, expeditiously, into improved design practice.

The participants agreed there is a need to understand better basic fire processes and their scientific basis. They recognized that the proportion of national resources dedicated to resolution of the fire problem has always been meager. This is not the first committee to recognize this problem. Prior activities include:

- The Presidential Commission report, America Burning;
- The National Academy of Sciences Committee on Fire Research proposals for a national fire research program in both 1959 and 1969;
- The National Research Council's report, Improving Communications Between Fire Researchers and Building Owner-Operators; and
- The National Bureau of Standards' report, National Fire Research Strategy Conference Proceedings, July 21-25, 1985, sponsored by the National Fire Protection Association and the National Bureau of Standards.

There was consensus that the fire community (which includes representatives of the research, design, regulatory, and manufacturing sectors) should build upon its strong links with one another by undertaking and supporting the tests, documentation, and assessment of the user's level of trust and confidence of the analytical methods selected. Through such work, the profession will better understand the processes needed to validate other analytical methods.

RECOMMENDATIONS

The Committee on Analytical Methods for Designing Buildings for Fire Safety recommended that the National Research Council, through its Building Research Board (BRB), provide oversight in the development, validation, delivery, and implementation of analytical fire methods. BRB should explore and develop methods to promote teamwork with others (including the international community) for developing and evaluating analytical methods. In this light, the National Bureau of Standards, the U.S. Fire Administration, and the National Fire Academy should be provided with resources necessary to fulfill the obligation for technology transfer assigned it by Congress under Public Law 93-498.

In addition to this general recommendation, the committee recommends five specific actions:

1. **Validate analytical fire models** Validations should answer the question--is the model technically sound? The creator of the model should document the science and engineering procedures used, the assumptions made, why they were chosen, the results of tests or others means used to compare model predictions with reality, and the resulting limitations. This evaluation should be guided by a national research organization with stature in fire research and technology delivery. In addition, a mechanism is needed to evaluate and approve for use the many new computer fire models. This should involve appropriate research and user organizations.

2. **Provide education** Educating the researcher about the needs of the practitioner, and the practitioner about the value of analytical fire methods is necessary. Technical and professional organizations and universities concerned with fire safety should hold continuing education activities in addition to stronger degree programs at the B.S., M.S. and Ph.D. level.

Publications should feature the latest information on new analytical methods. The information could be featured in special columns that highlight good practices and "horror stories." The media should provide a forum for identifying ideas for future technology to improve fire safety design.

Education contributes to meeting the need of gaining the confidence of building users, designers, and code officials to accept analytical methods in their profession.

3. **Identify research needs** The committee recommends an ongoing effort to identify research needs. The committee cites some examples where a significant increase in the current research effort could improve the vitality of analytical methods for fire safety: a scientifically valid means of quantifying fire suppression; algorithms to predict fire growth and burning rates; prediction methods for flame radiation properties; combustion processes and the production of toxic species, particularly in poorly ventilated spaces; and modeling of flame spread over surfaces of vertical walls and ceilings.

4. **Improve delivery of research results** The communication process is inadequate for effective implementation. Practitioners do not

generally read scientific journals. They tend to rely on engineering and technical publications, technical conferences, and short courses on new technologies. Strengthening the delivery methods of research findings will raise the confidence of practitioners in the use of analytical methods. Calling attention to the education process will help advance technology delivery. Public and private laboratories, academia, and the professional and technical organizations should undertake the following: (1) establish a library (perhaps a video tape library) of case studies of applications including successes and failures, (2) prepare manuals on applications of fire models, and (3) consider disseminating information to a wider range of publications including international journals. Improved delivery of technical findings will encourage the building community to become more involved in the development and adoption of analytical fire methods.

5. **Include cost-benefit approaches into analytical fire methods** Analytical fire methods provide the ability to evaluate and compare different design solutions based on cost, as well as effectiveness, in reducing the level of hazard. The building community's recognition of these potential financial benefits should assist in more widespread use of analytical methods.

The cost-benefit approach will provide the practitioner with information about using or not using specific analytical methods. The scope could include cost-benefit for quality control for use by the fire engineering profession. It may include plans and specifications, materials, and installation techniques. For example, using a cost-benefit approach the user could determine the cost-benefit of various design approaches to remove unsatisfactory risk.

Individual summaries of the six working groups follow in Chapter 4. These summaries provide the building community's perspective about the state of the art in fire safety design. The summaries also offer some conclusions and recommendations developed by the working groups.

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WORKING GROUP REPORTS

FIRE PROTECTION ENGINEERS WORKING GROUP

It was the consensus of this working group that analytical methods are applicable to fire safety design, and that these methods have been proven useful in direct applications. It is expected that this usefulness and applicability will expand and grow in the future. However, the applicability, limitation and future of the three types of analytical methods should be addressed to ensure continued development of the field.

Numeric analytical fire methods have broad applicability and are generally accepted. They can be simple to use and provide explicit results. They have a limitation in that they are subjective but they do provide comparisons and relative rankings.

Deterministic analytical fire methods also have proven their applicability and acceptability in solving specific engineering problems. They identify actual performance and can provide relative ranking when combined with other tools, e.g., cost-benefit analyses.

Probabilistic analytical fire methods are in a developmental stage, but exist at a level sufficient to provide relative ranking or comparisons. They demonstrate good potential given the development and compilation of a verifiable data base.

Needs

Several needs of fire protection engineers are addressed by analytical fire methods. Quantification of the effects of a given fire on its surrounding environment generally can be determined and documented. In addition, analytical fire methods provide the basis for relative ranking and setting of priorities.

The working group noted that the limitations of specific methods that are currently available have not been adequately identified and communicated. This concern has resulted in diminished confidence in the proper application of several of these methods.

Recommendations

The working group agrees that future development of analytical fire methods must continue to move toward more objective analysis rather than a sole dependence on qualitative analysis. The working group developed three recommendations:

1. **Validation** The research community must validate better the analytical fire methods used. This action can be accomplished through normal communications and feedback from the practitioners, quantification of societal accepted risks (goals implied by the existing building regulatory system), and compilation of detailed empirical and statistical data. This mandates an improved system for collecting such data and a depository for maintaining fire data.
2. **Documentation** Better documentation for all specific methods and for the overall concept is necessary. Specifically, the applicability and limitations must be made readily available. Advantages and disadvantages must be detailed; limitations are not considered a disadvantage.
3. **Education** The National Academies of Sciences and Engineering (or another recognized advisory body) should recommend, encourage, and advocate enhancement and continued growth of an educational infrastructure for fire protection engineering to fulfill the continuing needs of the research, design, regulatory, and operations communities.

CODE OFFICIALS WORKING GROUP

Code officials are responsible for developing, maintaining, and enforcing code requirements relating to the design, construction, and maintenance of buildings. Code officials keep abreast of new techniques, materials, and concerns relating to building design and construction. The code official, therefore, has a key role in the acceptance and use of new analytical methods of fire safety design.

Construction codes define a set of minimum requirements for the design and construction of a building. Although intended as a minimum, most fire safety code requirements often become the standard of design. Yet fire safety requirements cited in building codes and fire codes continue to be heavily specification-oriented, rather than performance-oriented, which limits implementation of new technologies.

The development of analytical methods of fire safety design has given the designer a means to address fire safety from a performance standpoint, rather than from the traditional specification standpoint. However, many practitioners perceive the use of new analytical methods as being hindered by building codes.

Most codes have a procedure to use new methods and materials in building design and construction. The acceptance of these new methods is dependent on the confidence that the building official has in the method. The challenge, then, is to establish or increase the building official's confidence in the use of these new analytical tools to gain wider acceptance.

In one form or another, there are already analytical methods related to fire safety design in use. These are generally used to supplement existing code concepts and to assist in the approval of buildings by the appropriate authority. Certain methods, such as calculated fire resistive ratings or the appendix of National Fire Protection Association (NFPA) Standard 72E, are used as tools for parts and portions of an overall fire safety analysis. Other methods, such as the Fire Safety Evaluation System (FSES) or the Building Officials and Code Administrators International (BOCA) Article 32, are used in a more comprehensive manner for evaluation of fire safety in existing buildings.

Analytical fire methods have not been widely used in the current code development process; however, it is clear that such methods can provide valuable information for consideration of future code and standards development.

Needs

Where these analytical methods reside, and how they are disseminated to the code enforcement community (e.g., put them in the body of the code, in an appendix, or in a separate referenced document) can be a determining factor in how effectively the methods are understood, accepted, implemented, and maintained. There are advantages and disadvantages to each potential location; care must be taken to choose the most appropriate. New analytical methods to which a working group subscribes should first appear in manuals as a means to introduce the user to the new technique. After the technique is considered common practice, it should be incorporated into the code. "Putting it in the code" is sometimes the first instinct, but may not always be the best choice.

Codes must establish the performance to be achieved. The workshop participants were clear that analytical methods could potentially serve as design tools, but that it was the role of building code authorities to determine what level of performance would be required for public safety.

Code performance objectives must be quantified and stated in easily understood terms. It is useful for the consensus standard approach to be used to validate and standardize those limited, but critical, assumptions that require judgment (as contrasted with those unusual cases where variables are pure enough to be determined by scientific means).

Future parameters for the use of analytical fire methods must be established. In many cases, the parameters can be based on existing codes. In other cases, new parameters will have to be established. In all cases, there will have to be discussion among the researchers, developers, and users so that parameters can be agreed upon.

Recommendations

The working group believes that there are no insurmountable obstacles incorporated in codes. They agreed, however, that there are system barriers to using analytical methods. The group developed three recommendations to help overcome the barriers:

1. **Confidence** The confidence of any method, whether a numerical grading system, an analytical hazard or a risk evaluation technique, depends upon the validity of the method being used. The practitioner must be convinced that the model does what it was designed to do. The user must be convinced that the model has been validated by appropriate comparison tests and peer review. It may be necessary to establish some form of third party certification of the computer code of the analytical models to give practitioners a level of confidence in their use.
2. **Understanding and "user friendliness"** The practitioner must understand what the model is designed to do and its limitations. The inputs to the models must be readily available and easy to use. If each use of the model results in a separate research project to arrive at the input numbers, usage will suffer.
3. **Training** Training for properly using the models is essential to prevent misuse. Understanding how the model works, its assumptions, and its limitations is essential. Without it, practitioners may extend the use of any model well beyond its limitations. Most, if not all, analytical models require use by an experienced practitioner. Warnings about novice use may need to be developed.

WORKING GROUP REPRESENTING BUILDING OWNERS AND USERS, INSURANCE COMPANIES, DEVELOPERS AND TESTING LABORATORIES

This working group made several observations during the workshop:

1. Analytical fire methods may be in the form of numerical grading systems, deterministic engineering methods, fire risk assessments or other methods. The critical path should be the progressive movement to a greater scientific, and less intuitive, base.
2. Developers should adopt broad views of the fire problem and not limit their studies to life safety applications (including property conservation and continuity of operations).
3. Working group members expressed concern about probabilistic approaches. The effects or consequences of saying there is a specific chance of failure are questioned.
4. Current analytical models are inadequately detailed once automatic suppression systems are activated. The working group suggests that this need receive future attention.
5. The working group asked who should provide the link between development/validation and application?

Needs

Several needs were identified by the working group:

1. There is a rapidly growing knowledge base in the physical, chemical and biological sciences that is important to fire safety efforts on a national basis. This knowledge needs to be nurtured, increased, properly transferred to, and incorporated into the design, evaluation and regulation of building fire safety.
2. Limitations, applications and purposes of the analytical methods need to be made more evident to practitioners.
3. There is a need to establish standard terms and definitions.
4. There is a need to validate analytical methods of designing buildings for fire safety prior to widespread application.
5. Subjectivity needs to be minimized to the extent practicable. To achieve this, a coordinated national plan should be initiated to develop further analytical methods including timetables and data collection. The development of the plan would assist in securing funding for development of analytical methods.
6. A national focus and leadership are needed to promote the research agenda; develop the science into useful technology; assure the credibility of results; and prepare the user community to adopt and apply the emerging knowledge and techniques.

Recommendation

The working group makes one key recommendation that it addresses issues raised during the workshop to solve programmatic and technical deficiencies in analytical fire methods. This recommendation is the designation of a national coordinating entity, such as the National Research Council's Building Research Board, or another appropriate neutral body, to develop and carry out a long-range plan for fire analysis and modeling in the United States and to perform related tasks (i.e., through a Joint National Committee for Fire Analysis and Modeling).

The recommended plan, as performed by this national committee, should include:

<u>I. General</u>

- A. Purpose of the committee
- B. Strategic policies of the committee
- C. Observations/assumptions
- D. A core plan, including:
  1. Primary (broad) objectives
  2. Strategies
  3. Subobjectives
  4. Substrategies and annualized goals

II. Selected Core Elements

A. Identify methods, models and applicable user situations.

B. Validate the identified applicable analytical fire methods. Validation may be achieved by:

1. Experience and examples from real world situations
2. Data base comparisons/evaluations
3. Testing (existing data and model-oriented experiments)
4. Comparisons between models

C. Identify and record limitations, purposes and applications of methods and models, and research needs.

D. Establish a national implementation plan to:

1. Develop practices and procedures for adoption, use, and reference by code groups; product, system and device certifiers; insurance authorities; standards developers; and engineers.
2. Build confidence in the methods via use and education.
3. Identify and develop funding methods.

E. Establish guidelines to define acceptable levels of risk and probability for use in applying and adopting methods.

F. Study, develop and propose methods to construct a data base upon which analytical fire methods can be used.

G. Identify and describe the effects of suppression systems on analytical fire analysis methods.

H. Study and develop methods to standardize terminology, reporting procedures and forms.

ARCHITECTS AND ENGINEERS WORKING GROUP

One of the strongest concerns of this working group is that fire safety should be one part of the whole picture of building and public safety. The working group members did not wholeheartedly believe that existing codes are particularly good. Codes are an existing tool with limitations, although working group members were quick to admit they did not have an alternative.

The working group also, expressed concern about keeping up with the various design changes made by building owners and the need to determine the impact these changes have on building fire loads.

The contents of the building (furniture, etc.) are major problems as they tend to change with design modifications. The working group posed a number of questions: Is it valid to design a building based on the original given conditions? Given three methods to design a building, how far apart will each resulting design be from one another? Does each get its base from a presumed fire size? These are important real world situations facing the designer. Predicting fire loads under these conditions is extremely difficult and cannot be done accurately today.

Needs

The working group recognized that research on analytical fire methods should continue. Analytical fire methods are currently based on assumptions. To create convincing analytical methods that will be embraced by the design professions, comparisons with real events and tests are needed.

FSES-type systems are a valid interim tool. They should be improved and enhanced by other analytical procedures.

Definitions of risk management and hazard analysis are needed for use in making decisions on levels of acceptable risk. New or revised building codes could then be based on new and better knowledge. Also, new analytical methods may lead to the elimination of occupancy classifications, which are crude expressions of anticipated fire loads. With this new knowledge, codes may be more flexible.

The analytical methods presented at this workshop conference appear to be valid and usable tools when used by specialists.

A method of packaging analytical methods is needed for acceptance by fire specialists, generalists, and enforcing agencies . Parameters for use need to be documented and alternatives listed. Used properly, analytical fire methods are valuable decision-making tools.

Recommendations

1. It is essential that the design professions receive information on the use and benefits of analytical fire methods. These methods should be described in a language understood by designers.
2. The working group seeks continued participation and involvement with the design professions in the development of analytical methods.
3. It is important that these methods be shared with the building code officials for implementation into the process of generating building codes and standards.

EDUCATORS AND RESEARCHERS WORKING GROUP

This working group summarized six primary areas of interest:

1. **Code, Numerical Grading, and Quantitative Inputs** The working group was impressed with the magnitude of the body of formulated analytical approaches to the fire hazard problem. These approaches include both the qualitative analysis exemplified in grading systems such as FSES and the quantitative analysis that has yielded mathematical models of building fires or parts of them, or closed-form solutions to many parts of the problem of fire safety.

The working group believes in the importance of close coupling of the elements of a tripartite system: (1) the fire code, (2) a numerical grading system, and (3) a way to supply inputs to that system derived, as far as feasible, from basic principles of decision science. The advantage of keeping numerical grading systems in the trio is that they provide a coherent structure that still allows some qualitative analysis of fire safety. These systems also readily accept change associated with aspects of operations research, management science, risk analysis, and quantitative analytical solutions or models to the fire safety problem or parts of it. This change, in the opinion of most of the group, has the best chance of effecting a formal code when the numerical grading system, having only an advisory status, and the code, having a firm legal position, are closely associated.

2. **Communication** As is so often the case with sophisticated quantitative technical problems, an increase in effective use of the quantitative output of researchers on fire safety depends critically on improvements in communication. There are at least categories of concern that the working group identified. They are: ambiguity and implementation.

The group noted that several terms used in the workshop were ambiguous and, therefore, generating confusion at the conference. "Code" should refer to standards or requirements having legal status. The term should not be used to describe the components of a mathematical model of fire phenomena unless preceded by "computer-." "Probabilistic" has several meanings. It should not be used to refer to personal opinions. It can be quantitative or qualitative. It may or may not be associated with analysis of a large body of data used to generate a distribution curve. Two quite valid but different meanings of "analytical" have already been used.

The term "model" has many meanings. A physical model permits a study of a real situation, such as a fire or a two-fluid model of buoyancy-driven phenomena. It is usually scaled down in space and up or down in time, using dimensional analysis, and it is constrained in its capacity to handle complex fire situations by the small number of dimensionless groups that can be made identical in model and prototype. A mathematical model can handle a far more complex mixture of parameters and variables, but it is usually coupled with physical assumptions that are not always valid. The models proposed at this workshop were mathematical.

There is merit in assembling data, on all models considered ready for use, into a matrix form with rows headed by model name and columns headed with the various phenomena that have been taken into account in formulating the model.

The second area of concern under communication involves implementation or the inadequacy of the literature that describes the various models of fire growth and spread now ready for use. The composition of the workshop participants reminded the researchers that their technical papers are often written for others in their field, not for architects, builders, owners, code officials, fire engineers, or manufacturers of building furnishings. Some of the fire-growth models are now so old that a complete description of them may be found buried in old literature or in journals that are never read by prospective model users. A fire model should be presented with a full description of the input data needed, such as properties, physical enclosure dimensions, fuel, spacing of combustibles, wall and ceiling description, and a qualitative description of all the forces, energy rates, and mass rates allowed. It should be carefully written and detailed enough for a non-mathematically oriented user to be able to form an opinion of the model's validity.

The question of who is responsible for seeing that every model claimed to be ready for use is accompanied by an adequate description of strength and limitations was not answered by this working group. Doing it properly will take much effort, much time, and much money, especially if verbosity is minimized and clarity emphasized.

3. **Validation of models** An analytical fire model should never be recommended for use until its validity has been proven through physical testing. Many good full-scale fire tests, (yielding data obtained at considerable expense) still await comparison with model results.

4. **Additions to Models** Many quantitative fire safety analyses and mathematical models are ready for use; but most do not model primary fire growth starting with a postulated energy release rate by combustion. Consequently, there are a number of physical phenomena not in current models that should ultimately be included as a part of a complete computer-based fire model. These phenomena include fire suppression and extinguishment or control; combustion of fuel gas produced when primary combustion occurs in ventilated atmospheres; allowance for the spread of flame over the surface of vertical walls and under ceilings; and more deterministic flame radiation models. Each of these topics is discussed below:

- Current fire models cannot be used to predict the effect of fire suppression agents. Deterministic models should be available that include the effect of sprinkler spray on predicted fire growth.* A strong incentive for accomplishing this exists in the need for engineers to have a concrete demonstration of how sprinkler protection can help reduce risk or better satisfy code requirements. Deterministic models should not only predict how sprinkler spray suppresses fire growth by direct water impingement, but they should also include indirect effects on flame radiation and vitiation of the environment. For comprehensive room-fire models to predict spray effects, it may be necessary to incorporate results from more detailed models that examine the complex droplet-gas dynamic interactions.
- In poorly ventilated room fires, the room oxygen concentration can drop far below the ambient value. Also, in the later stages of a fire the ceiling layer may approach the floor level and cause most of the fuel to burn within the ceiling layer. Under these circumstances, the combustion processes can be profoundly affected. Two effects are clearly important and should be included in fire models. First, the gas produced in the flame can be fuel-rich and contain large concentrations of carbon monoxide and other toxic species. Second, the fuel-rich ceiling layer may become flammable, and its secondary combustion can produce both a large increase

* The only sprinkler model known to the working group is one that predicts when a detector or a first sprinkler would be actuated.

in radiative flux to materials within the room and the transport of flaming gas into adjoining rooms.

- A primary failing of most current fire models is the lack of an algorithm to predict fire growth rates and burning rates without having to run extensive preliminary fire experiments. This failing is especially critical for fire spread up combustible walls and under combustible ceilings as the result of small ignition sources. The ability to predict fire growth involving combustible chamber linings is especially important for defining the fire environment for production and transport of toxic gases and thermal energy to remote areas of a building.
- Flame radiation is the dominant mode of heat transfer in all hazardous-scale fire spread in practical fuel arrays. Although the deterministic models include thermal radiation effects as an intrinsic part of the problem physics, there has been very little national effort to provide techniques for measuring material properties needed for models in this critical area. Methods or tests have not been formulated for obtaining flame radiation properties that will allow models to predict fire growth. There may be similar difficulties in measuring other material properties required by current models, but flame radiation is particularly critical.

Unresolved Problems. Three important unresolved problems were identified by this working group: (1) how best to transfer analytically generated outputs about fire safety from the research laboratory to users such as those who attended this workshop; (2) the furtherance of a safe process for changing adherence to fire codes from the satisfying of prescribed items to the satisfying of performance-related items coming out of decision science; and (3) the provision of a satisfactory way to put a stamp of approval on those decision-science-generated outputs on which consensus has been reached as to their validity and readiness to affect a grading system.

BUILDING PRODUCT MANUFACTURERS WORKING GROUP

The working group members represented building product manufacturers whose products range from plastics to noncombustible materials, to sprinkler systems and smoke detectors. These products are regulated by building codes; any changes in the codes or the way compliance is determined will have an impact on the manufacturers' business.

The working group made their observations from three perspectives of manufacturers of building products: (1) application of analytical fire models, (2) concerns about existing models, and (3) concerns about applying the models to building codes.

Application of the Models

Applications of analytical fire models are beneficial in the following ways:

- To save money on large-scale fire tests currently required for product certification;
- To prove code compliance of a new product;
- To assure the fire safety of a new product, thereby addressing liability concerns;
- To evaluate trade-offs or equivalencies to current code requirements; and
- To provide a more rational basis for decisions.

Concerns About Existing Models

The following are concerns about the analytical fire models as they currently exist and perceptions of future trends:

- There appears to be a proliferation of required product tests (rather than a decreased reliance on testing). There was concern expressed about the cost of these tests and the possibility of liability associated with the lack of standardization. Product manufacturers should not have to determine which tests are appropriate for their product. The working group members seek a reduction in required full-scale testing for code compliance.
- The documentation of the models is weak, particularly with regard to their assumptions; what is and is not assumed and how the assumptions are developed. There is concern about the degree to which judgment is used in the models, instead of facts.
- The National Fire Incident Reporting System (NFIRS) data base is biased toward the negative; i.e., the failures, and does not reflect good performance. The working group members are concerned that the data collected are all failure data.

Concerns About Applying the Models to Building Codes

The following concerns were voiced about using analytical fire models to determine the level of fire safety in a building:

- Subjective judgments used in the modeling process are not exposed to the rigors of the consensus process.
- Models tend to focus on life-safety concerns. While building codes address property protection, this should not be neglected if models are to replace building codes.
- Models should not be used to determine the acceptable level of risk. This should remain in the code domain.
- Deterministic models do not take maintenance issues into account (for example, sprinklers being shut off or fire barriers being penetrated).
- Code officials must understand the current level of risk provided by codes so that they can accept a finite risk determined by modeling.

- If specific application of analytical fire models becomes standardized, it then becomes the responsibility of product manufacturers. These are associated liability concerns.

Recommendations

1. Analytical fire models are ready for use as alternative tools to individual code provisions (i.e., to determine equivalency); however, they are not ready to replace the current code requirements. After further refinement of these models, it is recommended that a new code approach be developed, based on a required performance level of risk to be evaluated by the model, rather than a replication of current code provisions.
2. Analytical fire models should not be used to determine acceptable levels of risk; these quantitative design objectives must remain in the public domain through the building code process.
3. Research should be continued. The working group recommends the consideration of the following priorities among those now under consideration:

   - Models of fundamental generic material properties rather than standard tests,
   - Smoke transport in buildings,
   - Extinguishment (still a weak point in buildings), and
   - The role of barriers in building design for fire safety

4. The NFIRS data base should be improved to include the small fire, the role of construction type, the architectural layout on the fire, and other information useful to modelers.
5. The analytical fire models should be better validated (need an accepted way to run a model through the validation process).
6. Assumptions in the fire models should be clearly documented.
7. A clear statement of input information for the fire models should be made.
8. It is important to use opportunities, such as this workshop, to describe collectively research needs and priorities. There is a need for the development and oversight of a framework or matrix illustrating modeling research goals that can serve to identify research needs and priorities and eliminate duplication.
9. Implicit in the quantification of fire spread is the quantification of risk. An essential first step in making the building code community comfortable with this concept should be the quantification of the risk inherent in today's code-complying buildings.

APPENDIX 1

PAPERS PRESENTED AT THE WORKSHOP

Builing Research Board
Workshop/Conference
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Analytical Method of Fire Safety Design

Overview - Numerical Grading Systems

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ABSTRACT

This paper address the background, theory, methodology, potential and limitations of numerical grading systems. A number of dirrerent systems are briefly discussed. Particular attention is given to the methododology involved in the developoment of the Fire Safety Evaluation Systems (FSES's) and the approaches used to enhance professional judgement in this process. The futrere potential of replacing major elements of professional judgement with engineering clalculations is discussed.

1. INTRODUCTION.

A numerical grading system can be defined as a catalog of definitions or other descriptive guidelines that:

Relate important, physical features, protective systems or other elements of a facility to numerical values. Usually the numerical values have no dimensions.

Contain a method of combining the numerical values to produce a grading. The form, nature, and purpose varying widely from grading system to grading system.

Often, but not always, provide a method of relating the grading to a standard of quality.

Fire hazard grading systems have been in use for fire insurance underwriting purposes since the first decade of this century. The best known advocate of such systems was A.F. Dean [1900 and 1901]. Dean [1903] promulgated his grading systems to avoid a chaotic system of actuarialy unsound competitive bidding. In his day this left some insurance companies without sufficient funds to pay losses. The dominant force in fire safety for the first half of this century was insurance economics. Insurance grading systems had a primary intent of equable spreading the loss. These systems did not address life safety or mission capabilities.

After World War II, The Ministry of Works in the United Kingdom [1946] published a system titles "Fire Grading of Buildings". This was probably the first grading system related life safety in commercial and residential buildings. Extensive application of grading systems to life safety did not come, however, until the advent of the fire safety evaluation systems in the United States and the Gretener and related national systems in Europe.

2. System Methodologies

All grading systems operate on the basis of assigning values to conditions. Nevertheless, each system has its own value assignment and grading method. The methods vary from ad hoc judgment by the user to detailed procedures with elaborate formulas and extensive catalogs of support information.

Scores are usually developed into a grading in by:

A. Addition of assigned values.
B. Multiplication of assigned values.
C. Selection of a single value. Normally either the highest or lowest value, depending on which is more significant to the intended use.

D. Manipulation of the assigned values to produce a hazard profile.

2.1 Matrix Systems

The simplest type of grading system is a matrix. There are many versions of this type of approach. Figure 1 is a hypothetical example. The approach shown is common to many matrices. The entries into the matrix are determined on an ad hoc judgement basis by the user. In Figure 1, the rows represent potential types of fire impact. The columns, the likelihood of occurrence. The numerical values within the matrix are assigned, by the matrix originator. In Figure 1 different fire impacts (rows) are assigned different values for the same likelihood of occurrence (column.) This to recognize the relative level of importance of each type of impact in the opinion of the originator. With this arrangement the grading is derived by adding the values selected for each row. This produces a single score that combines the conditions evaluated by the user with the value judgement of the originator. This is useful in appraising a large inventory of a differing facilities. Such approaches are frequently used to set priorities in limited situations.

Matrices are also been used in more sophisticated analyses systems. Systems have been developed where a series of matrices are used. Often one matrix produces the inputs to others and the scores produced by the individual matrices are multiplied to derive a single result [Watts, 1981; Department of Fire Safety Engineering, 1982; Stolard 1984].

2.2 Graphic Scales

Some grading systems use a graphic scale to expose a reasonably complex system as a visual presentation. Figure 2 is such a system developed by the author to grade hazard in office type structures [Nelson, 1974]. This provides the user with a scoring system expressed in terms of the physical conditions. As compared to a matrix, a graphic scale requires less sophisticated judgement on the part of the user but greater responsibility on the part of the originator. In this system, the left side represents conditions that determine the size of fire, the right, those that determine the likelihood of fire. The presence or absence of sprinklers is used as a general modifier of the right side score. The system approximates multiplying maximum potential by the likelihood of fire occurrence.

2.3 Insurance Underwriting

A number of various grading systems have been used for insurance underwriting. The system with the most sophisticated rationale, is the Analytical System for the Rating of Fire Hazards originally developed around the turn of the century by Dean [Dean, 1903.] This system was used until the 1970's for insurance rating. Functionally, the system uses from a large catalog of charges for construction, occupancy, and hazard. The system is elaborate and during its use, the insurance industry had an extensive infrastructure to support it. This included rating bureaus, actuarial bureaus, and an educational network. One aspect of the educational underpinning was the Fire Protection Engineering degree course then offered at Illinois Institute of Technology.

The analytical system examined the basic construction and finish of the building, the fire protection equipment (other than sprinklers), and the classification of occupancy. Hazard of occupancy was based on fire causes, media evaluation, and damageability. The media evaluation included factors related to rate for fire spread and rate of heat release. The exposure of one building to another was also evaluated. All scores were expressed as monetary charges or credits.

Within the analytical system are methods for the development of the charges and credits from the descriptions of material and use. This even if the particular type of materials or operation is unlike any entry in the catalog. If Dean were alive and active today, I believe he would replace his broad narrative descriptions with material properties, calculations of fire growth, and response of protection equipment to produce deterministically based rates.

In the Dean system, the rate was generated with one charge addressed to the structure and a second charge addressed to the contents. By this, Dean recognized the susceptibility of the contents of a building to harm.

2.4 Gretener's Method

A number of company countries in Western Europe use one of the variation of Gretener's method [1976]. In many ways, Gretener's method is an updated version of the analytical system. It is very extensive and complex. It is, however, based on the simple formula

$$R = P/M$$

Where: R = potential risk of actual fire
P = potential danger
M = protective measures

The value of P is derived by a multiplication of individual values developed for heat load, combustibility, number of floors, size of rooms, danger of fire, danger of corrosion, danger of fire activation, and combustibility of values.

M is similarly developed by a multiplication of factors assigned for standard protective measures, special protective measures, and fire resistance rating.

There are several versions of Gretener's method. Each is accompanied by a large catalog that uses graphs, tables, formulas, and other entries to develop the individual values for each factor. In each case, these individual values are based on the physical characteristics or other measurable factors. The conversion of these measurements to the entries in the risk formula involves a wide range of weighing factors. These factors are judgement derived by the system originators.

2.5 Fire Safety Evaluation Systems

Over the past decade, a series of grading systems called Fire Safety Evaluation Systems (FSES) have been developed at the Center for Fire Research, National Bureau of Standards (CFR). Those developed at CFR range over a number of occupancies including health care, detention, correctional, board and care facilities, apartments, hotels, and office and laboratory buildings. An additional FSES was attempted to address problems in coal mines. In that case we were unable to converge the judgement opinions sufficiently to develop a viable system.

In addition, various other organizations have undertaken grading systems patterned after the Fire Safety Evaluation Systems. Most notable of these is Article 25 of the Basic Building Code [BOCA, 1984.] In view of the author's familiarity with the CFR efforts, the discussion applies exclusively to the versions produced at CFR. Examples used are from the Fire Safety Evaluation System for Health Care Facilities [Nelson and Shibe,1978].

The core of the FSES lies in two tables. These are tiled Safety Parameter Values and Individual Safety Evaluation. (See Figures 3 and 4.) The FSES for Health Care Facilities is coordinated with the Life Safety Code [NFPA 1985]. Figure 3 presents the Safety Parameter Value table from that FSES. The Safety Parameter Values consists of two types of entries. These have been arbitrarily titled Safety Parameters and Parameter Values. The Safety Parameters list the basic requirements of the Life Safety Code.

The Parameter Values cover the usual levels of variation that can occur within these parameters. Later, this paper presents a more thorough discussion of the development of the individual parameter values. For each variable condition of each safety parameter, there is an assigned value. In some cases, two values with footnote instructions on which value to use.

In general, the terminology used to identify the parameters and their variable levels of performance is that used in the Life Safety Code. Persons familiar with the Life Safety Code can often complete the FSES fire safety parameter value form without any special instructions. A brief glossary is provided, however, to assist where questions arise.

A special feature of the Fire Safety Evaluation System is the second form entitled, "Individual Safety Evaluations." See Figure 4. The purpose of this form is to assure the degree of redundancy inherent in the Life Safety Code is preserved. Effectively this form constrains "trade-offs" to systems of safety where the impact of the protection that exceeds the normal requirements are directly compensating in terms of fire safety methodology for the those where the level is less than that normal.

In the Fire Safety Evaluation for Health Care Facilities, four separate individual safety evaluations are made. These evaluate fire containment, providing fire extinguishment, and people movement (and/or refuge) and overall (general) fire safety.

In using the FSES, the individual fire safety parameters are appraised with Safety Parameter Value form (Figure 3.) The values obtained are transferred to the Individual Safety Evaluation form (Figure 4) and each of the columns in that form is added. The total for each column is independent of that for any other column. The results produce a profile of four individual scores rather than a single value.

As used in the Life Safety Code, the Fire Safety Evaluation System is designed to determine the equivalency of an alternative fire protection system to one that would exactly meet the requirements of the Fire Safety Code. This is determined by establishing the profile of a hypothetical building that exactly matches the requirements of the Life Safety Code. Any building in which all four of the evaluations produce values equal to or greater than those of the hypothetical building is considered to be equivalent to the Life Safety Code.

If a building fails the FSES, it may or may not be equivalent to the Life Safety Code. This ambiguity arises because the FSES is limited to evaluating fire protection hazards and methods, the type and character currently listed in the Life Safety Code. There are other fire protection systems that could provide excellent protection that are not evaluated by this system.

3. LIMITATIONS

All current rating systems involve subjective judgment. Also, virtually all current codes and regulations are founded on subjective judgments. It is, therefore, legitimate to compare the quality of a grading system to the quality of a code or regulation. In both cases validity is a function of the care and quality of the methods and organizations involved in preparing the document; the extent, meaningfulness, and quality of review provided; and the quality of facilities built to conform with the grading system or the document.

The system with the greatest amount of experience is the Dean System [Dean, 1903.] This system was used for almost 70 years. Since it was an insurance underwriting system concerned with economic impact rather than the impact on individuals, it is judged as an actuarial system. During its hay-day, there were many actuarial bureaus oversighting its use.

The Dean System has a simple tuning mechanism. There is a set of conversion numbers (called basis rates) used as multipliers to adjust the analytical charge developed by the system. These basis rates used to be recelebrated every year to reflect the previous five years fire loss experience. To that extent, the Dean System is a charge back system designed as an equitable method of recovering fire insurance losses.

The accuracy of simple systems such as the single matrix and the GSA form depend on the relative transparency of the method itself. They are felt to be suitable for first order screening but not really appropriate for detailed decision making.

The FSES's, as developed by CFR, are designed for use with the appropriate designated reference codes (i.e. chapters of the Life Safety Code.) Since the FSES determines equivalency with a building that exactly meets the reference code, its use can readily result in buildings that are exactly at the level prescribed by that code. The user then must accept the level of fire safety provided by the reference code as his actual objective. If this is not sufficient, he must adjust upward the mandatory performance requirement in the FSES.

Beyond these, the prime limitation of the FSES is the degree of confidence that the user places in it. The Committee on Safety to Life of the National Fire Protection Association [NFPA, 1985] has expressed a large degree of confidence in the several that have been incorporated into the Life Safety Code. It would be inappropriate, however, to indicate that every member of that Committee is comfortable with the grading system.

The validity of the evaluation system approach then rests primarily on the three factors of:

a. the completeness of the universe of parameters and parameter levels in Figure 3;
b. the appropriateness of the relative parameter values assigned in Figure 3; and
c. the relationships established in Figure 4.

The system was developed and the above problems attacked using four different groups of technically qualified persons. Individual groups entered the process at various stages of development but continued to participate from that point until the essential conclusion of the project.

a. Project Staff. The project staff proposed the parameters, the variable levels of the parameters (but not the value of these levels) and the "redundant" fire safety objectives that constitute the column headings in Figure 4. The basic tools to achieve this consisted of a detailed analysis of the requirements of the Life Safety Code, and an event-logic evaluation of the fire safety methodologies available using references such as the National Fire Protection Association Decision Tree [NFPA, 1980]. The prime product was a form similar to that which now constitutes Figure 3 except that no parametric values were included.

b. NBS Delphi Panel. A Delphi panel consisting of the best qualified persons in CFR was assembled. This panel critiqued the proposed parameters and established the relevance of each to the redundant fire safety objectives in Figure 4. This panel also provided the initial estimates of the relative parameter values. The mechanism involved a cyclic delphi approach. Individuals privately made their best estimates of the parameter values. Each member of the panel made his estimates first in terms of the overall impact on fire safety in health care facilities. Each member of the delphi panel also made three additional appraisals. These focusing on the redundant fire safety objectives of containment, extinguishment and people movement. The process was cycled several times following traditional delphi concepts and eventually brought to initial consensus in panel sessions. The values for general impact were then used for the initial version of Figure 3. The relative values developed by the appraisal of the three redundant objectives was used to develop Figure 4. The basic methodology used to develop Figure 4 was to eliminate from consideration those parameters where the evaluation of the redundant factor showed little or no variation in impact between the highest and lowest rated level for a given parameter.

c. Peer Consultant Group. The Peer consultant group consisted of recognized authorities in fire safety, health care, and standards and regulation. The Peer consultant group compared the levels of safety produced the evaluation system relative to delivered by prescriptive compliance to the Life Safety Code. The techniques developed through these meetings are felt to be the most important new contribution to judgment enhancement from this effort and will be discussed further.

d. NFPA Task Group. At a point in the development of the system, it was formally submitted to the National Fire Protection Association Committee on Safety to Life as a proposed addition to the Life Safety Code. The responsible subcommittee of that organization set up a special task group to review this system. That task group was essentially a replication of the peer consultant group. It also provided special expertise in assuring that the parameter levels reflected the current technological base and intended meanings of the Life Safety Code.

The four groups worked in a cyclic feedback system. Each problem or question raised was recycled through all four groups until a broad based consensus was reached. The basis of consensus being that the results produced are equivalent to the level of safety achieved through explicit compliance with the Life Safety Code.

A number of tools were used to provide data to prove the system. Initially this was attempted with field tests, voluntary completion of the forms by facility administrators and engineers, and exercising of the system by fire authorities. All of these were useful. However, they tended to present cases in which the level of safety was either clearly poor or conversely obviously good.

It became apparent that the ability of the system to delineate those buildings that were marginal was not being appraised. To attack this problem, a computer sorting program was developed. This program is capable of presenting all of the possible satisfactory solutions for any building. Since there are between 300-500 million possible permutations of Figure 3, the computer program is arranged so that the user can set logical limits. It also reports only solutions judged by the FSES to be equivalent to the Life Safety Code. Normally, this process reduced the search for alternatives to less than 1,000. The staff then selected those strategies that represented the least demanding (from a fire safety performance view) acceptable solutions. In most cases, this reduced the number of strategies for examination to 10 or less. The residual critical cases were then presented to the Peer Advisory Group and the NFPA Task Group.

The method of presentation is shown in Figure 5. The left hand column of Figure 5 represents the parameter requirements specified for the particular class of buildings by the Life Safety Code. The right hand column represents the comparative set of performance requirements produced by the evaluation system for the case being appraised. The group then attempted to answer the two following questions.

a. Which of the two solutions produces the higher probability of freedom from fire harm for a patient over the life of his/her stay in the facility?

b. Would safety be enhanced if the evaluation system solution were revised to eliminate all of these features that exceeded the minimum requirements of the Life Safety Code in return for upgrading all features to the minimum required by the Life Safety Code.

The response to these two questions consistently brought out the strengths and weaknesses in the solution. The second question tended to eliminate habitual preference to the Code.

The vast number of possible parameters prevented such an examination of every conceivable alternative that could be produced by the evaluation system. The process, however, was repeated through each of questionable solutions. The selection of solutions to be evaluated was derived from conditions found in the field surveys, occurring in the sample evaluation system submitted, or raised by any member of the review groups or other source. The process resulted in a consensus of commitment to the credibility of the system by the collected advisory groups.

In application, the FSES systems have demonstrated an ability to:

a. Significantly reduce the cost of upgrading existing facilities to meet minimum levels of fire safety.

b. Permit increased flexibility in design.

c. Develop options more suitable to operating needs.

As the result of the level of interest in using this approach in other areas, the following brief protocol has been proposed as a guide to choosing problems amenable to solution by systems such as the Fire Safety Evaluation Systems.

a. The data on methods available to attack the problem involve degrees of uncertainty that preclude solution through traditional analytical methods. This type of consensus approach should be considered inappropriate in any case where its possible to apply basic principles of physics and chemistry, established deterministic engineering procedures, or statistical analysis from a sufficient data base. However, where the preceding are not sufficiently complete to provide the needed answer, an evaluation system approach should be considered.

b. The problem at hand involves complex interactions that have a potentially identifiable universe of parameters and the parameters have potentially identifiable levels of performance. The evaluation system appears to work best where the universe of the overall problem can be conveniently broken down into between 8 and 20 parameters and these individual parameters generally have at least three levels of performance.

c. The necessary degree of resolution of uncertainty is potentially within the limits of consensus by experts enhanced by the best available data and technology. It must be expected that there will be a degree of variation. If mathematical precision is necessary, this approach is inappropriate. If, however, the objective is to improve methods such as current codes and regulations that in themselves are produced by judgment, the evaluation system approach can both enhance the use of that judgment and bring those making the judgments to a finer level of appreciation and consensus in their efforts.

d. The necessary experts exist and will participate. This process is only as good as the talents of the participants. While the number of participants in any group appears to best function with 10 to 20 participants, the quality of the participants is significantly more important than the number. It is essential that participation in any of the judgment groups should be based on professional qualities rather than position per se.

e. Working conservative solutions as opposed to predictive models will meet the needs. Evaluation systems must, in all cases of dispute, reach consensus by moving towards the safe or conservative position. The end result will be a system in which error is to the safety of the individual. As such, it should always over perform rather than be an exact model.

f. Project direction involves one or more persons with broad knowledge in critical aspects of the problem. While functional knowledge of operations research, delphi approaches, and other data organizational and analysis means are important, the development team must include a strong background in the type of occupancy or facility being evaluated and the technology of the objective of the evaluation (e.g., fire safety, accident prevention, security, etc.).

5. FUTURE

As discussed, I believe that the place for the current types of grading systems is in those situations where the problem involves degrees of uncertainty that currently precludes solution through traditional analytical methods.

More important, I believe the future holds the opportunity for better fire safety through high-bred methods that merge deterministic computations with statistical data and enhanced consensus judgement as partners, not competitors. As I see it, as quickly as appropriate deterministic engineering calculation methods become accepted, they should be used as a principle element to derive scaling values in grading system. Also, the best mathematical fire models should be used to produce evaluations of the fire conditions developed in selected senecios. The range of senecios covering the variables permitted by the proposed grading system. The best qualified and supported judgement will still be required to propose the variables, select the computations and models, choose the senecios, and evaluate the impact.

A first, admittedly primitive, effort in the direction of combining computation with judgement in a grading system is incorporated in the last FSES developed at CFR. That FSES is titled "Fire Safety Evaluation System for NASA Office/Laboratory Buildings" [Nelson, 1986.] It is currently up for adoption in the Life Safety Code to apply to existing office buildings. In that FSES the judgement of the hazard of a laboratory is based on analytical estimates of the potential for flashover and the subsequent fire duration. Similarly, the charges for hazard resulting from unprotected openings between rooms and exit access corridors are based on a procedure for estimating the time to fill the corridor to head height.

Finally, I see a future where grading systems, hazard indices, deterministic calculations, mathematical modeling, and probabilistic systems combine in networks of systems with common roots, exchanged modules, but different applications. I hope that this conference will see this same potential and the tremendous value to society of setting our goals to achieve it.

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IMPACT	LIKELIHOOD OF IMPACT				
	CLEAR & PRESENT DANGER	ABOVE AVERAGE PROBABILITY	AVERAGE PROBABILITY	LESS THAN AVERAGE PROBABILITY	ALMOST NIL
A. MULTI-LIFE LOSS	10	7	5	3	0
B. MISSION DISRUPTION	5	4	3	2	0
C. SINGLE LIFE LOSS	5	4	2	1	0
D. SERIOUS INJURY	2	1	1	0	0

FIGURE 1. HYPOTHETICAL RISK EVALUATION MATRIX

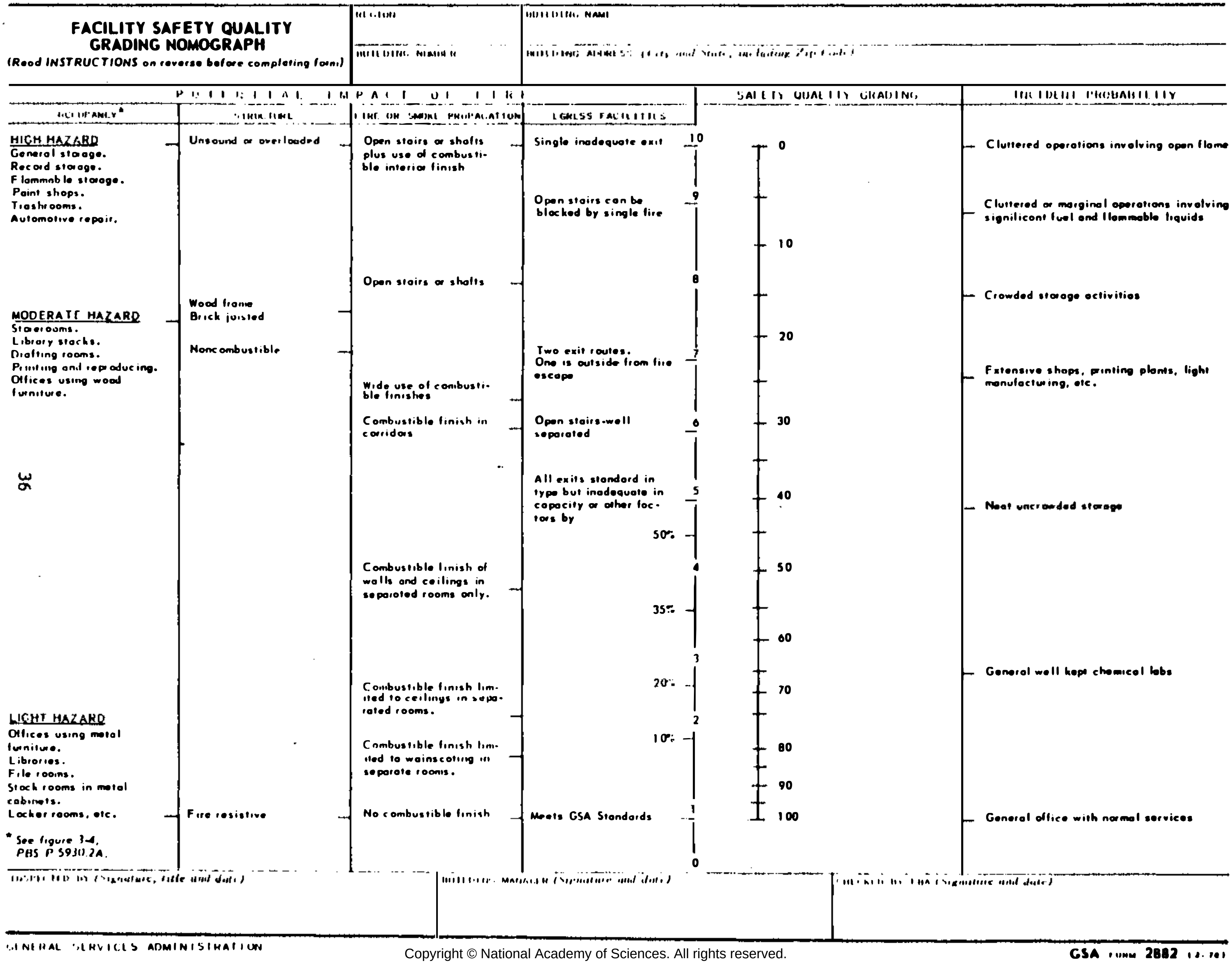

Figure 2 (Part 1 of 2) Facility Safety Quality Grading Nomograph

INSTRUCTIONS FOR FACILITY SAFETY QUALITY GRADING NOMOGRAPH

PURPOSE OF NOMOGRAPH

The purpose of this nomograph is to provide a simple quick method of determining relative safety of buildings by interrelating the most significant factors of the potential impact of fire against the factors controlling the probability of such fire occurrence.

POTENTIAL IMPACT OF FIRE (LEFT SIDE)

Factors governing fire potential are divided into four categories: (1) Occupancy; (2) Structure; (3) Fire or smoke propagation; and (4) Egress facilities. These factors of potential are arranged in descending order of importance, so that the most serious factor governs. Circle the most applicable condition in each of the columns. If none of the conditions described accurately indicate the existing conditions, select a point in the column appropriate to the situation as compared to the items listed, make a note in the appropriate open space, and mark that point in the column.

PROBABILITY OF INCIDENT (RIGHT SIDE)

Factors governing probability of incident also are arranged in descending order of importance and probability of a fire. Mark the appropriate point in the column.

USE OF NOMOGRAPH

When the selections are made in each of the five columns, the highest governing factor in the four columns on the left determines the point of the left entry line of the nomograph, and the point selected under incident probability determines the point on the right entry line of the nomograph. A line is then drawn connecting those two points. The point at which it intersects the numbered scale determines the relative safety quality grading of the building. The numbered scale on the nomograph runs from 0 to 100. The 100 point on the scale represents conformance with GSA standards in all factors.

The left hand scale on the nomograph is numbered from 0 at the bottom to 10 at the top. The fire potential scale corresponds to hazard as indicated below:

Index Number	Maximum Potential
10	Significant (Multiple) Loss of Life
7.5	Total burnout of all or a major portion of the building or a single fatality.
7	Permanent total injury.
6	Burnout of one floor
5	Permanent partial injury
4	Burnout of a corridor, series of rooms, or a large open space.
3	Temporary total injury.
1	Burnout of one room.
0.5	Minor injury.
0	Burnout of one workstation (desk, lab bench, etc.)

Sprinkler Protected Buildings

The numbered scale (0 through 10) on the potential (left) side serves a dual purpose. In any case where a building is totally protected by automatic sprinklers, the number initially entered should be divided by three and the entry made from the number equivalent to that quotient.

GSA form 2882 BACK (7-74)

Figure 2 (Part 2 of 2) Instruction for Facility Safety Quality Grading Nomograph

SAFETY PARAMETERS VALUES

PARAMETERS	PARAMETERS VALUES						
1. CONSTRUCTION	COMBUSTIBLE TYPES III, IV AND V				NON-COMBUSTIBLE TYPES I AND II		
FLOOR OF ZONE	000 (U)	111	200 (U)[e]	211 + 2HH	000 (U)	111	222, 332, 443
FIRST	−2	0	−2	0	0	2	2
SECOND	−7	−2	−4	−2	−2	2	4
THIRD	−9	−7	−9	−7	−7	2	4
4TH & ABOVE	−13	−7	−13	−7	−9	−7	4

PARAMETERS						
2. INTERIOR FINISH (Corridors & Exits)	CLASS C	CLASS B	CLASS A			
	−5	0	3			
3. INTERIOR FINISH (Rooms)	CLASS C	CLASS B	CLASS A			
	−3	1	3			
4. CORRIDOR PARTITIONS/WALLS	NONE OR INCOMPLETE	<1/3 HR.	≥1/3<1.0 HR.	≥1.0 HR.		
	−10 (0)[a]	0	1 (0)[a]	2 (0)[a]		
5. DOORS TO CORRIDOR	NO DOOR	<20 MIN. FPR	≥20 MIN FPR	≥20 MIN FPR & AUTO CLOS		
	−10	0	1 (0)[d]	2 (0)[d]		
6. ZONE DIMENSIONS	DEAD END			NO DEAD ENDS >30' & ZONE LENGTH IS		
	> 100'	50'−100'	30'−50'	>150'	100'−150'	<100'
	−6 (0)[b]	−4 (0)[b]	−2 (0)[b]	− 2	0	1

PARAMETERS					
7. VERTICAL OPENINGS	OPEN 4 OR MORE FLOORS	OPEN 2 OR 3 FLOORS	ENCLOSED WITH INDICATED FIRE RESIST.		
			<1 HR	≥1 HR <2 HR.	≥2 HR.
	−14	−10	0	2 (0)[e]	3 (0)[e]
8. HAZARDOUS AREAS	DOUBLE DEFICIENCY		SINGLE DEFICIENCY		NO DEFICIENCIES
	IN ZONE	OUTSIDE ZONE	IN ZONE	IN ADJACENT ZONE	
	−11	−5	−6	−2	0
9. SMOKE CONTROL	NO CONTROL	SMOKE BARRIER SERVES ZONE	MECH. ASSISTED SYSTEMS BY ZONE		
	−5 (0)[c]	0	3		
10. EMERGENCY MOVEMENT ROUTES	<2 ROUTES	MULTIPLE ROUTES			
		DEFICIENT	W/O HORIZONTAL EXIT(S)	HORIZONTAL EXIT(S)	DIRECT EXIT(S)
	−8	−2	0	1	5
11. MANUAL FIRE ALARM	NO MANUAL FIRE ALARM		MANUAL FIRE ALARM		
			W/O F.D. CONN.	W/F.D. CONN.	
	−4		1	2	
12. SMOKE DETECTION & ALARM	NONE	CORRIDOR ONLY	ROOMS ONLY	CORRIDOR & HABIT. SPACE	TOTAL SPACE IN ZONE
	0	2	3	4	5
13. AUTOMATIC SPRINKLERS	NONE	CORRIDOR & HABIT SPACE	ENTIRE BUILDING		
	0	8	10		

NOTE [a]Use (0) when item 5 is −10.
[b]Use (0) when item 10 is −8.
[c]Use (0) on floor with less than 31 patients (existing buildings only).
[d]Use (0) when item 4 is −10.
[e]Use (0) when item 1 is based on first floor zone or on an unprotected type of construction (columns marked "U").

Figure 3. Safety Parameters Value Form

INDIVIDUAL SAFETY EVALUATIONS

SAFETY PARAMETERS	CONTAINMENT SAFETY (S_1)	EXTINGUISHMENT SAFETY (S_2)	PEOPLE MOVEMENT SAFETY (S_3)	GENERAL SAFETY (S_G)
1. CONSTRUCTION				
2. INTERIOR FINISH (Corridors & Exits)				
3. INTERIOR FINISH (Rooms)				
4. CORRIDOR PARTITIONS/WALLS				
5. DOORS TO CORRIDOR				
6. ZONE DIMENSIONS				
7. VERTICAL OPENINGS				
8. HAZARDOUS AREAS				
9. SMOKE CONTROL				
10. EMERGENCY MOVEMENT ROUTES				
11. MANUAL FIRE ALARM				
12. SMOKE DETECTION & ALARM				
13. AUTOMATIC SPRINKLERS			÷ 2 =	
TOTAL VALUE	S_1 =	S_2 =	S_3 =	S_G =

Figure 4. Individual Safety Evaluations Form

SAFETY PARAMETER	Life Safety Code (Multi-story-new)		Alternative From Evaluation System	
	Score	Requirement	Score	Requirement
1. Construction	4	≥ 2 HR Fire Resistive	2	≥1 HR Fire resistive
2. Interior Finish (Corr. & Exit)	3	Class A (Flame Spread) ≤ 25	3	(Same)
3. Interior Finish	1	Class B (Flame Spread) ≤ 75	- 3	Class C (Flame Spread ≤ 200)
4. Corridor Partitions/Walls	2	≥1 HR Fire Resistance	0	< 20 MIN. Fire Resistance
5. Doors to Corridor	1	≥20 Min. Fire Resistance	0	< 20 Min. Fire Resistance
6. Zone Dimensions	0	100 - 150 Ft. (33 - 50 M)	- 2	>150 Ft. (> 50 M)
7. Vertical Openings	3	2 - HR Enclosure	0	Non Combustible Enclosure
8. Hazardous Areas	0	None	0	(Same)
9. Smoke Control	0	Smoke Partitions	3	Mechanical Assisted by zone
10. Emergency	0	Multiple Routes	- 2	Deficient Capacity
11. Manual Fire Alarm	2	Fire Alarm Connected To Fire Dept.	- 4	No Manual Fire Alarm
12. Smoke Detection	2	Corridors Only	0	None
13. Automatic Sprinklers	0	None	8	Corridors & Habitable Spaces

Figure 5 Comparative Presentation of Alternative (typical)

FIELD APPLICATION OF FIRE SAFETY EVALUATION SYSTEMS

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ABSTRACT

This paper addresses field experience with the Fire Safety Evaluation System (FSES) after its initial development by the Center for Fire Research at the National Bureau of Standards. Topics such as training programs for Code users, acceptability as a new concept, cost savings and cost avoidance are discussed along with a view to the future for FSES documents and their use.

Key Words: Fire Safety Evaluation System, FSES, Medicare-Medicaid, Life Safety Code.

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1. INTRODUCTION

1.1 Background

We, as a nation, spent 458.2 billion dollars on health care last year; or approximately eleven percent of the Gross National Product. Roughly one-third of this was paid by the Medicare-Medicaid program. Medicare is an insurance program directly administered by the Federal Government while the Medicaid portion is a social welfare program administered through the various States.

1.2 The Life Safety Code

It is the Medicare-Medicaid program that has been responsible for the successful acceptance of the Life Safety Code and the Fire Safety Evaluation System for Health Care Facilities (FSES-HCF). Further references to the FSES in this discussion are to the Health Care Facilities version. As you may know, the Medicare-Medicaid program was enacted by the Congress back in the 1960's to reimburse health care facilities for services provided to insured or welfare recipients. In the 1960's there were several health care facility fires which caused great concern among members of congress.

1.3 Annual Inspections

As a result, the Social Security Act was amended in 1970 to incorporate a "condition of participation" based upon compliance with the Life Safety Code. An annual fire safety inspection program was instituted with the various States providing the service, called surveys, under contract with the Federal Government.

These annual inspections, with the authority of the Federal Government behind them, virtually eliminated the type of disasters that plagued the health care industry in the decades leading to the 1970's. Most of you can probably recite the few serious fires that have occurred in health care facilities since the adoption of the Life Safety Code by the Congress.

1.4 Correction of Deficiencies

These improvements have not been without cost. Expenditures for correction of fire safety deficiencies in hospitals and nursing homes have amounted to many millions of dollars.

Unfortunately, in the Codes there is no priority of requirements, so a relatively minor deficiency was often corrected at considerable expense rather than requesting relief from the requirement. The surveyors performing the inspections and their supervisors lacked the necessary judgemental experience in fire protection engineering to know when one deficiency was more serious or which deficiency could be waived.

1.5 An Example

A prime example occurred in late 1977 as a result of a survey at the Massachusetts General Hospital when over four million dollars of deficiencies were cited on 186 pages of survey forms. When the plans were filed with the City of Boston showing the corrections, the City promptly required additional changes which boosted the amount to nearly 15 million. Then the State added some more changes which made the total reach nearly 34 million dollars. In reviewing the survey forms, I found that most of the deficiencies involved the replacement of fire doors and frames merely because they lacked fire door or fire door frame labels. Of several hundred doors cited as deficient, only three needed to be replaced; the remainder were perfectly acceptable.

1.6 An Aside

It was about this time that the Fire Safety Evaluation System was being born at the Center for Fire Research with Harold Nelson as the Midwife. If I had to venture who was the father of the FSES, I would guess Irwin Benjamin. The mother was Jeff Shibe.

2. BENEFITS

What has the FSES done to relieve situations like those found at Massachusetts General Hospital?

2.1 Uniformity Improved

The FSES, because of the emphasis on critical fire safety parameters, like automatic sprinklers, and their mathematical relationships (points) has resulted in a more uniform way of looking at the Life Safety Code requirements. This arrangement of fire protection features has improved understanding of the Life Safety Code and is permitting better engineering judgement to be used in determining when a Code requirement can be waived or postponed.

2.2 Priority of Corrections

The FSES has enabled the establishment of priorities by indicating which Code requirement is more important than another. When a series of safety parameters can be linked together in a manner that shows their relationship to one another and given finite numerical values which can be used to evaluate the fire safety features of a building, the accuracy and repeatability of such a system is greatly improved. Experience with the FSES has improved uniformity of interpretations because once the numerical values are assigned to a parameter, all determinations are decided by the system.

2.3 Cost Savings

Application of the FSES has allowed reduced expenditures by health care facilities in achieving compliance with the Life Safety Code. At the onset of the official adoption of the FSES by the Department of Health and Human Services, the then Secretary, Joseph Califano predicted that use of the FSES could save this country over two billion dollars during the next decade. The first two years that the FSES was used, we documented over a half a billion dollars in savings to the health care community.

Sometimes cost savings can be combined with cost avoidance. If there is a code requirement that does not have to be done because of the FSES, the anticipated expenditure is not made at all. If a hospital does not need to build a new million dollar stairway to correct a travel distance deficiency as a result of an equivalency in the FSES; is this not cost beneficial? A strict application of the Code would have required the stairway to be built.

3. APPLICATION

3.1 Legal Acceptance

In the legal application of the FSES, the biggest obstacle has been its acceptability at the State and Local Government level. However, it is important to note that the Life Safety Code is structured to include the FSES as part of the Code in addition to the equivalency concept contained in the Administrative portion of the Code. A key concept which has been difficult to get accepted is that the FSES is the Code. To some people the term, "equivalency" means less than the Code. Waivers and exceptions may be a relaxation of the Code, but equivalencies are not.

3.2 FSES for New Buildings

Probably the most controversial question about the FSES deals with its application to new buildings. The general feeling is that when a building is being designed, there should be no problem in meeting all the requirements of the code, but I believe there is merit in being able to apply the FSES to new designs in order to determine priorities and trade-offs.

3.3 Disadvantages

If there are disadvantages to the FSES, they are due to the limited number of parameters covered in its grading system. There are too many "checklist" item that must be completed when all the Code requirements are to be included.

4. TRAINING

4.1 Training FSES Surveyors

By early 1979, the Health Care Financing Administration (HCFA), which oversees the Medicare-Medicare Program, authorized a series of training programs for State surveyors who were involved in making inspections of hospital and nursing homes under contract to the Federal Government. The "dry run" of this three day course took place in August of 1979. The first formal course was conducted the following month in Dallas, Texas. In the years that followed, the American Hospital Association (AHA) and the Joint Commission on Accreditation of Hospitals (JCAH) both conducted training in the use of the FSES. There was also a one-time training course where we certified about 25 instructors.

4.2 Surveyor Acceptance of the FSES

Another roadblock to acceptance of the FSES has been resistance on the part of experienced fire safety surveyors. Most enforcement authorities accepted the FSES because of the training they received and we found them receptive to such new ideas. The greatest problems we encountered in the training courses were based on the operational mechanics and the concept of equivalency, but once the background was explained, and the mechanics of the FSES understood, it was usually accepted. Most of the non-acceptance can be attributed to a "not invented by me" syndrome. We still see this syndrome today.

5. FUTURE

5.1 Development of New Industries

You have already heard about an FSES which will cover offices and laboratories. One of the largest industries by the year 2000 will be biomedical research and manufacturing. Today we are striving to determine the type of fire protection needed by existing laboratories that will lead to the new industry. Another unknown area is how to protect valuable research animals. We can't use typical sprinkler systems and smoke detectors, nor audible fire alarms.

5.2 A Non-Fire Application

Appendix "F" of the Life Safety Code is a grading procedure for determining the evacuation capability of residents in a building. This system hasn't been mentioned; but I think this rating system has great potential in non-fire application by the mental health community. When they discover that it can be used in their day-to-day work with mental patients, it will become a classic and maybe even surpass the interest in the FSES.

5.3 Building Construction

A specific future need is a sub-system type FSES for the classification of building construction. We all know there is no such thing as a fire resistive building, but the Codes keep insisting that construction is a key element in fire protection and life safety. One of the most difficult tasks a building authority faces is determining the construction type of a building.

With an FSES for construction classification we might even get out of the nineteenth century when it comes to building materials. Some day we may see buildings without floor slabs. Without floor construction as we know it, the space between stories would be fully accessible from both above and below. Who knows, the supporting structure may even be plastic instead of steel.

5.4 The Immediate Problem

At present, the various FSES's are bound as appendices of the Life Safety Code and referenced as "alternatives" in the body of the Code. There is an upcoming proposal to place the FSES's in a separate document, to be known as 101 M.

This is supposedly being done to keep the Life Safety Code from becoming too thick, but the NFPA doesn't seem to worry about the thickness of the National Electrical Code. I am concerned that putting the various FSES's in a separate document, especially if that document is distributed separate from the Life Safety Code, will have the result of making the FSES's less available to Code users. They will, in effect, cease to be part of the Code. Is this the direction we should be moving?

A USER'S PERSPECTIVE OF A FIRE SAFETY ANALYTICAL METHOD: THE FIRE SAFETY EVALUATION SYSTEM (FSES)

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ABSTRACT

Analytical methods for evaluating fire safety include numerical grading systems which are usually a point scheme which either gives credit or penalizes for the fire safety features present in the facility. These systems were developed to provide an alternative to prescriptive code requirements. One such method which has been developed for the health care industry is the FSES (Fire Safety Evaluation System) analysis. The FSES was developed by the National Bureau of Standards and later was incorporated into the National Fire Protection Association Standard No. 101, Life Safety Code. This FSES analysis is one example of an analytic method which has been used extensively and successfully.

The VA (Veterans Administration) decided to embark on an ambitious program to utilize this FSES analysis to evaluate the fire safety risk at their hospital facilities where the analysis could prove to be of beneficial value. Prior to starting this program, the VA had previously identified those facilities with literal code deficiencies. However, the VA determined that the corresponding corrective actions were not often very cost effective. The VA then established policies, procedures, technical guidance and training regarding the use of the FSES analysis. Facilities were surveyed by fire protection engineers and several solutions to compensate for the deficiencies were presented. Individual hospitals decided on the corrective action which best suited their needs. The FSES analysis has proven so far to provide the VA with an analytical tool to ensure that an equivalent level of safety can be provided at the most reasonable cost and impact to the facility.

INTRODUCTION

Analytical methods for evaluating the level of fire safety have begun to appear for use by the fire protection engineer and others seeking an alternative to prescriptive code documents. Why is this? One reason for this is that as codes have been revised over the years, successive levels of requirements have been incorporated, each trying to address a particular fire safety hazard and concern. Sometimes the requirements do not necessarily take into consideration the other fire protection features which are present or are being provided. This can result in excessive fire protection features or may not provide the most effective solution for the lowest cost to the client. By developing a systems approach utilizing analytical methods one can evaluate the overall level of safety. Another reason why these analytical methods are being developed is that there is a wealth of technical information made available through research to users of fire protection standards and codes. However, the technical data and the analytical methods are often in a format which may be intimidating to the user. Also, if the user has not had training in the application of an analytical method, the user may apply the method incorrectly. However, these analytical methods can provide fire protection engineers and others with scientific and professional tools commensurate with their knowledge. It is expected then that one does not have to rely strictly on prescriptive "cook-book" approaches to fire safety problems.

NEEDS OF A USER

What does a user then look for in an analytical method? The method must be relevant to the needs of the user whether the user is an individual or an organization. The method must be able to effectively measure the fire safety risk and if applicable, must be able to provide corresponding corrective actions. The method must be one which will be acceptable to others external to the immediate user or client if approval of others is necessary. The method must be a repeatable system which gives uniform results. The method must be designed to meet the qualifications of the user and their knowledge of fire protection. Training or instructions must be available for the user in the application of the method.

FIRE SAFETY EVALUATION SYSTEM

One type of analytical method is the numerical grading system. There are several examples of this method available utilizing a point scheme. One of the most commonly used is the Fire Safety Evaluation System (FSES).

There are several FSESs which appear in the appendix of the Life Safety Code, National Fire Protection Association Standard No. 101. The first to appear in the 1981 edition of the Code was a FSES for Health Care occupancies. There are also FSESs now for Board and Care occupancies and Detentional/Correctional occupancies and one planned for Business occupancies in the 1988 edition of the Code.

How does the FSES work? Although each system in the Life Safety Code is based on the literal requirements in the body of the Code, the methodology is designed to give credit for the fire protection features present and deduct for those that are not provided. The FSES is a system for measuring the relative level of fire safety. It is only an analytical tool which assists one in the decision making process and does not make any judgements for you. Also, the use of the FSES is based on the equivalency concept found today in all codes and standards.

First, the building is divided into zones and a separate analysis is conducted for each zone. Individual fire safety parameters are established which are of importance to the particular occupancy. For health care occupancies, the parameters include those fire safety features such as corridor walls and doors, smoke barriers and compartments, protection of hazardous areas, construction type, interior finish, egress paths, horizontal exits, protection of vertical openings, smoke detection, transmission of an alarm to the fire department and sprinkler protection. A specific point value is assigned for different conditions for each of these parameters. The corresponding point value is selected which reflects the actual conditions as found in the facility.

Next, other factors are considered such as the occupants' evacuation capabilities. For health care, this evaluation centers on the patients and their location in the building, age, physical mobility, number and the availability of staff to assist in evacuation. Then there are four areas of fire safety which are considered in light of the individual parameters; containment, extinguishment, people movement and general safety. Not all of the individual parameters however are considered in each area since they would not have an impact in that area. Finally, a mandatory point value is established for each of the four areas. A comparison is made of the point values chosen and what they have added up to in the four areas of consideration with the mandatory values to see if the facility has an equivalent level of fire safety. One last evaluation is made of the entire structure for various miscellaneous items such as compliance of the ventilation and electrical systems with established code requirements.

FSES SOFTWARE

They are the programs written to computerize the usage of the FSES analysis for health care occupancies. One such program used by a fire protection engineering consulting firm is available via the BASIC and LOTUS 123 programs on IBM compatible personal computers. Raw data is entered regarding the parameters and other inputs and the program provides you with information whether the zone passes the FSES and if not, provides alternative solutions. This greatly simplifies the mechanics of conducting the analysis via the FSES worksheets/tables. However, it only provides a number of possible solutions which must be judged and evaluated to see if they are appropriate before selecting the final solution.

APPLICATION OF THE FSES

Why would a user decide to use a fire safety analytical method such as the FSES? The VA (Veterans Administration) decided that when the FSES for health care occupancies was being developed to embark on a program to use it. The main reason that pushed the VA in this direction was a series of fire safety inspections of each of our medical centers conducted by outside consultants in 1975 and 1976. The VA needed a comprehensive survey at the time to identify all of the fire safety deficiencies in our facilities. The most common deficiencies which were identified and did not lend themselves easily to a practical solution were dead end corridors and inadequate types of construction.

But first, what kind of facilities are the VA responsible for to construct and maintain? The VA operates 172 medical centers along with numerous outpatient clinics, nursing homes, research laboratories and other office space. This includes thousands of buildings from large, high-rise hospitals to turn-of-the-century historical structures including hundreds of patient occupied buildings. Engineering services are provided at each facility by a VA staff of engineers and plant technicians. In addition, a group of engineers, architects and planners are located in the VA Central Office.

After this series of inspections, the VA grappled with the magnitude of the deficiencies and what were the best solutions to them. For example, providing a new stair tower for a dead end problem was not an attractive solution for several reasons. First, health care occupancies rely on moving patients horizontally to a safe place of refuge. Stair towers would not significantly increase the level of fire safety. Secondly, the cost of constructing a new stair tower was not considered cost effective for the amount of additional fire safety being provided plus there was the potential impact on the loss of bed space.

At the same time, NBS (National Bureau of Standards) had been requested to research and develop an equivalent approach to meeting the literal requirements of the Life Safety Code for health care occupancies. As the FSES took shape, the VA started applying it in-house to ongoing fire safety improvement construction projects to see if cost savings or better protection could be provided. As the value of the FSES became obvious and its potential acceptance by others, an ambitious program was planned to use it throughout the VA.

OBJECTIVES

What were the VA's objectives? First, we expected our medical centers to establish plans of corrective action to eliminate fire safety deficiencies based on the FSES analyses. Secondly, we wanted to coordinate this plan with each facility's five year construction plan which detailed all of their improvement projects to their facilities. Thirdly, we hoped to correct all of the deficiencies in a timely manner. Fourth, the objective was to produce the most cost effective solution that would be operationally acceptable to the medical center. Next, the FSES process would find approval by accreditation bodies such as the Joint Commission on the Accreditation of Hospitals, and finally, each facility would be provided with an equivalent level of fire safety.

PROCEDURES

What were our procedures to implement the use of this FSES? The first step was deciding when and where to use the FSES. The VA has a staff of technical fire safety personnel who are advisors to each medical center. These are our Safety and Fire Protection Engineers (SFPEs). They were asked to work with the Chief Engineers at each medical center to determine if a facility could benefit from a FSES. The inspection reports mentioned earlier were consulted to see if the facility had code deficiencies which did not lend themselves to a literal correction. Next, we decided that only qualified professional personnel should conduct the FSES analysis. It was decided that outside consultants should be used. They would have to be knowledgeable of the Life Safety Code but also of fire protection systems and concepts. We felt that fire protection engineers who had the qualifications of or be equivalent to a full member status of the Society of Fire Protection Engineers should conduct the surveys. Selection of the consultants was based on their qualifications, experience in health care occupancies, and the proposed cost of the contract. In addition, we trained our own SFPEs to review the analyses. The analysis would include a thorough inspection of the site and then preparation of the FSES documents. A draft copy and a final copy of the report were to be provided.

Since the FSES was new and unfamiliar to most of the people involved with the process, the VA developed a series of our own interpretations and technical guidance for use by the consultants and SFPEs. The surveys were contracted for in 1983 and 1984. As part of the analysis, the consultants were asked to provide at least two separate solutions including cost estimates. The individual medical centers then could choose which alternative was the most attractive to them. The SFPEs would also provide them guidance. The different solutions proposed were to also include an evaluation of the impact of the corrective actions on the facility. Finally, each medical center would then develop a plan of corrective action indicating how the corrective actions were to be implemented. After the corrective action was completed, then the medical center could request an equivalency from the VA's Authority Having Jurisdiction and from the Joint Commission.

What about the use of the FSES during design and construction of new health care facilities? The VA has used the FSES exclusively for existing facilities and not for new construction except in a few rare occasions to help resolve complex building design issues. It is the VA policy not to use the FSES as a tool to specify the design but rather as an analytical method for evaluating the level of fire safety during the design.

RESULTS

What were the results? A total of over 500 buildings were surveyed. We found that less than five percent of the structures were already code complying or needed only minor improvements or routine maintenance. These facilities would therefore not need any further consideration. As was expected, the dead-end corridors and the deficient types of construction deficiencies were encountered. The most popular type of corrective action chosen was automatic sprinkler protection. Although more costly at first to install than other improvements in some cases, the advantages gained from this type of protection provided medical centers with the most flexible solution in the long term. New stair towers were selected in only two cases where dead end corridors were a deficiency. Smoke detection systems also proved to be a popular method of upgrading the level of fire safety although the current problem with false alarms and the continuing maintenance and testing costs detracted from their selection. Although precise quantitative figures are not available, it is estimated that the VA has already saved tens of millions of dollars in lieu of installing stair towers, etc., while providing each medical center with a unique solution to their facilities. In many cases, an increase in the level of safety was also achieved. Were we satisfied? Yes, this analytical method has proven to be a valuable tool to assist our decision makers in the efficient and sound expenditure of funds while providing a fire safe environment for our patients and VA employees.

ANALYTICAL METHODS FOR FIRE SAFETY DESIGN

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ABSTRACT

The ability to predict aspects of fire and its impact on a building's structure, contents and people is discussed in terms of its application to safety design. It is presented from the perspective of how research has addressed the prediction of fire phenomena. A review of the state of the art on the capability for predicting the fire, its impact and response, is given. Examples are cited to illustrate the scope and accuracy of predictive methods and how they are being incorporated into some codes and standards.

1. INTRODUCTION

By analytical methods for design, we mean the ability to perform calculations to assess the correctness of the design in terms of scientific principles. Once a design is conceived, we can use an analytical method to select the size, shape and nature of its materials and component parts. In the design of a complex system, it is usually not possible to have a method to predict all the interactions of the component parts. But by having an understanding of the system in terms of parameters -- properties and variables -- consistent with requirements of the analytical methods, complex systems can be designed. This understanding allows us to break the problem into tractable pieces, whose solutions in the end provide the system design. As we learn more about the system, we can integrate the analysis to couple more and more of its elements together, or we can justify single-element approaches with more certainty.

Fire itself is a complex physical and chemical system so that the inclusion of its effect on structure and people make the situation more difficult to address. This is the realm of fire safety engineering and its application to fire safety design. It has only been over the last twenty-five years that a more quantitative understanding of fire and its impact has led to analytical methods for its prediction. It is therefore not surprising that the current prevailing design practice is not based on analytical methods. The current practice of fire safety design is based on meeting specific requirements in building codes and regulations that do not necessarily require any scientific analysis to achieve. The requirements are expressed for specific components of the system. and the methods for evaluating the performance of the component are given in terms of standards and test methods. For the most part, performance rankings by a specific test have been established by consensus and are applied to indicate implied performance in a particular design application or use; and in other cases, specifications are given without any scientific justification for the specific system under consideration. For example, the requirement that a wall lining material in a corridor must have a rating of less than 75 by a specific flammability test is an expression of performance. For an analytical method to be applicable, an alternative statement for the performance must be developed such as: the material must not allow sustained flamespread in the specific corridor in a given time for a given ignition intensity. The exact values of the performance parameters are not important here, but they must be given in scientific terms. Of course the numeric values do become important when we wish to establish levels of equivalent performance with current notions of safety.

Therefore, the ability to assess the applicability of analytical methods for fire safety design depends on two factors. The first is the adequacy of the knowledge base to allow suitable and sufficiently accurate predictions. The second is the ease of recognizing the relationship between predictive capabilities, and the practices and issues that arise in applying fire safety codes and standards. This discussion will address the first factor in some detail, and attempt to give some examples which illustrate the second factor.

The process of developing the knowledge-base for fire has emerged from the agenda set by the research community. This agenda has been determined by a desire to understand all aspects of fire and its effects. Over the last fifteen years, this research has been oriented to the issues of fire growth in buildings. Fifteen years ago our knowledge was very sparse, so that a discussion on the prospect of using scientific analysis in fire safety design would have been premature. The ability to predict aspects of fire had to first gain credibility among scientists. In 1959, the International Symposium on the Use of Models in Fire Research was held [1]. Its focus was on fundamental knowledge and not its use, but the papers presented demonstrated the feasibility of fire prediction and quantification. In the mid-70's the term "fire modeling" was coined to describe the various methods, mainly computer models, to predict the development of fire in a room. A review of compartment fire modeling, its nature, accuracies, and needs, was given by this author in 1984 [2]. In 1986, Emmons [3] reviewed the needs of "fire science" in terms of research needs, but with a view to solving practical problems. In this review, he cites 141 references which give some support to an emerging ordered-set of information -- a science of fire. A recent book, intended for educational purposes, by Drysdale [4] on ways to compute aspects of fire is a further demonstration of progress in the development of the knowledge base. The demand to assimilate this knowledge has been high. I believe Drysdale's book is now in its third printing. Several years ago I saw the new Japanese Fire Protection Handbook. It was very different from its previous editions because the first few hundred pages dealt with the science of fire and quantitative methods. Those sections reminded me more of the handbooks available to other engineering professions. It is noteworthy that in the USA, the Society of Fire Protection Engineers is now attempting to develop a handbook that will contain much new information from research. Thus, we see an evolution of the development of fire knowledge of sufficient scope and depth to now allow its orderly description for practitioners to learn and use. This is a significant milestone, but recognize that it has taken 15 to 25 years to achieve. Moreover, the depth of knowledge in particular areas is shallow and in some cases we have holes. Also, prediction capability on fundamental aspects of fire research do not always yield analytical tools for design.

2. ANALYTICAL APPROACH TO FIRE PREDICTION

Here I use the term analytical methods to mean any technique that will allow quantitative predictions. The technique could involve approximate or exact mathematical solutions, numerical solutions using computers, or analog and scaling techniques. Often scaling techniques have allowed formulas which have a wide range of applicability to be developed from experimental data.

2.1 Discrete Phenomena

Part of the progress made in fire prediction has been the ability to identify important features of the fire processes. This has come about due to experimental observations, conceptualization into a defined element for study, and then the development into a validated predictive result. For example, in a room fire, we identify the fire plume, a ceiling jet, a hot upper layer and flows at vents. Features associated with these elements have been studied and predictive prescriptions developed. In many cases, correlations have been developed from experimental data so that algebraic formulas comprise the nature of the results. Examples of reports which describe computational techniques for discrete phenomena have been given by Lawson and Quintiere [5], and Nelson [6].

2.2 Systems

Typically a fire problem will involve many processes, and it could be viewed as a set of interacting discrete elements. The degree to which we couple these elements depends on our knowledge and understanding of them. For example, the evacuation of people in a fire will be affected by the fire conditions. Thus a complete analytical method for evacuation should take the relevant fire conditions into account. The temperature in a beam heated by a fire will affect its structural properties and determine the likelihood of failure. The beam temperature arises from the thermal state of the exposing fire, and all of this depends on the conservation of energy.

A particular approach to predicting fire conditions in compartments has been to mathematically couple together regions of distinct physical character. This relies on the application of the conservation laws, assumptions of the property distributions within the regions, and the predictive ability to describe the transfer of mass and energy at the boundaries of the regions. This has come to be called "zone modeling". The solution of this system mainly involves the solution of nonlinear algebraic and ordinary differential equations in time. The solution to partial differential equations could also arise. Thus, a small (PC) to medium-sized (mini) computer is necessary in its solution.

2.3 Exact Solution of the Basic Laws

It is possible to write the governing equations, based on mass, momentum and energy conservation for reacting fluid systems. In principle, their solution achieved by numerical methods on computers can lead to a complete description of the variables over space and time. However models need to be assumed for turbulence and for chemical reaction so that even these solutions based on the exact differential equations are approximations. The models for turbulence and chemistry come from applications other than fire, so questions of their appropriateness are still not resolved. But a careful application of this approach to fire problems can lead to proper results, and this has been demonstrated in a number of applications. Fire researchers have come to call this approach "field modeling".

2.4 Scale Models

The analytical methods we are discussing are mathematical in nature. But we could utilize scaling techniques based on the laws of physics to develop physical scale models to generate quantitative information for fire safety design. This has its counterpart in wind tunnel testing of aircraft. For example, it has been demonstrated that the thermal and flow conditions in rooms adjoining the fire room can be reasonably predicted in full scale systems by using scale models [7,8].

3. STATE OF THE ART FOR DESIGN

I would like to review the capabilities for making predictions for various aspects of fire, its development and interactions as they relate to design. Where available, examples of their use in standards will be given.

3.1 Fire Source

No general predictive method exists for the generation rate of fuel mass, energy and combustion products for materials and products that make up the contents of buildings. But for many design applications, the initial fire source conditions might be specified in terms of a plausible or maximum credible fire condition for the problem under investigation. A suitable database of information on fuel packages, or a means to obtain the information must then be available. This is possible by measuring the combustion product concentrations in a collection hood above the freely burning fuel package [9].

Many research laboratories have such devices so that examples of results can be found in the literature.

For simple solid fuel systems, namely flat surfaces, burning rate theories and correlations exist to predict the steady rate of mass loss. From collection hood apparatuses, energy and combustion product yield data can be generated on a per unit mass loss basis [10]. The availability of these data provide a way to estimate steady generation rates for simple systems of arbitrary size.

The ability to predict ignition and flame spread only applies to flat solid fuels also, and requires particular data for the material. For example, these models use the concept of an ignition temperature so it must be appropriately determined for the material. A practical measurement technique to estimate such properties is available [11].

From a hazard point of view, it is useful to know the flame height. This can be computed with good accuracy for design purposes from correlations that depend only on the energy release rate of the fire and the equivalent diameter of the fuel base [12]. The maximum velocity and temperature distributions along the centerline of the fire and its noncombusting plume can be estimated in terms of the same variables required for flame height [13]. This appears to be successful over an extensive range of scales comparable with normal design needs.

The inability to completely predict the radiation heat transfer from flames in terms of practically measured properties limits models for burning rate and spread at relevant scales of interest. However we do have some knowledge of the range of radiant heating in some situations which can prove useful in design estimates. Except for distances very close to the flame, the radiant heating of the surroundings by the flame can be computed with good accuracy provided the fraction of energy radiated is known. This quantity is available in the literature for some materials and tends to vary from 15 to 50%. It can be deduced from the free burn fuel package experiments.

3.2 Effect of Surroundings on the Fire

We know that the temperature and oxygen concentration of the atmosphere around the fire affect the burning and mass loss rate of the (solid) fuel. Also radiant heat flux from the surroundings is a factor along with any imposed wind conditions. Models for steady burning and flame spread for simple configurations provide a means to quantitatively estimate the magnitude of these environmental effects. In some cases, algebraic expressions exist for the steady simple configurations. For the more general case of unsteady burning of a complex fuel package, no generally acceptable procedure has been developed. Sensible extrapolation of the mathematical relationships governing simple fuel configurations is certainly viable and reasonable for design use. Again property data for the fuel package is needed; a key property is the effective heat of gasification. In general, this property is time-dependent, and no standard test exists for its determination. But time-averaged values have been determined for a number of materials [10]. The heat of gasification is essential in determining the rate of gaseous fuel generation from the available fuel packages as their decompositions are augmented and initiated by heat transfer from the environment. This is a feedback process that the fire lives and dies by. As the fire grows, environmental oxygen decreases and the environmental heat transfer increases. If the fuel package is totally immersed in an atmosphere of decreasing oxygen, flaming combustion will cease at some critical value of oxygen concentration. This value is not unique, but some data and crude methods exist for its estimation. Ten per cent or less is a nominal rule of thumb.

In addition to the effect of the fire environment on the fuel generation rate, it is well known that the products of combustion change with the available oxygen supply rate. We can think of this as two streams: the fuel stream caused by heat transfer to the solid fuel surface, and the oxygen stream entrained into the fire plume. The entrainment rate can be calculated [12,13]. For several fuels, Beyler [14] has determined and tabulated the product yields as a function of the oxygen and fuel supply ratio. For water vapor and carbon dioxide, estimates could be adequately made from the known chemical composition of the fuel. But for carbon monoxide, the major toxic fire product for most common fuels, the experimental determination procedure described by Beyler [14] offers the only means for estimating CO in fire problems. Thus, estimates of CO are possible over a wide range of fire growth conditions, provided the fuel and oxygen supply rates can be determined. Since only limited material data exist, judgement must be used to extrapolate to other materials. Nevertheless, this approach might be perfectly valid in design situations where an evaluation of a specific material is not at issue.

3.3 Effect of Fire on the Surroundings

A primary effect of the fire on its surroundings is the heat transfer caused by the direct interaction of the flame and its plume with surfaces and objects. For fires along walls there are good results available to assess convective heat transfer [15], and a correlation has been developed to estimate the total heat flux distribution for flames of moderate size (< 2 m) [16]. For larger flames within the flame zone, radiation heat transfer is not generally predictable, but some limited data exist to show its magnitude. A similar state of knowledge exists for flames impacting ceilings; however, more work has gone into the study of this problem than for walls. Again, convective heat transfer is well predicted [17], and a more limited knowledge is available for the flame impingement region [18].

Very little general predictive ability for objects in fire plumes has been pursued, but to the extent that the velocity and temperature fields are available, estimates of heat transfer to objects in these plumes can be made. In particular, a number of studies have been made to enable the prediction of the velocity and temperature distribution of a ceiling jet that arises due to the interaction of a fire plume with a ceiling. It should be mentioned here that the principle variables required to make these calculations of heat transfer are the energy release rate of the fire and geometric variables which describe the configuration.

An example of the use of ceiling jet research is in determining the response of alarm and suppression devices located in the jet. The standard, NFPA 72E on automatic fire detectors, contains supplementary information on how to determine the spacing of thermal detectors based on the rate of growth of a design fire, the ceiling height, and the response characteristics of the detector to temperature [19]. Much of the research that underlies this procedure was developed at Factory Mutual Research Corporation (FMRC), and is described in the Standard. This procedure has been further developed into a series of PC compatible computer codes (DETACT) for more general application [20]. A necessary ingredient of this procedure, is the availability of test data on the thermal response of the detector. Essentially the detector is approximated as a uniformly heated object in gas stream of known temperature and velocity. The overall convective heat transfer coefficient is determined from this test (commonly known as the "plunge test") and then related to the ceiling jet characteristics. This is an approximate method that has been shown to work, and refinements can even make it better. It is significant that it requires data for the detector or in general, the thermally responding device. The data are realizable from a test procedure, and are compatible with an analytical procedure to make general predictions of performance under fire conditions.

3.4 Fire Conditions in a Room

I would now like to turn my attention to computer models that describe the conditions that arise in a room due to the presence of a fire. There are many computer codes available and I will not enumerate them all, but refer you to the citations given in References 1 and 2. They differ in approach. The field models attempt to represent all of the fire phenomena by solving the conservation equations. The zone models tie together homogeneous phenomenological regions and relationships which describe their interaction by globally applying the conservation laws to these regions. The current state of computers allows three dimensional solutions in the field models, and more than one room is possible. The zone models differ in scope and generality, with some including a limited amount of the known physics, or are restricted to a specific class of problems. Few of the room models address the effect of the surroundings on the fire, with many relying on a prescribed fire. Let us examine two classes of problems: fire in a closed room, and fire in a vented compartment. I will try to give some background and a measure of success and application.

3.4.1 Fire in a Closed Room

Fire conditions in a closed room can be solved by the zone modeling strategy to give the depth and properties of the hot upper layer formed by the collected fire gases. Typical models consider no pressure rise for a room with a leak, which is characteristic of conventional rooms in buildings. It is possible to overcome this restriction. The basic theory was first put forth by Zukoski [21], and later a computer version was developed by Cooper [22] which has seen popular use. That computer model is known as ASET and is limited to just the closed room. This zone modeling approach has yielded good results in the prediction of the layer characteristics in time for smoldering fires [23], and for a variety of flaming conditions in complex closed configurations. In a series of experiments designed to test the approach, it was found that the smoke layer descent is predicted very well in time, but the temperature results are only approximately predicted since the actual thermal stratification is more gradual than the square-wave approximation of the zone model [24]. These experiments were done in a cubical room, 6 m on a side -- a large room. Bengston and Hagglund [25] applied their model to an entire building having a floor area of 1000 m^2 and a height of 9.5 m producing also good agreement between the model and measured results for the layer descent [25]. Nakamura [26], using a more sophisticated zone model than ASET, demonstrated good predictive ability for the layer temperature and descent rate for experiments conducted in a large exhibition hall with a domed roof -- 2000 m^2 of floor area and 19.2 m high. Thus, this approach appears quite valid regardless of the scale of the fire and the compartment. Of course, the fire source must be specified and is not influenced by the conditions in the compartment in any of these models.

Field models have also been applied to this problem with good results. The range of predicted variables is basically the same as those of the zone models; however, they can not predict the degree of stratification. Cox et al. [27] show good results for temperature and carbon dioxide distributions in experiments in a six-bed hospital ward. Waters [28] has used the same model to evaluate particular fire safety issues in buildings under design. These included the issue of safe egress time due to a fire in a large airport terminal, and the effect of initial thermal stratification of a fire in an atrium space.

3.4.2 Vented Compartments

Field models do a good job at predicting the velocity and temperature distributions in compartments including the flow at door or window vents [29,30]. These verifications have been made for relatively small fires that only fill a small portion of the room.

The use of the zone model for vented compartments was made possible by the ability to predict the pressure-driven vent flows using a simple hydrostatic model with an orifice. We now have good confidence in this vent model. Recently, this model was proven to be very accurate for fire flows between two rooms with a fire room temperature as high as 1000 C [31]. In the application of this hydrostatic model to the zone modeling approach, the added assumption of uniform temperatures in the upper and lower layers is invoked. To the extent that these uniformities occur and to the extent that the zone model can predict the layer temperatures, the pressure-driven vent flows should be well predicted. Where flows across vents are due to instabilities or turbulent diffusion, such as the flow through a single ceiling vent in a heated compartment, we have no generally accepted way to compute the flow.

A typical indication of the accuracy of the zone model capability has been reported by Mitler and Rockett for the Harvard Fire Code [32]. An improved version called FIRST has been developed for general use. In their comparisons with two simulated bedroom fires, they obtain good predictions for layer position, temperature and the primary combustion products (not CO), vent flow, and the burning rate of the fire. The model is also capable of predicting the surface temperature of a target and its ignition. It also can include thermal feedback effects to the fuel provided the fuel properties are appropriately defined, and a compatible model is supplied for the fuel package of interest. The Harvard model has probably accounted for the effect of the surroundings on the fuel as much or more than any other zone model. But the capability still needs to be improved in dealing with feedback effects on the fire and for the case of the fuel-rich fire.

The problem of a roof-vented compartment fire, with a sufficient vent below, was studied by Thomas and Hinkley nearly 25 years ago [33]. It was based on the zone modeling approach, and was intended for the sizing of roof vents in fire. The principles of that analytical method formed the basis for several European venting standards, and a modified version has now become the basis selecting the vent area in the standard, NFPA 204M [34]. A set of design fires, described in terms of their rate of growth, is provided. Other needed information is the height of the building and the configuration of the curtain boards. The vent area can be computed for a particular fire condition, or selected period of effective operation. A similar analytical method has been included in another standard [35] which addresses the recommended mechanical exhaust capacity for smoke control in a multitiered open cell block. Thus, we see that some applications of the zone modeling approach are finding their way into standards of recommended design practice.

3.5 Fire Conditions in a Building

The zone modeling approach appears to be the only viable way to predict the conditions in a building due to fire. These conditions pertain to the motion of fire gases, their temperature and combustion product concentrations, and the speed at which spaces of the building fill with the gases. These computations require mini-computer capacity in the least. Also they would require judgement in the way a building geometry is approximated in terms of the necessary model input. All aspects of a building's rooms and vents would not be feasible to include.

A measure of the accuracy of zone models in predicting the fire conditions in more than one room has been described by Rockett, Morita and Cooper [36]. They examined data from a relatively small fire in a series of three rooms. The results for temperature and layer height are estimated quite well for each of the three rooms. Nakamura [26] and Tanaka [37] have demonstrated computations for multi-storied buildings of up to 10 stories and 50 rooms. Stairwells or vertical shafts are currently treated as tall rooms. We know this assumption is not satisfactory once the plume gases fill the cross section of the shaft, but we do not have a measure of its inaccuracy or an alternative approach. A similar limitation applies to the motion of fire gases through corridors, since the concept of uniform filling from the top of the corridor is not compatible with our observations. This limitation will cause a discrepancy when the corridor smoke transit time is long compared to its filling time. Again we do not have a good measure of issue. While it is possible, the zone modeling applications to buildings have not incorporated the effects of the forced air heating and cooling system, nor have addressed the initial and ambient conditions that pertain to "stack" (buoyancy) or wind effects. Although small specified fires have been considered for the most part in these applications, it is possible to consider larger fires that become oxygen deficient [37]. Thus it is possible to predict conditions as a fire might spread from room to room, but we do not have good experimental data to support the assumptions needed here.

3.6 Effect of Fire on the Structure

Analytical methods for predicting the load bearing capacity of structural elements in a fire are based on the current structural design methods and the ability to predict the structural property data at high temperature. Much work has been done in this area, and sufficient property data exist to consider concrete, steel and even timber construction. A good discussion on the state of the art was recently prepared by Pettersson [38]. This approach considers a specified heating load to the structure, and proceeds to compute the temperature distribution, usually in two dimensions, over time by a finite-element method. This is primarily a heat conduction computation with the possibility of phase change modeled for some materials. Sufficient confidence in this approach has led some European countries to accept a computation to predict the failure time of concrete or steel beam or column elements as exposed to a test fire, a time-temperature curve representative of a standard furnace test. I have been told that Sweden, Denmark and Norway have such provisions in their national fire safety codes, and others are considering similar adoptions.

In some of these applications, the fire heating load to the structure is computed from compartment fire models or correlations for fully developed fire conditions. These give the heating time-temperature curve in terms of the compartment size and thermal properties, vent area, and fuel load which is usually in based on data for wood cribs. Improvements are needed here. We need better and more complete ways to predict the post-flashover compartment thermal conditions for other fuel types and configurations. The thermal boundary conditions which express the transfer of energy between the fire and the structural element need more attention. And heating effects of fire plumes to structures need to be characterized. All of these issues fall on the side of the fire and combustion scientist; the structural engineering ability appears to be in good shape provided the heating conditions can be established.

3.7 Effect of Fire on People

A major requirement of the fire safety design of buildings is the safety of people. Their ability to safely egress the facility in a given period of time is essential. The fire behavior in a design calculation can determine the critical times required for safe egress. Most current fire safety codes impose exit width requirements based on the type of facility and its expected population. Time for egress is not an explicit requirement. Based on studies of crowd movement in buildings and exit ways, correlations have been developed which allow the computation of the people movement speeds, the number of people per unit time, and the overall egress time of the building population. A review of these methods and the state of the art has been given by Kendik [39], and a book on the subject has been translated from the Russian literature [40]. Kendik points out that only the building codes in the Soviet Union require a mathematical proof of their exit width requirement. A recent edition of the NFPA Life Safety Code 101 provides information on alternative calculations for determining stair widths based on crowd egress time [42].

We are seeing more and more considerations of matching the hazard time of the fire with a computation of egress time for the design population of the facility. For example, the exit design of a large enclosed stadium with a capacity of 11,500 people was evaluated by computations of the smoke movement from a selected design fire and the traffic flow speeds of the spectators [42]. A formal adaptation of this process is currently under consideration in Japan as a Fire Safety Design Method to be used as an alternative to the Building Standard Law [43]. This design method addresses computations for smoke movement and people movement.

For the most part the egress models referred to above are independent of the effects of the fire on the people. A complete analysis must consider the effects of smoke on visibility; the impairment, toleration and lethality caused by the fire and its products; and the behavior of people in a fire environment. We are limited in our ability to quantitatively address all these effects. Human tolerance limits are not precise, and our ability to convert these effects into mathematical models with a complete set of variables will always be imperfect. But for design or hazard analysis, it is possible to address some of these interactions. Methodology which is indicative of the state of the art has recently been published and is being evaluated by an interested group [44]. This approach, limited to residential single-family dwellings, contains computations on the fire; critical impairment to the people; and the motion of the people based on behavioral decisions, smoke conditions and a simple traffic flow model.

4. APPLICATIONS

The review presented above has been qualitative in that the specific level of the accuracy of the various methods must be assessed by an individual examination of the literature. Another measure of accuracy is the wide spread acceptance of an approach by the scientific developers, and its adoption by the engineers. I have tried to show some sense of that dimension. Many of the analytical methods are generic because of their wide use, but have been individualized in vehicles of execution -- mostly computer codes.

The application of these analytical methods for fire safety have ranged from assessing a particular feature of a new facility in the design stage, to assessing conditions in an existing structure. They have been used to justify alternatives to the specifications in building regulations, and have been even included in standards as prescribed alternatives to traditional practices. I have tried to give some noteworthy examples above, but I am sure that they only represent a small proportion of the use of analytical methods by consultants, and the trend in their use has increased in recent years.

A more dramatic use of analytical method in fire is in the reconstruction of an accidental fire disaster. This is design analysis in reverse, in that it suggests what should have been done. Moreover, it provides a more quantitative basis for establishing remedial actions. The fact that regulations might have been violated before a fire disaster may have nothing to do with the consequences of the fire. There have been several fire reconstructions of real disasters -- some due to a formal investigation, others mostly due to litigation over damage claims. A recent analysis which used a very simple form of analytical relationships and computer models, but applied in a comprehensive way, was able to reconstruct the events of a fire growth in a hotel and its consequences [45]. The accuracy of the results appeared to be consistent with the events, but that is not as significant as its illustration of the ability to quantitatively analyze a complex sequence of fire growth.

5. FACTORS AFFECTING THE USE OF ANALYTICAL METHODS

I see three factors which are important to the use of analytical methods in fire safety.

First, the results from scientific research suitable for design application must be assembled into a logical description for ease in understanding and learning. This is an educational and technology transfer process. Because the field of fire protection engineering has relied on non-analytical techniques, the background required for these engineers to comprehend the analytical methods must be provided in their training and formal education. Text books are sorely needed. The use of user-friendly computer codes might tend to off-set the need for a complete understanding of the particular analysis, but there is a risk of their misuse. The user must have sufficient understanding to effectively question the computer answers, and to apply the computer code to problems within its valid scope.

Second, research must continue to fill the gaps of knowledge needed by analytical methods in a timely manner. If a method does not fulfil all of the expectations and needs of the designer due to limits in its scope, it could lose its appeal. This loss is not necessarily due to its lack of technical quality, but due to its completeness. Speedy and plentiful progress has been limited in developing the knowledge of fire safety by the complex nature of the fire problem, its dependence on the maturity and analytical state of the related scientific disciplines, and the lack of great attention to its research. Most of the analytical capability we see emerging has had its basis in fundamental research. That fundamental research has needed a luxury of deliberate study and evaluation to reach a sound conclusion. Patience is a necessity here. We have seen good progress over the last 25 years, but the most systematic and fruitful progress with benefit to design has come when a number of researchers have focused on similar research issues with resources for long range studies.

Third, a good dialogue must exist between the researcher and the practitioner. Design problems must be identified and formulated by the fire safety engineer and official, and articulated effectively to the researcher. In many cases, the research developments have motivated progress in design applications. Fire researchers tend to pick problems of interesting scientific challenge and logical extension of existing research. Fire safety research needs more direction from the practicing community, especially by those you have gained an appreciation of analytical capabilities.

6. FUTURE PROSPECTS

Based on the recent interests in analytical methods in fire safety, we are likely to see their increasing use. The ability of accessing analytical methods by personal computers is accelerating their use. The research developments are not advancing as swiftly as this transfer process. This may ultimately disappoint some.

A computer format for the transfer of analytical methods may serve to cloud knowledge rather than transfer it. The issue of one method versus another will always be present, and standard computer benchmark codes will have to be rigorously developed to make these evaluations. The benchmark codes will have to be judged by scientific peer review.

Analytical methods will influence the way we test components for attributes of fire safety. Data for components will be needed in a form required by the mathematical model. The model itself will establish the form of the data. The more general the results, the more their use will become. Ultimately this will change the nature of our existing fire test methods, and influence the way we express our codes and standards. The feasibility of predicting the fire growth and the egress of people in a large building is possible. Its acceptance as a viable analytical method will alter the way accepted levels of fire safety are expressed. Analytical methods have now given us more information and more variables. Our criteria for safety must now be couched in these new terms. This will take continual discussion and reconciliation with current practices.

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FIRE PROTECTION ENGINEERING APPLICATIONS OF DETERMINISTIC MODELS

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ABSTRACT

Fire protection engineers work in a number of different areas, many of which can benefit from the use of analytical methods. This paper addresses the application of deterministic models currently in use by practicing fire protection engineers, and focuses mainly on the use of two related models, the DETACT-QS and DETACT-T2 models, as developed at the National Bureau of Standards Center for Fire Research and promoted through the Society of Fire Protection Engineers. Along with a basic description of the models and their development, examples are given of their application to several areas of fire protection: fire protection systems design, fire investigation, and standards development. Additional discussion is provided relative to the use of other deterministic models in building design, smoke control system design, and building code development.

The paper includes a discussion of user needs and concludes that in order to facilitate the use of deterministic models it may be necessary to submit them to the concensus standards approach, permitting standardization of critical assumptions.

1. INTRODUCTION

Deterministic methods and models are those which involve a prediction of results based on known physical variables. This identification of known physical variables and their relationships is what distinguishes deterministic methods from numerical grading methods or probabilistic methods of analysis. More than anything else, the application of deterministic methods constitutes what we commonly think of as the practice of engineering. For the purposes of this paper, a mathematical relationship describing a particular process or phenomenon is considered a deterministic method, while a computer program written to haudle a complicated method or series of methods is considered a deterministic model.

Before a deterministic method or model can be made available to practicing engineers, the physical variables of a particular process or phenomenon must be identified and correlations between the variables established by researchers. This has been slow in coming in the field of fire protection engineering due to the complexities of fire phenomena. As a result, today's fire protection engineer relies heavily on prescriptive approaches, with only a few applications of analytical methods, some of which are deterministic and some of which are of the numerical grading type.

2. COMMON DETERMINISTIC METHODS AND MODELS

The fire sprinkler industry employs deterministic methods more than most other areas of fire protection, due to the heavy interface with the more-established field of hydraulics. The most basic deterministic method in wide use in our industry is the calculation used to predict flow from an individual sprinkler:

$$Q = K\,(P)^{1/2} \qquad (1)$$

where Q is the flow from a sprinkler in gpm, P is the total pressure at the sprinkler in psi, and K is a discharge coefficient of the sprinkler or nozzle. This deterministic method has been in common use for decades and is fundamental to the hydraulic design of a sprinkler system.

A more elaborate deterministic relationship also in common use is that developed by Hazen and Williams for friction loss in piping:

$$p = \frac{4.52 \quad Q^{1.85}}{C^{1.85}\ d^{4.87}} \qquad (2)$$

where p is the frictional resistance in psi per foot of pipe, Q is the flow in gpm, d is the internal diameter of the pipe, and C is a friction loss coefficient relating to the expected roughness of an aged sample of pipe.

It is interesting to note that when hydraulic calculations were first permitted for widespread use by the NFPA sprinkler installation standard in the early 1970s, hand calculations employing the above methods were the norm, assisted by tables of precalculated "friction factors." The added complexities of looped and gridded piping networks, however, have now led the industry to use computer models. Melly [1] has described the characteristics of more than a dozen such models presently being marketed in this country.

With regard to fire phenomena, there are also some relatively simple deterministic methods available. Lawson and Quintere have compiled a number of these, which provide a deterministic basis for estimating the growth of fire in compartments and its consequences [2]. Indicative of the state-of-the-art, however, the equations often apply only to specific fuels or conditions.

A number of deterministic fire models have been developed in recent years. Budnick and Walton [3] have listed 14 zone type deterministic fire models presently in the public domain (Table 1), along with 10 special purpose fire models (Table 2). While these models may be in the public domain, very few are in use by practicing fire protection engineers. Based on the distribution of program disks by the National Bureau of Standards and the Society of Fire Protection Engineers, it is estimated that ASET and DETACT have seen the widest circulation and are in the hands of about 300 engineering offices. FAST is next in line with about 100 copies distributed.

Compared to the sprinkler hydraulics programs, the fire models are seeing very little use in practice at the present time. They are sometimes being applied to special problems and situations by individual engineers, but are certainly not in the mainstream. Nevertheless, use of these programs can be a powerful tool in the hands of the fire protection engineer.

3. A SAMPLE DETERMINISTIC FIRE MODEL: DETACT

The DETACT models developed at the National Bureau of Standards Center for Fire Research, based on work done at Factory Mutual Research Corporation and elsewhere, provide an excellent example of the range of uses to which a deterministic fire model can be put in current fire protection engineering.

In the past fifteen years, a great deal of effort has been put into the development of a method to predict the operating times of heat detectors and sprinklers. This effort is grounded in research aimed at a basic understanding of the temperatures and velocities of ceiling air flow produced by fires. The first such work brought to the attention of the practicing fire protection engineer was that of Alpert [4], who in 1972 published a technical article which contained correlations of ceiling flow temperature and velocity with total heat release rate from steady state fires.

The direct application of these correlations to the prediction of response time of detectors and sprinklers was not possible until the measurement of thermal sensitivity of detectors and sprinklers was pioneered by Heskested and Smith [5,6]. Through the use of the plunge test, the thermal inertia of the detector or sprinkler could be quantified. This property was first identified as the time constant or "tau factor", which was dependent on the velocity at which it was measured in the plunge test. Later, the term RTI (Response Time Index) was created by multiplying the time constant by the square root of the velocity at which it was determined [7]. The Factory Mutual researchers determined that this product could be used as a basic property of the detector or sprinkler, since it was essentially independent of both gas temperature and velocity.

Recently the concept of the RTI as originally defined has been challenged, based on evidence that conduction of heat away from a sprinkler operating element to the sprinkler body, the pipe fitting, and the water in the piping can increase the RTI, especially at relatively low gas temperatures and velocities [8]. This has led to a proposed modification of the RTI concept to incorporate a conduction term, but has left the basic application unchanged as the key to predicting detector and sprinkler response times [9].

Two separate computer models are presently being used to predict sprinkler and detector response: DETACT-QS and DETACT-T2. DETACT-QS is based on Alpert's 1972 correlations, while DETACT-T2 is based on experiments conducted for the Fire Detection Institute in the late 1970s by Heskested and Delichatsios [10].

Both DETACT-QS and DETACT-T2 were written at and are available from the National Bureau of Standards Center for Fire Research [11].

The DETACT-T2 program is restricted to applications in which the fire increases in heat release rate proportionally with the square of time from ignition, such that:

$$\dot{Q} = \alpha t^2 \qquad (3)$$

where $\dot{Q}$ is the heat release rate, α is a constant, and t is time.

A large number of fires have been found to exhibit this type of growth rate. As a result, fire researchers have designated several "standard t-squared" heat release curves. These range from a "slow" fire growth curve which reaches 1000 Btu/sec in 600 seconds to an "ultra-fast" fire growth curve which reaches 1000 Btu/sec in 75 seconds. The DETACT-T2 program was made possible by Beyler's correlations of Heskested and Delichatsios' data [12].

DETACT-QS is capable of use with any arbitrary heat release rate history. The energy release rate of the fire is represented by a series of straight-line segments connecting individual data points of time and associated total heat release rate. For rapidly-developing fires some inaccuracies may be introduced unless the quasi-steady approximation is taken into account. This means that the model is assuming that changes in the heat release rate at the fire source are immediately affecting the gas flow past the sprinklers or detectors.

Both of the programs analyze response under large unconfined ceilings, based on the experiments which led to the temperature and velocity correlations.

4. FIRE PROTECTION ENGINEERING APPLICATIONS OF DETACT

4.1 Fire Protection Systems Design Applications

The fire test series that provided the basis of the DETACT-T2 program was initially used to write Appendix C of NFPA 72E [13], with verification from a series of furniture tests at the National Bureau of Standards.

Appendix C of NFPA 72E addresses spacing of heat detectors and was published as part of the standard for the first time in the 1984 edition. It is intended to provide a method for modifying the listed spacing of both rate-of-rise and fixed temperature heat detectors to achieve detector response to flaming fires at a specific fire size, taking into account the height of the ceiling on which the detectors are mounted and, for fixed temperature detectors, variations in the ambient room temperature.

The appendix recognizes that existing listed spacings for heat detectors are based on relatively large (1200 Btu/sec) fires burning at a constant rate. The allowable spacing given any detector in its listing is that which shows comparable response to a 160°F standard sprinkler installed on a 10 foot by 10 foot spacing.

The tables that appear in Appendix C were not based directly on DETACT-T2 but rather a Factory Mutual model. Nevertheless, the DETACT-T2 program, since it is based on the same experimental data, provides close results. An extensive series of tables generated using DETACT-T2 has been published by the National Bureau of Standards [14].

Using the tables within Appendix C of NFPA 72E, a time constant value for a fixed-temperature detector is first estimated based on the listed spacing of the detector. This time constant is then used as input to the tables, along with the difference between detector rated temperature and expected ambient room temperature, ceiling height, expected fire growth rate, and desired threshold fire size at the time of detector response. The tables provide the allowable spacing of detectors to achieve this desired threshold fire size. Separate tables are provided to evaluate rate-of-rise detectors.

Using the DETACT-T2 program, input consists of ambient room temperature, detector RTI and activation temperature, detector rate of rise criteria, ceiling height, detector spacing, radial distance from the centerline of the fire to the detector, and choice of slow, medium, fast or other fire growth rate. The output is a time of detector actuation.

Either method permits the fire protection engineer some degree of control over the expected performance of a detection system.

4.2 Fire Investigation Applications

Fire investigation and reconstruction probably provide the best current application for deterministic fire models for one main reason: the universe of variables is smaller. A specific case rather than overall building fire safety is to be considered. In the aftermath of a fire, the point of origin and initially involved fuels are often known, and information on specific room geometries and characterisitcs can be used as input to a model. Furthermore, the output is often used only to enhance engineering judgement, so the validity and accuracy of the model is not being depended on for actual building safety.

Several memorable fire investigations have employed deterministic methods. One of the earliest was Emmons' hydraulic modeling of corridor gas flow at the Beverly Hills Supper Club fire of 1977 [15]. Most recently, Nelson employed a number of individual deterministic methods and models in his analysis of the Dupont Plaza Hotel fire [16].

In the latter half of 1985 I was able to use the DETACT-QS model as a major tool in a analysis of one of the other well-publicized fires of the decade: the Six Flags Great Adventure "Haunted Castle" fire [17]. The analysis was performed to determine if it was likely, as stated in defense expert witness testimony, that if sprinklers had been installed in the walk-through amusement facility, they would have suppressed the fire only after the development of lethal conditions in the vicinity of the eight teenagers who were killed.

To the extent possible the analysis relied upon assumptions made by the defense expert witnesses. These included assumptions as to the likely time of flashover of the room of fire origin (three minutes) and assumptions as to the type (dry) and specific design of the sprinkler system which would have been installed. Another key assumption made by defense experts was that for the first 90 seconds of the fire, an exhaust fan located over the point of fire origin was assumed to have removed the heat and smoke from the fire. This necessitated the use of the DETACT-QS program rather than DETACT-T2, so that the apparent heat release rate of the fire could be modified to simulate this loss of heat.

Based on these assumptions, the analysis proceeded with the following steps:

1. Selection of Model Fires

A minimum rate of heat release necessary for room flashover was estimated based on the geometry of the openings in the room of fire origin (the Strobe Room) using a rule-of-thumb developed by Babrauskas [18]. Determined by a heat balance in the upper gas layer, this represented the size of a constantly-burning fire which could produce flashover. Based on this value and the assumed time of flashover, the "ultra-fast t-squared fire" was selected as the model, on the basis that it reaches 6 MW at 180 seconds. For the sensitivity analysis, a second fire growth curve was developed based on the same key point of 6 MW at 180 seconds. This curve represented a faster-growing fire, in which heat release was proportional to the fourth power of time.

2. Confirmation of Fuel Load

The ability of the combustible walls and ceilings of the Strobe Room to produce a 6 MW fire was confirmed by a review of Park Service tests conducted at the NBS in rooms with similar fuel loads.

3. Placement of Model Fire

The fire was assumed to start at a point three feet below the ceiling at one end of the Strobe Room on the vertical surface of a flexible polyurethane foam pad, in accordance with trial testimony.

4. Selection of Sprinkler Sensitivity

Three different sensitivities of sprinkler response were selected for analysis. Response time indexes (RTI) of 50, 210, and 500 $ft^{1/2}$ $sec^{1/2}$ were used to respectively represent quick response sprinklers currently available, the most sensitive standard sprinklers available at the time the Haunted Castle was constructed, and standard sprinklers toward the least sensitive end of the spectrum.

5. Modification of Model Fires to Simulate Assumed Field Conditions

The two fire growth curves were modified by eliminating almost all heat release for the first 90 seconds, resuming to full heat release at 100 seconds into the fire. This represented the assumed influence of the exhaust fan.

6. Calculation of Sprinkler Operating Times

The modified fire growth curves, along with fire point source and sprinkler sensitivities, were used as input to the DETACT-QS program. The heat release rates were doubled during program input to reflect the fact that the fire was located against a wall, reducing air entrainment and increasing the temperature of the fire gases. Sprinkler locations were based on design drawings prepared by defense expert witnesses.

7. Modification of Sprinkler Operating Times for Quasi-Steady Assumption

The sprinkler operating times predicted by the DETACT-QS program were increased by 1 second per meter of distance between the sprinkler and the fire to account for the flow time needed for the hot gases. The results indicated that the time of first sprinkler operation following ignition would depend on the sprinkler sensitivity and the fire growth curve, and would range from 98 to 122 seconds.

8. Calculation of Dry Pipe Valve Trip Time

The time taken for a dry pipe valve to trip after first sprinkler operation was calculated, taking into consideration the operating times of the second and successive sprinklers using a method developed at Factory Mutual [19]. It was determined that system dry valve trip times ranged from 14 seconds with the RTI 50 sprinklers in the t-squared fire to 22 seconds with the RTI 500 sprinklers in the t-fourth fire.

9. Calculation of Water Transit Time

Using a model developed by Factory Mutual [19], the time taken for water to travel from the system dry valve to the first open sprinklers was calculated and found to range from 4 seconds for the RTI 50 sprinklers in the t-squared fire to 9 seconds for the RTI 500 sprinklers in the t-fourth fire.

10. Comparison of Predicted Water Delivery Time to Field Tests

As a check on the validity of the dry valve trip and water transit models, a calculation was made of expected time of water delivery to a simulated inspector's test connection and compared against survey results for systems of similar shape and size. The comparison indicated good correlation.

11. Calculating Total Time of Water Delivery to Fire

Combining the predicted initial sprinkler operating time with the valve trip time and water transit time, the total time from the start of the fire to water delivery was determined to range from 116 to 154 seconds. In all cases the water delivery time was found to take place prior to Strobe Room flashover at 180 seconds into the fire.

12. Comparison of Modeled Results to Experimental Data

To check the reasonableness of the DETACT program input, a comparison of ceiling temperature profiles was made between the simulated fires and a corridor test conducted at the National Bureau of Standards in 1976 [20]. The test involved a very similar geometry and combustible wall and ceiling finish. The comparison indicated good correlation between the two sets of data for ceiling temperatures at the one-third, center, and end points of the corridor. Since the NBS test was stopped when flames reached the far end of the corridor and was not permitted to go to flashover, the comparison also indicated conservative assumptions were used relative to the simulated fire growth histories.

13. Calculation of Sprinkler Discharge Densities

Using a sprinkler hydraulics model, the water discharge densities which would result from opening as many as thirteen sprinklers were calculated, and determined to be well in excess of that needed to suppress the fire.

14. Review of Tests to Determine Suppression Ability of Sprinklers

Conclusions from two separate test programs conducted at the National Bureau of Standards were used to demonstrate that control of fire on upper walls and ceilings would have been achieved.

15. Review of Tests to Determine Life Safety Impact of Sprinkler Suppression

The life safety impact of sprinkler suppression was addressed through reference to NBS test programs which indicated that if flashover of the room of fire origin is prevented, life-threatening conditions do not develop in remote areas.

16. Calculation of Life Safety Impact of Sprinkler Suppression

The life safety impact was also addressed through a calculation method using an LC50 of 40 mg/liter for both flexible polyurethane and plywood. A value of three times the LC50 was assumed as safe for the two to three minute exposure necessary to exit the building. Assuming all products of combustion were spread evenly throughout the top half of the corridor space outward from the fire source, the length of hazardous corridor over time was estimated. It was determined that at the time of water delivery to the sprinklers, hazardous conditions would have been confined to the Strobe Room or shortly outside. However, within another 60 seconds of unsuppressed fire, hazardous conditions were predicted to have spread beyond the area where the teenagers were killed, and throughout the entire Haunted Castle in less than four minutes from the start of the fire.

The analysis made it clear that several factors had been overlooked in the trial testimony. Starting from the point the exhaust fan was overwhelmed, it was assumed that sprinkler operation would have proceeded as if a small fire was just starting out. Instead, a large and growing fire was well under way, and would have resulted in fast operation of even the slowest standard sprinklers. Also, the estimate of the delay time caused by the hypothetical dry system was based on typical water delivery times associated with dry pipe valve trip tests in which a single sprinkler is opened. For a growing fire situation, the rapid opening of additional sprinklers would have substantially reduced trip time, resulting in a shorter water delivery delay. Finally, the estimate of the ability of sprinklers to provide life safety was based on the residential sprinkler test program. The primary intent of the residential sprinkler program, however, was the development of a low-cost system capable of suppressing fires with very limited water supplies. Unlike the residential sprinkler test systems, the system installed in the Haunted Castle would have been capable of delivering high water application densities without fuel shielding. Also, the residential sprinkler program was aimed at maintaining tenable conditions within the room of fire origin. In the Haunted Castle the deaths occurrred some 100 feet down a twisting corridor from the room of fire origin.

The anaylsis concluded that if a properly designed and maintained sprinkler system had been in the Haunted Castle at the time of the fire, it is likely that the loss of life would have been prevented.

An analysis of this type shows the strength of the deterministic models available to the fire protection engineer as part of an overall analytical approach. In all, three different deterministic models and four simple deterministic methods were employed, along with reference to nearly a dozen other experimental programs for purposes of basing assumptions and checking reasonableness of calculated results.

4.3 Standards-Writing Applications

In a sense, the use of a detector actuation model to create the tables within Appendix C of NFPA 72E was an example of standards-writing applications of deterministic models. A related effort is currently underway in the sprinkler field.

One of the biggest challenges currently facing the writers of sprinkler installation standards is how to address the use of quick response sprinklers. The residential sprinkler and the ESFR (Early Suppression Fast Response) sprinklers were each developed as a type of fast response sprinkler intended for special application, with installation criteria developed as part of the same test program as product development. Listed quick response sprinklers, however, were developed simply by putting fast response into sprinklers qualifying as standard sprinklers. At present there is no specific installation guidance available, and in fact there is some concern that the use of quick reponse sprinklers under standard sprinkler design criteria may be disadvantageous. The concern is that if the quick response sprinklers fail to suppress the fire early, the heat released during a "control" mode may activate an excessive number of sprinklers, overtaxing the water supply and leading to system failure.

The National Fire Protection Research Foundation is addressing this concern through its Quick Response Sprinkler Research Project. The project has included a series of tests intended to measure the suppressibility of two fairly severe fuel packages: an upholstered furniture corner scenario and a 6-foot high arrangement of polystyrene cups in corrugated cardboard cartons. In these tests, modeled after Factory Mutual's RDD (Required Delivered Density) work in the development of the ESFR sprinkler, the effect of various rates of water application are investigated, commencing at various points in the fire growth history [21]. The total heat release history of the fire is measured by conducting each fire test beneath a large calorimeter.

In this program, the DETACT-QS program is being used as an analtytical tool in two different ways.

Primarily, the program is being used to help determine which sequences of heat release history data can be interpreted as indicating suppression took place. To do this, assumptions are made of quick response sprinkler RTI, temperature rating, and spacing. Successive iterations are then made using the DETACT-QS program, using heat release data of the fire prior to the application of water. Various ceiling heights are tried until the program indicates that operation of the first sprinkler(s) would have taken place at a time corresponding to the time water was actually applied during the test. Using this height for the remainder of the calculations, DETACT-QS is employed to determine if the heat release history of the fire after the application of water would result in operation of "second ring" sprinklers, those in the next radial grouping from the fire. If the second ring sprinklers are shown to not have operated, and if the fire did not proceed to the edges of the fuel package, the test sequence is classed as a successful suppression.

It is agreed that this approach is only roughly approximate, in that the nature of the fire plume and ceiling flow would be disturbed by the opening of sprinklers, a factor ignored during the calculations. Also, the method assumes that when a fire is situated between two or four sprinklers, all first ring sprinklers open simultaneously to provide the water application density. Nevertheless, the DETACT-QS program is the only tool available for this type of analysis at the present time. Further, it is noted that the approach is conservative in that the atmospheric cooling ability of sprinklers to prevent outer ring sprinklers from opening is ignored.

Another avenue of analysis being investigated is one which looks at the possible use of quick response sprinklers in a "fire control" design approach. For the two fuel packages tested, the RDD data represents the results of a large number of water application sequences, some of which can be considered to have resulted in suppression, some of which can be considered to have resulted in successful control, and some of which can be considered unsuccessful in both suppression and control. Using the DETACT-QS program as outlined above to determine an effective ceiling height corresponding to the time of water application, it may be possible to estimate the relative numbers of both quick response and standard sprinklers which would have operated in a large open area during the water application sequence.

The results of this second "control mode" analysis may make it possible to estimate the degree of expected disadvantage or advantage from quick response sprinklers. If so, such a relative condition could be accounted for in the area/density design approach through the use of an area modifier, similar to the 30 percent increase assigned to dry pipe systems.

It should be noted that in both of these approaches, the DETACT-QS program is being used simply as an analytical tool. Full-scale confirmation tests will be needed prior to the final development of installation standards based on the analyses.

Depending upon the degree of sophistication which the standards-writers will permit, future editions of the sprinkler standard might contain tables for system design which incorporate the output of the DETACT models, or permit a direct application of the models as part of the design process. If it is shown that suppressibility of a fire becomes more difficult as water application is delayed, then the sprinkler system design process should take into consideration those variables which affect sprinkler response. Deterministic models make that possible.

5. CURRENT APPLICATIONS OF OTHER MODELS

5.1 Building Design

Like the use of deterministic models in fire investigation, building design applications are generally those which call for consideration of a special case. To begin with, the building design problem must warrant the necessary engineering time. For the most part this would be the case only with large or expensive buildings, or other cases where a single compartment is of concern. For example, a number of engineering firms have employed the two-zone room model ASET [22] in combination with DETACT in occupancies ranging from nuclear power plants to exhibition halls. ASET provides information on the smoke layer temperature and descent in a closed room. The combination of the two most widely distributed fire models has been used to answer the following types of questions, given a certain fire growth condition and room geometry:

1. Will proposed detection systems operate provide early enough alarm to allow effective manual suppression, or will the descent of a smoke layer inhibit effective manual fire-fighting, creating the need for automatic suppression systems?

2. Will proposed automatic suppression systems operate early enough to prevent specific types of damage, as represented by limiting temperature conditions in the upper layer?

3. Will the time between detection system activation and the descent of the smoke layer permit adequate egress time considering the proposed arrangement of exits?

To some extent deterministic methods are in use in the area of fire resistance calculations. The Standard Building Code, for example, has for years included an Appendix P which, with the consent of the code official, permits calculation of the fire resistance of specific materials or combinations of materials [23]. While the steel industry has met with success in some jurisdictions in promoting the adoption of FASBUS-II as a method of calculating fire resistance of steel structures, code recognition of fire models is still rare. However, all of the major model building codes do presently contain language to permit design alternatives or equivalent methods of achieving the same or better construction method than that specifically outlined in the code text. In practice, some fire protection engineering firms are taking advantage of the opening these sections provide for the use of deterministic models.

5.2 Smoke Control Systems

The publication of an ASHRAE manual for the design of pressurized stairwells and zoned smoke control systems has provided an excellent example of the integration of various deterministic methods with a computer model into a design manual [24]. The ASCOS model provides a means to calculate the airflows and pressure differences throughout a building in which a smoke control system is operating.

NFPA 92A, a recommended practice for the design and installation of smoke control systems, is based on the ASHRAE manual and is scheduled for adoption at the 1987 Fall Meeting. In general the document defers to the ASHRAE manual for detailed engineering design information and as a reference for deterministic methods. For example, the document suggests maximum pressure differences across doors for various door sizes and door closer forces, based on the 30 lbf maximum door-opening force mandated by NFPA 101 Life Safety Code [25]. For other door-opening forces or other door sizes, the user of the proposed recommended practice is referred to the calculation procedure provided in the ASHRAE manual.

It is important to note that the smoke control methods and models are not actually fire models since they deal with air flow other than the fire condition. In that sense they are comparable to the sprinkler hydraulics models.

5.3 Code-Writing Applications

In the current amendment cycle of the Life Safety Code the ASET model was used as the direct basis for a code change proposal. This may have been the first such attempt to use a deterministic fire model directly in a code writing proposal.

The particular code change proposal dealt with a requirement to sprinkler "small pods" less than 2500 square feet in detention and correctional facilities, a pod being a cell housing area within a perimeter wall.

Proposed from within the NFPA 101 Subcommittee on Detention and Correctional Facilities, the intent of the change was clarified through a proposed new appendix section:

> "A-14-3.1.2(d) This requirement mandates automatic sprinkler protection throughout housing areas less than 2,500 sq. ft. because a "small" pod creates a worse situation. The small volume allows for more rapid heat buildup and for greater concentrations of smoke to be present. The resulting untenable heat and impaired visibility conditions justify the sprinkler requirement..."[1]

The fact that fire modeling was used to develop this proposal was made a part of the public record only during consideration of public

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[1]1987 Fall Meeting Technical Committee Reports, Proposal 101-522, National Fire Protection Association, Quincy, MA

comments, when the proposed change was overturned. Perhaps this reversal indicates a lack of confidence in present use of fire models. Nevertheless, it is interesting that the nature of the proposal, a recognition that the hazard may be worse in a small occupancy as opposed to a large occupancy, is the type of insight which may be gained from application of fire models. Conventional engineering judgement would not be likely to foresee this situation.

There are many other potential applications. For example, use of a particular wall finish material might be evaluated by using its measured burning characteristics as input to a fire model, then determining the rate of hazard development and the likely time of operation of detection and suppression sysrtems. It could be determined if a particular flamespread of finish is likely to "outrun" protection measures.

6. USER NEEDS

The discussion of applications has shown that the use of deterministic fire methods and models can help us improve the application of engineering judgement, can help us move closer to defined performance levels, and can help us avoid costly repetitive fire testing. But the prospective user of these models and methods must have support.

6.1 Documentation

The most obvious user need is the need for documentation, for "user manuals" for all deterministic methods and models. This documentation should clearly identify the intended applications of the method, the limitations of the method, and the possible margin of error. The user needs to understand what physical assumptions are being made as part of the modeling process. Especially critical is advice dealing with required user assumptions.

Without such documentation, the potential exists for unrealistic assumptions and applications which conveniently reach the desired conclusion, for hand calculations as well as computer models. Deterministic calculations based on totally inappropriate assumptions are worthless. A common example involves the cooling ability of water in an exposure protection situation, and the erroneous assumption that virtually all of the water absorbs heat with total efficiency.

The ideal form of documentation for deterministic methods is an authoritative textbook. The recent publication of such a text on the subject of fire dynamics is a major step forward [26].

6.2 Comparative Experimentation References

At the first tutorial on fire models sponsored by the Society of Fire Protection Engineers in May of 1985, instructors Doug Walton of the National Bureau of Standards and Phil DiNenno of Hughes Associates urged the attendees to avoid use of fire models without full-scale test data for back-up comparisons. This remains good advice today.

There is a need for an accessible inventory of experimental and experiential data. Even with the best intentions, it is very easy to misapply a deterministic model and obtain highly inappropriate results. A library of reference tests can be used as a check against reality.

6.3 More Complete Deterministic Abilities

There is a need to fill in some of the major gaps in our understanding of fire phenomena. In the sprinkler industry, for example, we feel the researchers have made great strides in understanding the science of sprinkler response, but only limited steps in the area of sprinkler suppression. The analysis of the Great Adventure Fire was only possible because the answer to the suppressibility question was obvious. It is possible to determine if there is more than enough water for suppression, but extremely difficult to determine if there is just enough. We look forward to the results of further research, and hope that the federal effort in all aspects of fire research will grow stronger rather than weaker.

Even existing models can be improved. An enhancement to the DETACT model to account for the effects of a compartment is already in use at the National Bureau of Standards, although the corresponding computer code has not yet been made available to the public [27]. This enhancement, makes use of the ASET model, taking into account the heated upper layer of gases accumulating within an unvented compartment. The air entrained into the plume is warmer, permitting higher temperature gas flow past the detector or sprinkler, resulting in faster operation. Evans has indicated that compartmentation can reduce the time of response by as much as 40 percent.

Another enhancement which will be needed is the inclusion of the conductivity term within the RTI factor. As mentioned above, this can be important for low-velocity low-temperature fires, and especially for the types of sprinklers which have their operating element in close proximity to the sprinkler body and waterway. Conversely, it is of little importance for sprinklers which are well insulated between the operating element and the sprinkler body, such as glass bulb sprinklers.

6.4 Widespread Training

There is a need to move deterministic methods more into the mainstream of fire protection engineering. This conference is, of course, one step along that path. The Society of Fire Protection Engineers is also working in this area through its "mini-seminars", distribution of computer codes, calculation handbook development, and other programs. It is important to note that training must include authorities having jurisdiction as well as design professionals, since the inability to properly review a deterministic approach will work against its general acceptance.

7. CONCLUSIONS

Using one deterministic fire model as the primary example, it has been shown that there are many possibilities for application by fire protection engineers. At the present time, however, the limitations discussed as user needs prevent a wide application of deterministic models. The gaps in our knowledge, the lack of understanding among not only design professionals but the review authorities, and the complexity of fire phenomena and the models themselves all work against the idea of a totally performance-oriented approach to fire protection at the present time.

Until these needs are met, deterministic methods should continue to grow in use as an aid in improving the prescriptive approach. Those who are on the forefront of this new technology have an obligation to work within the present system, pointing out ways in which the new methods can fill gaps and create efficiencies.

By way of introduction to the use of deterministic models I discussed the widespread use of hydraulics models within the sprinkler industry. Perhaps some lessons can be learned from the way in which those models gained acceptance. It was through the concensus standards system, which permitted a degree of confidence among users and enforcers in the validity of the methods. The concensus standards also enforced the use of certain assumptions with the methods, preventing abuses. In other words, a sprinkler system designer cannot arbitrarily choose a C-factor for pipe friction loss calculations, nor can he even elect to calculate pipe friction loss using a method other than Hazen and Williams. Those choices have been made for him by the NFPA Committee on Automatic Sprinklers.

Another fact that should not be overlooked is that sprinkler hydraulic calculation methods quickly gained favor due to an economic incentive. More efficiently designed piping systems were less expensive, justifying the added complexity of calculations. If fire models are to achieve similar growth in use, they too must be shown to produce economic savings.

If we are to encourage widespread use of sophisticated fire models, we should seek to familiarize the writers of standards and codes with particular desirable applications, and then seek their support and endorsement for the use of those models in such applications. In the process the models might lose some of their magic and become encumbered with some degree of regulation, but this is a trade-off we should be willing to accept. Ultimately, the introduction of sound deterministic approaches into codes and standards should permit more effective and economical fire protection.

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Table 1

Listing of Enclosure Computer Fire Models

(from Budnick and Walton, NFPA Fire Protection Handbook, 16th Edition)

Model Name	Author	Maintaining Organization	Computer	Language	Applications Special Features
ASET	Cooper Stroup	NBS	Micro	Fortran	Single room enclosure fire model
ASET-B	Walton	NBS	Micro	Basic	Single room Enclosure fire model
BFSM	Swartz Berlin Fahy Connelly Demers	National Fire Protection Association	Mini	Fortran	State transition model based on statistical likelihood of events
BRI	Tanaka	Building Research Inst., Japan	Mini	Fortran	Multi-room, multi-floor enclosure fire model
CALTECH	Zukoski Kubota	NBS Calif. Inst. of Technology	Mini	Fortran	Two room enclosure fire model
COMPBURN	Siu	UCLA	Mini	Fortran	Single room enclosure fire model, developed for nuclear power facilities
COMPEZ	Babrauskas	NBS	Mini	Fortran	Single room, post-flashover enclosure fire model
DACFIR-3	MacArthur	FAA	Main	Fortran	Enclosure fire model for aircraft cabin geometries

Table 1 (cont.)

DSLAYI	Hagglund	National Defense Research Institute, Sweden	Mini	Fortran	Single room enclosure fire model, smoke filling
FAST	Jones	NBS	Mini	Fortran	Multi-room enclosure fire model
FLASHOVER	Hagglund	National Defense Research Institute, Sweden	Mini	Fortran	Single room enclosure fire model
HARVARD	Emmons Mitler	NBS	Mini	Fortran	Enclosure fire model, version 5 single room, version 6 multi-room
OSU	Smith Satija	Ohio State University	Mini	Fortran	Single enclosure fire model, input from ASTM E 906 calorimeter
RFIRES	Pape Waterman	Illinois Inst. of Tech. Research Institute	Mini	Fortran	Single enclosure fire growth model

Table 2

Special Purpose Computer Fire Models

(from Budnick and Walton, NFPA Fire Protection Handbook, 16th Edition)

Model Name	Author	Maintaining Organization	Model Type	Computer	Language	Applications Special Features
ASCOS	Klote	NBS	Smoke Control	Micro	Fortran	Steady state network flow model for smoke control evaluation, no fire condition
DETACT-QS	Evans	NBS	Thermal device actuation	Micro	Basic	Calculates actuation time for heat detectors and sprin- klers, unconfined ceilings
EVACNET+	Kisko Francis	University of Florida	Building egress	Mini/Micro	Fortran/Basic	Network model for calcu- lating evaluation time: multi-rooms, multi-floors
FIRES-T3	Iding Bresler Nizamuddin	American Iron and Steel Inst.	Structural heat transfer	Mini	Fortran	3-dimensional heat transfer analysis through structural assemblies

Table 2 (cont.)

FASBUS-II	Chiapetta Bresler Iding Jeanes Breese	American Iron Steel Inst.	Structural response	Mini	Fortran	Finite element analysis of structural response of steel framed floors
FEES/MB	Alvord	NBS	Emergency escape	Mini	Fortran	Simulation of emergency escape and rescue times, developed for board and care facilities
FOREST FIRES	Rothermel	US Dept of Agriculture	Fire spread	TI-59		Prediction of spread and intensity of forest and range fires
HPO 10	Hansever	Technical Univ. of Braunschweig, Germany	Structural response	Main	Fortran	Finite-element analysis of reinforced concrete beam structural and thermal response
HSLAB	Abrahamsson Hagglund Janzon	National Research Institute, Sweden	Heat transfer	Mini	Fortran	One-dimensional calculation of transient temperature in concrete slabs
MINE VENT	Greuer	Michigan Technical University	Shaft vent	Mini	Fortran	Simulation of under-ground mine fire interaction

FIRE RISK ASSESSMENT PROGRAMS

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ABSTRACT

Fire risk assessment involves the coupling of probabilistic concepts, such as the likelihood of ignition and the expectation of finding a given fire load, to deterministic fire models, which predict fire conditions as the result of known physical variables. This presentation, based on the National Fire Protection Research Foundation Fire Risk assessment Project is an update and discussion of how the method is designed. The approach is to emphasize products found in buildings rather than design features of the buildings themselves, although the latter can be incorporated as well. Scenario analysis often simplifies the computational tasks: for example, most typical residences are of a size that life safety effects are not influenced either by very small fires or by details of the post-flashover situation. Although post-flashover fires are important in larger buildings, relatively simply computational schemes can sometimes be used because less-detailed knowledge of the fire environment is required. Present approaches are to use a fire data system, such as NFIRS, to weight the outcome of the modeled scenarios by the likelihood that ignition will occur. Much of the fire load data must be supplied by industry sources, or by panels of experts. Preliminary results of the method's application to upholstered furniture are discussed, as well as a description of the work undertaken in Phase Two of the project, commencing in Fall of 1987.

1. INTRODUCTION

Being able to supplement experience with technology has always been a goal of those who build and regulate structures. When it comes to safety, experience has served us well. It is not too difficult to see a regular decrease in fire life losses, beginning before the turn of the century, which follows the development of building codes. As an understanding of the dangers of fire has improved losses have gone down. Where once we worried about losing entire cities to fire, we were subsequently able to confine fire to individual buildings, then individual floors of buildings, now well separated by fire resistant barriers and, finally, to the individual rooms of fire origin. Today, most fire deaths are closely associated with a single room on fire. Losses have been declining slightly in the past few years, but are fairly stable at about 30 deaths per million population in the United States. Other industrialized countries do considerably better, and the reason for this disparity are not particularly well understood.

In the past 15 years, renewed attention has been directed to fires in buildings and their contents, partly because of changes in building trends and partly as the result of using new classes of materials. It is useful to recall that, up until about 1950, almost all combustible materials in a building had their origins as wood, wood products, or cotton, (which is chemically similar). Therefore, the only materials which were likely to appear in smoke were carbon, hydrogen and oxygen. As new synthetic materials were developed, an entire menu of elements began to appear in the smoke: nitrogen, chlorine, fluorine, bromine, sulfur and others. Hundreds of years of experience with wood smoke was no preparation for this at all. In addition, many of these new materials burned qualitatively differently than the traditional ones, so that we were poorly prepared to predict their fire performance and to forecast the impact that smoke from them might have on building occupants.

This recognition prompted a spate of new, much better, laboratory-based test methods for building components, contents, and designs. It also spotlighted how hard it is to predict the course of a real fire from laboratory measurements. The best test of a building's performance is burning it down after it is built, but an acceptable method has to be somewhat less destructive. This need is the justification for mathematical fire modeling as we know it today. Several speakers here will be discussing how mathematical models are developed, how they can be applied to buildings, and will give you some indication of the power they offer.

Irwin Benjamin and I founded Benjamin/Clarke Associates in late 1981 largely on the expectation that modern fire science - - new test methods and mathematical models in particular - - was ready to be applied to real fire situations. There is a growing list of such applications. For example, Howard Emmons' elegant reconstruction and analysis of the Beverly Hills Supper Club fire (1), using many elements of modern modeling, is a particularly noteworthy case. More recently, we at Benjamin/Clarke have used a multi-room fire and smoke transport model, the second generation of the famous Harvard Fire Code, to analyze events in the Biloxi, Mississippi jail, the scene of a tragic fire in 1982. You may also have seen Bud Nelson's recent description of the DuPont Hotel fire in Puerto Rico (2). In all of these fires, computation using the building layout and structure played a key part in answering questions as to the progress both of the fire and smoke. Similar methods are also applicable to individual building components. At Benjamin/Clarke Associates, we routinely use room fire models to estimate the fire performance under actual use conditions of things like cables (3), various types of upholstered furniture (4), and combustibles concealed behind walls (5). In particular, mathematical modeling played a significant role in recent changes in the National Electrical Code, to allow wider use of flexible non-metallic conduit.

Two years ago, the National Academy of Sciences empaneled a Committee on Fire Toxicology. The group's initial focus was solely on the toxic potency of smoke, but the Committee members soon realized the necessity of evaluating all important aspects of a developing fire before a fair judgement of fire hazard can be rendered. The Committee enthusiastically endorsed mathematical modeling as the right way of dealing with problems in fire hazard. I invite your attention to two brief case studies, which the Committee carried out on a abbreviated basis, which appear in their 1985 report (6).

Fire hazard assessment tells what will happen <u>if</u> a given fire occurs in a given building environment, <u>if</u> it encounters a given set of combustibles, and <u>if</u> the smoke reaches a given population of potential victims. It does not tell you, however, the likelihood that any of those conditions will be fulfilled. If the probability that the various components of hazard can be established, then the ingredients are there to predict the <u>risk</u> of the fire. This kind of approach had its origins in the fault tree work common in various safety-related disciplines, and in particular with the work carried out by NFPA committees and GSA, in the 1960's and 70's, which provided the analytical framework for such risk based systems if the numbers could be supplied (7). Bob Fitzgerald's progress on the building L curve, which you will hear more about in this meeting, is the latter day descendent of this approach.

Recently, the National Fire Protection Research Foundation, the research arm of NFPA, has undertaken a generalized risk assessment project aiming at marrying fire experience data with fire hazard assessment in order to provide some overall quantitative estimate of fire risk. In the following sections of this paper, I will describe the rationale and logic of the risk system, results to date - - which are admittedly preliminary - - and finally offer some thoughts about where I think this approach fits in the general scheme of improved analytical methods of building fire safety.

2. FIRE RISK ANALYSIS

The objective of the fire risk analysis project is to develop a readily used, quantitative, general method of characterizing the fire risk of products in terms of their expected use and measured fire properties.

In the best of all worlds, the way to do a fire risk analysis of a product is to keep track of all fire incidents in which the product is involved, garnering all relevant information about each incident. Then a relationship can be drawn between the fire properties of the product, as measured in the laboratory, and the circumstances and effects of each fire which actually occurred. Occasionally, something like this approach is taken. The Flammable Fabrics Accident Case and Testing System (FFACTS) operated by NBS under the Flammable Fabrics Act in the late 60's and early 70's, actually tracked down a sizable fraction of the more serious flammable fabrics incidents which occurred in the nation every year.

Although such a program is a feasible general approach, especially when ubiquitous products like upholstered furniture are considered, if an approach like this could be followed, the next step would be to group product fires into similar categories; those occurring in residences would have different characteristics than those occurring in public assembly occupancies, for example. The combination of circumstances of location, type of ignition, spread of the fire, and similar qualifiers together constitute what is commonly called the "scenario" of the fire. In principle, all product fires can be grouped into a family of scenarios: the narrower the circumstances of use of a product, the fewer the kinds of fire scenarios in which it is involved. Finally, to estimate how important each kind of product fire is, we need to know the relative likelihood, or probability, of each fire scenario. For example, fatal fires from ignition of upholstered furniture by cigarettes, (which leads to a smoldering fire), are more common than those from ignition of upholstered furniture by a match or lighter (which a flaming fire is usually the result). So, risk assessment of upholstered furniture must be able to deal with the possibility that improving furniture's resistance to one kind of fire, e.g., smoldering has a different payoff, because it is a more common fire, than improving resistance another kind, e.g., open flame ignition.

It is obvious that many simplifications are necessary to produce a practical one for a risk assessment system. Several million fire incidents occur in the United States each year, and doing an in-depth investigation of even a small subset is well beyond anyone's capabilities. So the problem is to synthesize nationally-aggregated data and what is known about fire phenomena in order to develop a predictive method, or "model", of the relationship between product fire properties and risk. These considerations produce several self-evident characteristics:

1. The system is tied to a fire data collection source. The present system uses the NFPA fire database, as expressed by NFPA 901, method of classifying fire information. It can in principle operate with others.

2. Since the NFPA system collects data primarily on products, as opposed to building types or occupant behavior, a product oriented risk analysis is produced. Equally fine-grained data on buildings could - - perhaps - - be used for a building-oriented risk system.

3. Since the system depends to some extent on aggregations of numbers, it does not predict changes in risk in any given incident, but expresses its results in terms of changes in the outcome of expected, average, or typical incidents.

The system itself is a marriage of fire experience data to fire hazard assessment models. In essence, it attempts to weight the calculated severity from a given scenario by the likelihood that that scenario will occur. It is only for the probabilistic elements that we must depend on the fire experience data. Other portions of the method, i.e. the hazard models, can still be used without probabilities to compare the merits of similar products in identical scenarios.

The method is intended to be general enough that it can be used for variety of products and, equally important, serve a variety of potential users. Three major classes of users are: product manufacturers; builders and building regulators; and insurers.

Product designers can use this system to evaluate the effects of improving fire performance under simulated in-use conditions. In particular, it allows one to choose among different options with potentially competing effects like lowering toxicity at the cost of flame spread. Product liability issues are particularly important today and techniques to identify unexpected exposure are helpful. This method is intended to answer questions like: Does one particular subset of the potential market represent a bigger fire risk than others, and is it therefore perhaps to be avoided?

A building official would make use of the same information quite differently. It allows him to identify what product offer the most potential for life safety improvements if their fire properties are improved. Conversely, it allows one to identify areas in which improvements in fire properties have little or no payoff in reduced life risk. These two attributes are of utility not only to the building official, but to those who design buildings as well. It provides a vocabulary, or a language, in which building fire safety regulations can be discussed. In effect, it puts the same tools into the hands of both sides of the question. Ultimately, such a method would be at the heart of completely performance based code, although it is not news that a performance based code is easier to do in the abstract than in concrete.

Insurers have a well-developed system for estimating property loss of fires but, until recently, life loss and the underwriting which goes with it has not received the same attention. It is anticipated that this approach could be helpful, if adapted to a fire database appropriate for insurance.

2.1 Logic of the Model

In order to synthesize a risk model, fire experience data must be converted to quantitative information about how fires burn. Specifying the product of interest (i.e., the one whose fire properties are going to be related to the risk) and the occupancy in which it is to be used (i.e., the kind of building: residences, offices, public assembly, and the like) allow one to define a typical set of physical circumstances, such as room size, layout of the continuous space and inventory of other objects likely to be ignited.

Reports of fire using the NFPA 901 system generally give the item-first-ignited and the limits of fire spread. If the geometry of the compartment in which a fire occurred can be approximated, and if the compartment contains sufficient fuel to carry the compartment to flashover, then:

a. The size the fire reached, in energy release rate, can be classified, since the energy release rate is directly related to upper room temperature, which is in turn related to fire spread.

b. The average rate of fire buildup can be estimated from a knowledge of the item ignited by reference to a two-parameter, 9-valued, table of possible fire growth and heat release rate which is used to characterize all items appearing in the NFPA 901 taxonomy.

c. The likelihood that the fire will spread to the product of interest (assuming it wasn't ignited originally) can be estimated from the intensity of the original fire (a. and b. above), the ignition characteristics of the product, and how far it is typically likely to be from the item first ignited.

For flaming fires, there are 40 possible combinations of fire profiles arising from these descriptors. Smolder-prone combinations of source and fuel fire sources are also treatable under this approach; these are relatively few in number. When smoldering and flaming fires are combined there are typically 40-50 total fire profiles which result.

To date this part of the model, the so-called "scenario generator" has been the most difficult to design and quantify; it is also where the greatest number of semi-quantitative estimates and averages must be made. By the same token, it is the heart of the method. As estimates can be improved, so can the utility of the results.

The scenario generator then "draws" the heat release rate curves of the family of fires to which the product of interest gives rise and weights them according to their frequency of appearance in fire statistics. The logic in a little more detail is shown in Exhibit 1.

The actual hazard depends on how smoke and heat are distributed through the space containing and adjoining the fire, and upon the escape capabilities of those exposed. Fire and smoke transport models are relatively well-developed (at least for single-floor spread): the system presently uses "FAST", a versatile model multi-room fire model which can predict time-based profiles or heat, hot layer depth, smoke density and fire gas concentration anyplace in a network of compartments from a heat release curve such as drawn by the scenario generator.

An adjunct program to FAST can compare the capabilities of various classes of fire victims to the conditions in the compartments and determine whether that victim can escape. Because potential victims can be young or old, healthy, or infirm, drunk or sober, a demographically based profile based on what a building class is expected to contain is required. For residences, a complete occupant set can be inferred from U.S. Census and related data; for other building types, those exposed may show less diversity in their escape capabilities but quantitative information is correspondingly less available. In any event, the method requires that a description of the occupants, in terms of their escape capabilities, be available.

This, then, is the general strategy:

1. Transforming fire experience into a manageable number of fire scenarios for a given product, where each scenario is characterized by a frequency of occurrence and a single, quantitative fire profile.

2. Calculating the development of heat and smoke in an occupancy, using this family of fire profiles and obtaining a separate answer for each scenario.

3. Comparing the calculated levels of heat and smoke with the escape capabilities and location of those who can be expected to be exposed. An expected mortality count or "deaths per fire" is thus obtained for each scenario.

4. The scenarios are weighted according to their frequency of occurrence, leading to an overall expected mortality associated with a given product.

2.2 Benchmarks and Standards

In order to determine if a change in product properties changes the fire risk, it is necessary to have a benchmark product or product mix, associated with the present level of risk, against which improvements can be measured. The room in which the fire occurs is generally reported for each occupancy, but the room size, total number of rooms in the occupancy and their arrangement is not, so the characteristics of standard occupancies containing the rooms in question must be inferred.

Specifying benchmark fire properties characteristics is done by expert judgement. In some cases, such as upholstered furniture, a good deal of information is available from published studies on the ignition properties, heat release rates and smoke toxicity of various furniture materials. Synthesizing this information into a description of the typical, composite, article of upholstered furniture was done by a panel of experts.

For residences, the annual housing census carried out by the U.S. Department of commerce provides much of the needed data on size and live load. For other occupancies, a variety of sources are tapped, including occupancy and building census data from landlords and building managers, e.g. GSA.

A fairly complete list of the benchmark data needed is presented in Exhibit 2.

2.3 Building Capabilities

The risk assessment scheme is intended to be general, but it must be configured and loaded with data specific for each product and occupancy.

In the course of evaluating the fire risk of upholstered furniture in one and two family residences, the first application undertaken, the model must be programmed with the relevant characteristics of the benchmark houses - - room size, layout, thermal characteristics of walls, etc. - - and the properties of the composite furniture chosen to be typical of today's household furniture inventory. If, as a second candidate, we were to choose to look at fire risk associated interior finishes in residences, we would obviously have to supply a new set of product fire properties, but we should not have to redo the occupancy characteristics.

In fact, the development strategy is to carry out a series of risk analyses for a product-occupancy combinations which have no commonalities, so that at the end of the development period (some eighteen months away) we will have the data available to do a substantially larger number of cases with relative ease. The second case chosen is floor coverings in commercial office occupancies. Thus, after this case is undertaken, we should be able to do floor coverings in residences and upholstered furniture in offices with relatively little further modification. We plan to do perhaps five more cases in the next eighteen months. If this expectation is realized, then, by the same logic, some 44 additional cases can be worked using the same data. (Not all of them are necessarily "real" cases, though.)

2.4 Execution

The actual computation consists of several different steps.

First, computation of the benchmark, or base case, using the input shown in Exhibit 2, Step 1.

Second, computation of the risk (i.e., the expected mortality) from introduction of the new product. Since the only thing that is changed in going from the old product to the new is the fire properties, only these must be changed in the model. As presently conceived, the frequency of ignition of the product benchmark case is used for the new case as well. However, better products will spread the fire more slowly (or not at all), and in scenarios where the product is not first-to-ignite, a harder-to-ignite product will be involved in a smaller fraction of the fires. If the new product produces less heat, smoke density or toxicity than the base, then the buildup of these threats in the occupancy will be slower and the escape time will be longer. Depending on who's exposed, this increase may or may not let someone get out who couldn't in the base case.

Third, Sensitivity studies must be run. In simple terms, this means picking another set of inputs, running the calculations again and seeing how the answer is affected. Since a large number of input parameters are necessarily estimates, this is particularly important.

To do a complete execution for one product the method must calculate the buildup of approximately 220 fires, assuming 45 scenarios potentially burning in any room of a 5-room occupancy. This corresponds to some 50 hours of computing using a minicomputer similar to a VAX. If a modern mainframe is available, the time required collapses to more like 30 minutes.

There are, however, a number of ways this computing time can be shortened. For example, often only scenarios involving the largest fires will lead to deaths, so the largest fires are run first. For a given room, the two flashover scenarios are run before those confined to the room of origin; those in turn are run before fires confined to the area of origin, etc. Once a room fire of given intensity is found to produce no deaths in an occupancy, it is certain that no deaths will be produced by fires in the same room which are smaller yet, so, in all such cases, the number of deaths per fire is zero. Thus, if flashover is required to produce death, as often found to be the case, only about thirty runs - - about a sixth of the total possible - - is required.

Nevertheless, the computing requirements of the method are now substantial. Almost all of the computing time is in the fire model. To the extent that simpler, i.e. more approximate, fire models can be used these requirements will become less onerous, although they probably will continue to necessitate the use of a 32-bit machine and a hard disk. It's really too soon to say, for certain.

3. DISCUSSION

Let us return again to the basic definitions. When we attempt to estimate fire <u>hazard</u>, we try to predict the severity of a given fire in a given set of circumstances, using a prescribed fuel. This hazard prediction can be done by actual fire experiments or by computation commonly called "modeling". When we change one of the conditions under which we make the prediction, e.g., a new set of fuel properties or a different environment in which the fire is to be burned, we also change the severity of the outcome. Hazard assessment is simply choosing what changes are to be evaluated, and comparing the outcomes, whether experimentally or computationally.

Risk is carrying the concept one step further. Since a real situation can potentially involve a number of different kinds of fires, a risk assessment begins with doing hazard assessment on each kind.

What distinguishes risk from hazard is simply the ability to weight these fires according to their expected likelihood of occurrence, so that a composite expectation of safety can be drawn. The special challenge of risk assessment is assigning the probabilities to the various foreseeable kinds of fires. Therefore, it is possible to do hazard estimates without knowing anything about risk, but it is not possible to do risk estimates without any knowledge of hazard. This makes the analytical methods which were the subject of the earlier part of this conference the soul of both approaches. It is worth returning to them to see what we can expect.

In my own view fire hazard assessment is a tremendously powerful tool, the potential of which has scarcely been realized. Conferences such as this are tremendously helpful in acquainting potential users of these techniques with their capabilities. But all the salesmanship in the world is not going to substitute for concrete results. It's time to spend more effort using what we have to try to solve problems rather than emphasizing what we don't know. Certainly, there are many details yet to filled in, but if we wait for a system of hazard assessment to be perfected, we will retard, rather than accelerate, its transition from an academic discipline into a practical tool.

In my view, we have often allowed ourselves to be wrongly influenced by the concerns of researchers, who understandably are concerned with making accurate and quantitative predictions. We have docilely accepted the researchers' view that modeling techniques are, to say the least, imperfect. But what we should be seeking is areas in which they're "good enough". Many practitioners do not need to know the magnitude of a hazard in great detail, they rely on such techniques mainly to make decisions such as: "do I use product A or Product B? Will extending a corridor, or reducing a floor area, increase or decrease the safety of a design?" In short, the techniques we are discussing today are intended to be aids to decision making; whether they are monolithic disciplines in their own right is a separate but irrelevant question. Once a technique has been developed sufficiently so that a decision can be made with greater confidence than it can without the technique, the utility of further development is increasingly to the researchers, and decreasingly to the decision makers.

It is certainly true that models allow one to draw incorrect conclusions and false inferences, and this danger increases as the experience and capabilities of those using the models decline. One would certainly view skeptically any decision based on modeling which conflicted with ones normal expectations, and in such cases the details of any model should be very carefully examined. But in my experience, it is the assumptions which underlie the computations which should get more scrutiny, most of the attention focuses on the computations themselves. This again underscores the need to use these analytical techniques as a backup to professional capabilities. It is common to ask what model was used in addressing a problem. It is less common, but at least as important, to ask <u>who</u> was using it. Modern analytical methods may make a mathematician out of a fire expert, but they cannot make a fire expert out of a mathematician.

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Exhibit 1
Scenario Categories

Set 1. Product is first item ignited.

- Draws curve up to $\dot{Q}_{max}$, using secondary items (unspecified) as necessary if $\dot{q}_p$ product alone not sufficient to reach Q_{max}.
- If $\dot{q}_p > \dot{Q}_{max}$, fire is cut off at Q_{max}.
- If $\dot{Q}_{max}$ is flashover energy, $\dot{q} = \dot{Q}_{max}$ until fire load of room is exhausted. If extent of fire spread is such that $\dot{Q}_{max}$ < flashover energy, fire declines as soon as $\dot{Q}_{max}$ reached.

Set 2. Product is <u>not</u> first item ignited and fire confined to object.

- Draws curve up to $\dot{Q}_{max}$ (from 2-parameter library of fire characteristics of items <u>not</u> product)
- If $\dot{q}_p < \dot{Q}_{max}$, secondary items (unspecified) as necessary to reach Q_{max}.
- If $\dot{q}_p > \dot{Q}_{max}$, fire cut off at Q_{max}.

Set 3. Product <u>not</u> first item ignited and fire spread beyond object of origin

- Finds maximum separation distance for ignition based on matrix of fire intensity and product ignitability; compares distance in matrix to item-product distance.

  3a. If product close enough to ignite.

  - Product ignites when RHR of initial object is large enough to produce ignition flux (determined from ignition ease of product and its distance from object).
  - If $\dot{q}_o + \dot{q}_p < \dot{Q}_{max}$, secondary items burned as necessary to reach $\dot{Q}_{max}$.
  - If $\dot{q}_o + \dot{q}_p > \dot{Q}_{max}$, fire cut off at $\dot{Q}_{max}$.
  - If $\dot{Q}_{max}$ is flashover energy, $\dot{q} = \dot{Q}_{max}$ until fire load of room is exhausted. If $\dot{Q}_{max}$ < flshover, fire declines as soon as $\dot{Q}_{max}$ is reached.

  3b. If product not close enough to ignite.

  - Product does not ignite (product too far away).
  - Sequence same as Set 2

Exhibit 2
Input Needed for Risk Assessment Model

Step	Input Needed	Source (for upholstered furniture)	Used In
1. Base case	1. Occupancy Characteristics - room sizes - room arrangement - doorway sizes	Census of Housing and Scenario Panel	Scenario Generator and Fire Model
	2. Fire experience data Fires in Occupancy chosen by: - room of origin - item-first-ignited - frequency of ignition	NFPA 901	Scenario Generator and Scorekeeper
	3. Fire properties of product - ignitability - smoldering time, if any - heat release rate - smoke obscuration - fire spread rate - smoke toxicity	Expert Panel, based on on measured properties of typical furniture	Scenario Generator and Escape Model
	4. Characteristics of other items first ignited - average, or typical, distance of items from product, by room - fire growth and peak heat release rate of items	Scenario Panel	Scenario Generator to predict secondary ignition of product
	5. Characteristics of those exposed - occupancy sets - frequency of sets in building	Estimates of expert panel	Exit model to predict who gets out and who doesn't
2. New Product	1. Fire properties of Product (same ones as 3, above)	Laboratory Measurements	Scenario Generator and exit model on new product
3. Sensitivity Studies	Changes in any input variable as appropriate		

An Integration Method

for

Translating Research into Engineering Practice

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Abstract

During the past quarter of a century significant progress has taken place in the understanding and quantification of many parts of the building firesafety system. The quantification through scientific research of theoretical relationships, deterministic equations, and complex computer programs provides an ability to study parameters and relationships in a more sophisticated manner than has been possible with experimental and experiential methods alone. In order to realize the full benefit of new discovery in the construction of buildings, an integrative framework is needed to coordinate the promise of research with the experience and needs of engineering practice.

This paper will describe briefly an engineering method that is structured to incorporate research results into performance related building firesafety analyses. Quantification procedures relating modern research tools with experience and practice to describe expected behavior are presented. An example is given to illustrate techniques for using deterministic relationships and computer models to establish probabilistic performance expectations. With this example as a foundation, additional topics include discussions of a computer program to assist in building evaluations, research into developing deterministic empirical equations with reliability assessments, practical applications, and capabilities and limitations of the method.

1. INTRODUCTION

The practice of building firesafety analysis and design is in a state of transition. In the mainstream of today's building firesafety, most decisions are based on prescriptive code requirements. Calculation procedures for certain isolated components of building firesafety are available. The interrelationships and interdependencies of the complete firesafety system generally are recognized. The capability to move from a conventional prescriptive code structure toward a performance oriented, integrated engineering method for firesafety analysis and design is almost perceptible.

During the past fifteen years, WPI, in collaboration with others, has been developing engineering procedures for evaluating the performance of the building firesafety system. At the present time, this method allows an engineer to structure building firesafety problems so that the technical basis for solution is organized and consistent. The method at present provides a framework for identifying specific problems and structuring the solutions. The framework delineates the functional fire-building system in a manner that enables interactions and interdependencies to be identified.

The method has an important attribute of organizational consistency. All of the tools that currently exist in firesafety may be incorporated where appropriate. This includes building codes, firesafety standards, experience, failure analyses, experimental research, theoretical relationships, and calculation procedures and models. The method provides a structure with which the scientific base may be linked to the engineering base.

The eventual goal is the development of integrated, calculation-based analysis and design procedures for use by practicing professional engineers. These procedures are envisioned to function in a manner analogous to structural and mechanical engineering methods. Although this building firesafety engineering method has reached a level of maturity where it can be used for applications today, it has evolved only part of the way toward the complete, evaluation based method that is envisioned. Each new application provides additional experience toward the evolution of this engineering method for fire. For both present uses and future developments, the objective is to design buildings for fire better and at less cost.

The framework for this system provides a structure that can relate both scientific research activities and building code requirements to functional performance components. It has been tested locally in academically related activities to build confidence in its applicability.

The main purpose of this paper is to illustrate how calculation procedures and computer models may be integrated into this framework for purposes of practical firesafety analysis and design. For this discussion, the method may be considered as an engineering practice oriented technique for risk analysis. However, before addressing a specific illustrative example, a brief discussion of engineering methods in general is given. The recognition of the nature of engineering methods is useful to put the evolution of building firesafety analysis and design into perspective. In addition, the techniques of quantification as they are used in this engineering method today are discussed briefly. These quantification procedures give a useful insight into relating scientific research and risk management.

2. ENGINEERING METHODS

Science and engineering are linked in the minds of most people. To the layman, the two often are synonymous. In research, development, and engineering practice, the distinctions may be recognized more easily. If one were to define the "scientific method", references would be readily available. However, if one were to seek a definition of the "engineering method", the available references are sparse. Often "engineering" is defined by the resulting product, rather than the process of how the product was created. Koen [1], in a recent book, defines the engineering method as

> "the strategy for causing the best change in a poorly understood or uncertain situation within the available resources."

The engineering method as defined above is valid regardless of the historical era in which it is applied. However, the engineering product that it produces is quite temporal and dependent upon the means, knowledge, and experience available at the time of its creation. Although the brief treatment of Koen's message given here is necessarily inadequate, a few of his concepts may be useful within the context of this paper.

A design strategy normally involves a number of alternatives, each limited by resources and constraints. The "best" solution depends upon the problem being addressed, and must be related to the needs and constraints present. Koen notes that "Best for the scientist implies congruence with an assumed external nature; best for the engineer implies congruence with a specific view of nature...One alternative does not replace another by confrontation, but by doing a better job in a given context".

An engineering product is temporal, and its design must be based on the state of the art at the time of its development. No matter how precise the deterministic base for quantification models may be, an amount of subjective decisionmaking and judgment is an integral part of the process. If a proposed solution deviates too far from what the engineer might expect, that engineer will question, recalculate, and challenge. The engineer judges solutions through his state of the art capabilities at the time.

It is important to recognize that the engineer must always provide an answer within the constraints of time, money, and the state of the art. Science is applied when appropriate. An engineering problem is defined by its resources, and the engineer must make decisions within the amount allocated. Developing, retrieving, and applying scientific knowledge always incurs cost. In some cases the resources are sufficient only to permit a solution based on past experience, intuition, folklore, and educated guesses. In other cases, the resources are enough to afford science. Koen notes that "We must admit that modern science has fueled the machinery of modern engineering, but we should not assume that it is the machinery itself."

The engineering profession itself usually provides the advancement of the state of the art through development of its technical base of professional practice. The fire protection engineering community has not yet established a technical base of engineering practice where cost and actual firesafety performance may be related in a meaningful way.

3. FRAMEWORK FOR BUILDING FIRESAFETY ANALYSIS AND DESIGN

The evaluation of building firesafety involves the integration of a large number of factors that comprise the complex firesafety system. Over the years, systematic procedures have evolved to structure the problems and solutions. The complete method consists of nine major parts that can be grouped into three categories:

A. Performance Identification and Needs

1. Establish Performance Criteria
    a. People
    b. Property
    c. Continuity of Operations

B. Building Analyses

2. Prevent Ignition and Established Burning
    a. Prevent Ignition
    b. Initial Fire Growth Hazard Potential
    c. Special Hazard Automatic Extinguishment
    d. Occupant Extinguishment

3. Flame Movement
    a. Fire Growth Hazard Potential
    b. Automatic Sprinkler Extinguishment
    c. Fire Department Extinguishment
    d. Barrier Effectiveness

4. Smoke Movement

   a. Air Volume Generation
   b. Smoke Generation

      - Obscuration particulates
      - Toxicity

   c. Air Volume Modifications
   d. Barrier Effectiveness

5. Structural Frame

   a. Heat Energy Impact
   b. Protection Effectiveness
   c. Deflection
   d. Structural Capability

6. People Movement Analysis

   a. Alert Effectiveness
   b. Path Movement

C. Building Design

7. People Protection

   a. Evacuation
   b. Areas of Refuge
   c. Defend in Place

8. Property Protection

   a. Move
   b. Defend in Place

9. Continuity of Operations

The anatomy of the five analysis components of Part B is an organized framework that identifies the interrelationships of the parts of the building firesafety system. Every part of the building construction or prescriptive building code requirement can be identified with a specific analytical component of the system. For example, a door latch becomes a part of barrier effectiveness for flame or smoke movement and the architectural layout is a factor in the analysis of fire department agent application.

The analyses of Part B above involve engineering procedures to predict the performance of an existing or proposed building and its firesafety system. Some parts of the framework are more fully developed than others. It should be noted that the anatomy of the framework is closely coupled with quantification techniques described in the next section. The organization and structure of the framework has been developed to address the functional engineering questions, rather than to conform to available data or computational models.

To illustrate briefly the types of issues that are addressed, consider the 'Performance Identification and Needs' of Part A. To the casual observer, it would appear that the establishment of performance criteria would be relatively simple. In fact, it is a relatively easy task to identify, on a superficial basis, the life safety needs and the items and locations of high property value at risk. Items that are critical to maintain the operational mission of the organization are more difficult to ascertain for a corporation having a number of interrelated sites. However, when one attempts to quantify performance measures and identify acceptable risk, the task becomes complex. In part, acceptable risk is dependent upon perception of and aversion to risk on the part of management or the public.

The total cost of protection alternatives, uninsured loss expenses, business interruption and market share losses, and long term operational expenses, including insurance coverage, must be weighed against a perceived level of risk. To a large extent, this more disciplined risk management must await the development of the firesafety analyses of Part B and the comparison of analytical results with recognized situations and case histories. If engineering analyses are made for building firesafety components for any unique building, then comparative cost-effectiveness relationships can be established for alternative solutions and effective risk management can be achieved. The degree of confidence in the results is dependent upon the level of confidence in the quantification. The concept to be recognized here is that, while attention to each component in isolation is necessary for development, the interaction of all parts are necessary for effective risk management.

4. QUANTIFICATION

The goal of this engineering method is to design buildings for firesafety better and at less cost. In addition, this method should permit more rational evaluations for risk management. Quantification is essential to evaluate the cost-effectiveness of alternative solutions and to select the most appropriate courses of action.

One purpose of this paper is to address the quantification in some detail because it is an important part of any engineering method, and it is essential for using fire research results in practical building applications. The framework, described briefly in Section 3, interrelates the many complex parts of the system. The quantification forces an explicit evaluation of the effectiveness of fire design for these parts. The framework and the ancillary computer model used to answer the "what if" alternatives have been structured in a manner that is compatible with quantification currently used, as well as the deterministic equation/reliability based procedures envisioned for the future.

Before specific illustrations of quantification are given, one should distinguish between the quantification envisioned "tomorrow" and the temporary quantification procedures used "today". Tomorrow, empirical equations are envisioned which will enable the engineer to evaluate or tailor hazards and solutions for unique buildings. These equations will calculate performance, and the resulting level of risk may be established by load and resistance factor or by partial safety factor procedures.

Today, the quantification utilizes the engineering knowledge and judgment as it exists, and applies science, as Koen notes, when appropriate. To do this, the analysis components described earlier in Section 3 are structured into network diagrams. Considerable effort has been expended to decompose the system in a manner that is clear to the user and allows an evaluation to proceed along a consistent, rational sequence. It has been apparent that these networks also enhance communication and understanding with related professionals, such as architects, engineers, code officials, and the fire service. The procedures are particularly useful for comparing design alternatives.

To provide a temporary bridge that allows the method to be used now in practical applications, the networks are structured to use probabilistic assessments. Although the quantification could utilize consensus values or long run statistics if they were available, these approaches have been consciously rejected. It is believed that premature use of statistics or consensus values will delay the development of engineering procedures based on science and experience. Consequently, the probabilistic assessments used in this method today are the subjective judgments of the engineer.

The structure of the networks provides a frame of reference for the judgmental evaluations. Using concepts of "divide and conquer", the network events have been carefully selected and tested. The necessary judgments are made within an ordered conceptual environment. While focusing on one component, the engineer has confidence that the other interrelated parts of the firesafety system will be addressed appropriately. In many ways, these networks are analogous to the free body concept of mechanics.

Although the networks structure the environment for the subjective assessments of the probability of success for the various system components, the basis for those judgments causes concern among many observers and users. The question constantly arises, how do I obtain appropriate probabilistic values? This is an important question that must be addressed in several ways.

A major concept is that the probabilistic assessments used today are a measure of the personal belief of the engineer, and not a frequency of occurrence based on long run statistics. Mosteller [2] notes that the personalist can apply probability to all of the problems an objectivist studies, and to many more. The objectivist likes to make interpretations only from repeated events. The personalist brings other kinds of evidence into his inferences. The probabilistic evaluations used today in this method are the professional opinion of the engineer. They depend upon the situation, conditions, and resources, and are based on a variety of sources including:

a. Physical and chemical phenomena
b. Fire test results
c. Codes and standards experience
d. Building performance analyses
e. Computational models
f. Statistical data
g. Personal experience

The technical base for contemporary firesafety has been improving exponentially. Nevertheless, it is still weak when fire technology must answer questions for a practical building analysis and design. The engineer must provide the link between technology as it exists today and the economic and safety needs of the building design.

The probabilistic assessment by the engineer within the framework of the anatomy provides the means by which the firesafety components may be quantified today. The quantification, therefore, provides a relative comparison of one alternative to another, or of one building to another. The probabilistic values should not be viewed as being necessarily synonymous with long run statistical predictions. However, even with the present limitations, the method provides a basis for design equivalency assessments and for comparative ranking of buildings.

The engineer is forced to make explicit evaluations of the probable success of the components. Initially, one usually is apprehensive about making these judgments. However, after one or two buildings are analyzed, and the functional simplicity of the process is recognized, the apprehension seems to disappear or decrease significantly. Currently, efforts are being directed toward developing guidelines and organized data to assist in making the evaluations. However, in the end the engineer is confronted with weighing the situation and the available information and applying his best judgment of the probable success in order to achieve the best solution within the available resources and constraints.

5. ILLUSTRATIVE EXAMPLE

One of the components that is evaluated in the flame movement analysis is the probability that the local fire department will be able to extinguish a fire in the room of origin before it becomes fully involved. This component was selected because it illustrates the quantification techniques of "today" and integrates current research studies into the engineering analysis for a very complicated problem.

As an overview of the analysis, we must evaluate the parallel evolutions of the room fire development and the fire department suppression activities. Time is the parameter that enables these two separate activities to be related. Determination of the probability that the room would flashover at all would have been included in an earlier component. Here, the analysis is based on the condition that flashover can occur.

Consider first the fire independently. Established Burning (EB) is the size of fire that the engineer selects as the start of the building analysis. A 25 kw flame size is a useful definition for Established Burning. With zero time set at EB, the time relationships for continued fire development are estimated until full room involvement occurs.

Consider next the building-fire department interactions necessary to apply extinguishing agent and put out the fire. The main events are (1) Notification of the Fire Department, (2) Agent application by the Fire Department, and (3) Extinguishment. Table 1 identifies the major evaluation events in the process. Each of these sequential events requires time to complete. As a preliminary indication of the likelihood of success in manually extinguishing the fire before full room involvement (FRI) occurs, the expected time for FRI is compared to the time of agent application. If the time to agent application is less than the time to FRI, the expected room conditions and building design features, as well as the fire department extinguishment capabilities, are evaluated to estimate the probability of success of extinguishment before the room becomes fully involved.

TABLE 1

1. FIRE DEPARTMENT NOTIFICATION

    a. Fire is detected

    b. Decision is made to notify the fire department

    c. Message is sent to the fire department

    d. Correct message is accurately received by the fire department

2. AGENT APPLICATION

    a. Equipment responds to the site

    b. Nozzle enters the room

    c. Agent discharges from the nozzle

3. EXTINGUISHMENT

   a. Enough water discharges from the nozzle

   b. Water discharge is continuous

   c. Blackout occurs

The engineering time available for analysis is directly related to the fee that the client is willing to pay. That fee is related to the purpose and needs of the analysis. Engineering office time is a valuable commodity. If buildings are to be designed for fire in a routine manner, professional practice procedures must be established in a manner analogous to structural engineering practice. The explanatory procedure that follows may appear to be complex and require unreasonable engineering time. However, experience indicates that design guides can make the process relatively efficient. The explanation here is intended primarily to identify a mechanism to integrate research studies with engineering practice.

As an illustration of relating research and practice, consider the room of Figure 1. Assume that this is a representative living room for an apartment building. One would be evaluating a specific building. Therefore, its location, size, architectural layout, and construction features would be known or identified as a design alternative. The available water supply, as well as the local fire department size, locations, and operating procedures also would be known or determined.

Given Established Burning, the time to FRI must be estimated. Assume that the room of Figure 1 measures 12 ft. x 9 ft. x 8 ft. and that one open door connects this room to an adjacent room. The furniture is as shown. Most pieces are relatively old and the combustible materials are predominantly cellulosic. The walls and ceiling are painted gypsum board.

5.1 Time to Flashover

A time duration between EB and FRI must be selected as a base for evaluation. Obviously, the location of the ignition source has a major influence on this time duration. Also, the stability of furniture arrangement, the movement in and out of occupant related materials (eg. papers, books, clothing, etc.), and the size and location of openings are other important factors. Nevertheless, a time duration from EB to FRI must be selected as representative for these conditions.

In the absence of guidelines, mathematical expressions, or codified procedures to identify the time duration quickly, the engineer has several options. One is to study the behavior of test fires in rooms that most resemble this room. Information selection and retrieval will usually be a problem in this approach.

A second approach might utilize the fire growth relationships recently incorporated in Appendix C of NFPA Standard 72E [3]. In this standard, the rate of fire growth is modeled in the form of a simple algebraic expression:

$$\dot{Q} = \alpha t^{\beta} \quad (1)$$

where,

$\dot{Q}$ = Heat release rate (kW)
t = time (S)
α = a pre-exponential constant which may be a kind of material property
β = the fire growth exponential factor, taken as 2 at present

The term α may be used to describe the combustion characteristics of the fuel packages. At the present time selection of values for α is judgmental. Free burn tests for specific representative furniture items can be assumed to be relatively stable and reproducible. When these items are close to a wall or a corner, more radiative feedback and less convective cooling will occur. This results in faster burning, and the value of α must be adjusted to reflect this enhancement. Similarly, when combustible contents can ignite combustible wall linings, the value of α can be increased significantly.

The rate of heat release, $\dot{Q}$, of Equation (1) must reflect flashover conditions. One approach is to assume that flashover occurs when the heat release rate reaches a value described by Equation (2). Still another is to use the Thomas flashover correlation available in reference [4]. The Thomas correlation assumes that no heat is lost through the bounding surface, and is more conservative than Equation (2).

Table 2

α	0.0014	0.0028	0.011	0.045	0.178
t	16 min	11 min	6 min	3 min	1.5 min

Values of α can be derived for individual items by matching the heat release characteristics from fire tests with the $\dot{Q} = \alpha t^2$ relationship. Reference [5] provides some data to do this. This may be augmented by engineering judgment to relate the actual conditions to the test conditions.

$$\dot{Q} = 610 \left(h_k A_w A_v \sqrt{H_v}\right)^{1/2} \quad (2)$$

where,

$\dot{Q}$ = rate of heat release (kW)

h_k = effective heat transfer coefficient through the bounding surface ($kWm^{-2}K^{-1}$)

A_w = area of bounding surface (m^2)

A_v = total area of vent opening (m^2)

H_v = height of vent opening (m)

Incorporating this value for $\dot{Q}$ into Equation (1) allows the time to flashover to be calculated as shown in Table 2.

To illustrate the differences, for the one open door for the room of Figure 1, $\dot{Q}$ is 1230 kw from Equation 2, assuming h_k is 0.035, and the Thomas correlation is 1380 kw.

The time to flashover may be calculated from Equation (1), assuming $\dot{Q}$ of 1250 kw. Table 2 shows the time to flashover for different values of α.

A third approach might evaluate different scenarios by using a computer fire growth model, such as the Harvard Code V, (now known as FIRST). The time to flashover might be selected as an intuitive "feel" after studying the results.

A modification of this last procedure can formalize the process significantly. Blaisdell [6], in an undergraduate WPI student project, developed a technique for establishing a probability of flashover and a time to flashover by applying a Monte Carlo simulation to the room of Figure 1 with Harvard Code. Figure 2 shows the results for the foam padded furniture and gypsum wall board conditions identified earlier. Heat release values were obtained from experimental tests on furniture that was assumed to be similar to that described in Reference [4].

Let us assume for the present that a time from established burning (EB) to full room involvement (FRI) of 16 minutes were selected for this room. A discussion of this estimate will follow the fire department suppression analysis.

5.2 Fire Department Suppression

Table 1 identifies the events that must be evaluated with respect to the expected design fire. "Today" this evaluation consists first of estimating the time duration of the events leading to agent application, and then, the probability of success for the events. The time related analysis gives an indication of the fire conditions to be expected at the time of agent application. This provides the base from which to judge the probable success of extinguishment before the fire extends. Table 3 provides some hypothetical, but realistic, times for this room on the second floor of a building located one mile from a fire station in a moderate sized city.

Table 3

EVENT	Incremental Time	Cumulative Time	Q(kw)
Detection	0		15
Decide to call fire department	2 m	2 m	70
Call fire department	1 m	3 m	120
Fire department receives message	1 m	4 m	170
Notification		4 m	
Alarm handling time	1 m	5 m	230
Turnout time	0.5 m	5.5 m	270
Travel time	2.5 m	8 m	400
Nozzle enters room	4 m	12 m	950
Water discharges from mozzle	1 m	13 m	1000
Agent Application		13 m	

In practice, it is relatively easy to estimate the fire size at the time of detection. The fire size at detection depends upon whether the human or the automatic detection system is used. If human detection is assumed, the number, activity, condition, location, and expected responses must be evaluated. If an automatic detection system is used, computer analyses such as DETACT [7] will give an indication of the fire size at the time of detection. This detection estimate links the fire growth and the fire department suppression time lines.

The "decide to notify", "send the message" and "receive the message" events must be estimated for time durations. If notification is by direct, automatic means, the time elapse is effectively zero minutes. If humans must interact, the time duration will be extended. Although no data is available for these events, it is not difficult to estimate times for selected scenerios. It may be noted that normally this component is evaluated separately for conditions where the spaces are occupied and for conditions where they are unoccupied.

The alarm handling time, turnout time, and travel time combine to determine the response time. The time to gain access to the building, locate the fire, reach the fire floor, and move the nozzle to the rooms combine to determine the time for the nozzle to enter the room. Adding the time for water to discharge from the nozzle provides the time for agent application. This time gives an indication of the size of fire at agent application by comparing the two time lines of Figure 3.

After understanding the operations and practicing a few times, most people become comfortable at identifying the time durations. Evaluating fire alarm tapes, turnout procedures for the specific fire department, and travel distances give good indications of expected time durations and their variability. The time to accomplish hose evolutions needs some training. Another student project demonstrated that Critical Path Method analysis can be an effective technique to evaluate the time duration between arrival at the site and agent application.

The final activity in evaluating the probability of success for fire department extinguishment is the establishment of probabilistic values. In the case of equipment, the installed and long term reliability are incorporated. For the other events, the only means at present is the personal belief that is the best judgment of the engineer for the conditions present. While this may appear to result in a wide range of values for a specific case, such does not occur. The framework is constructed in such a manner that the incremental judgments are comparatively easy to achieve. Illogical values are clearly evident.

Consistency of evaluation does not extend to one very difficult event in this component, however. This evaluation is item 3c of Table 1, the probability that a fire department can extinguish a fire of a given size before it extends. This event is difficult to assess without fire fighting experience. To alleviate this problem, another WPI undergraduate student project with a District Chief of the Worcester Fire Department, developed a rudimentary expert system to evaluate fire department suppression. This project is continuing in 1987-88 to improve the quantification and scope of options. This expert system project is not the issue here. Rather, the point to be recognized is that as weaknesses become identified, evaluative techniques evolve to enable the user to improve confidence in the assessments.

To complete this illustration, hypothetical, yet realistic probabilistic values are estimated for the events. For this scenerio, the probability of success in extinguishing the fire before full room involvement is $P(M) = 0.38$. A set of completed network diagrams are included in the appendix to illustrate the process. The calculations are not important here. Rather, it is the analytical process to evaluate the building, because the fire department suppression component actually evaluates the building's ability to enable the fire department to extinguish the fire before it grows to a predetermined size.

The uncertainty in selecting values for human activities can be criticized. To the casual observer, the exercise may be of doubtful value. However, in practical applications, an extremely good insight is gained for the building design with regard to fire department suppression. In addition, the exercise provides a vehicle for fire departments to articulate their concerns to the building designer. Experience has indicated that the fire service is usually comfortable in estimating times and likelihood of achievement, as long as the questions are framed in a careful manner.

The major benefit from this analysis is the ability to recognize the influence of the parameters on this component. For example, what if combustible interior finish or foam plastic materials cause the α factor to increase. If time to flashover were reduced by 4 minutes, the fire department has no chance for extinguishment before flashover. Whether that is important depends upon the objectives. On the other hand, if notification time is reduced by design, the probability of success is improved. Finally, if the room were on the twenty-second floor, rather that the second floor, the numerical values may vary because the conditions for building transportation reliability and water pressure may be different. The analysis, however, allows one to evaluate the conditions and to compare results on a relative basis.

6. APPLICATIONS

The principal focus of this engineering method is the routine analysis and design of buildings of all occupancies and sizes. The method is not yet in a stage of documentation and refinement that it can be used in an "off the shelf" manner. Nevertheless, it is being used in a variety of ways in building applications. Most of these applications might be described more properly as development activities to test the method, identify its strengths and limitations, and create new analytical tools for practical use.

This section will describe very briefly some of the recent projects that are being undertaken. Some have been completed, and a few are currently in progress. Most are student academic projects which are unsponsored. Over the years, a large number of student projects have been undertaken to address different analysis or developmental techniques. Most might be classified as feasibility studies in which techniques were developed to solve a problem. For example, several years ago a technique was developed to relate a building code to this method and to teach entry level engineers or plans examiners and inspectors both building code use and firesafety concepts. After developing feasible techniques for achieving this, the student activity was finished. The work was never written for the open literature, and the report became just another interesting application awaiting a potential opportunity for use.

To date, the most complete application of this engineering method has been the evaluation of the firesafety design of a new Polar Icebreaker Replacement (PIR) for the U.S. Coast Guard. The individual in charge of this project was Mr. Robert C. Richards, the Chief, Marine Fire and Safety Research Staff of the Marine Technical and Hazardous Materials Division of the Coast Guard Office of Marine Safety, Security, and Environmental Protection. The goal was to evaluate the proposed shipboard firesafety system using this engineering method. This project has been essentially completed, and papers are planned for the firesafety literature. A brief discussion of the project may be helpful to illustrate how the method may be used for a practical application of this type.

The project director was Mr. Richards. He was assisted by his staff, the Coast Guard ship designers in the Office of Engineering, the Center for Firesafety Studies at Worcester Polytechnic Institute, and engineers at Rolf Jensen & Associates. A computer program was used for the flame movement analysis of this 405 room structure. This program incorporated the fire growth hazard potential, automated suppression, manual suppression, barrier effectiveness and frequency of established burning to compute the relative frequency of failure of each compartment. Mission effectiveness for target rooms was evaluated using these results, and compared to the objectives set by the ship design team.

Evaluation of the components was accomplished by the team using available evaluation procedures. For example, two members studied a similar ship at sea for five days to understand and evaluate the operation, function, mission, and existing firesafety system. This information was combined with fire test data that had been developed by Coast Guard research results over the years and by the equipment evaluation by engineers at Rolf Jensen & Associates. These factors became the basis for the probabilistic evaluation for the proposed shipboard firesafety system. This evaluation exercise provided a good insight into the expected performance of the proposed firesafety features and their installation, and became the basis for the recommendations on the proposed fire protection system.

The Polar Icebreaker Replacement was the most extensive test of this method to date. Much was learned that will enable future applications to be evaluated better and more efficiently. The method becomes a natural organizational structure that allows research and experience to be used. As they are used, the evaluation base becomes enhanced, and each new piece of information can be added to the existing base. The quality of report for the next ship analysis will be greatly enhanced because the base of knowledge will be expanded, and because the naval architectural group and the engineers will have a better understanding of what can be accomplished.

In a similar manner, a number of student projects have been and are being undertaken to test the method, to establish a base of evaluation using modern research results, and to develop techniques of practical evaluation. An example of this activity is a three man graduate student project involving nineteen fraternity houses on the WPI campus. These buildings are lodging houses, all generally similar in size, style, construction, use, and occupancy. All are code complying. The project will attempt to use this method to develop techniques and their justification for ranking the buildings for life safety risk.

The evaluation utilizes existing flashover correlations, test data, fire development theory, smoke movement models, and other tools available to the fire community to evaluate the components. After a rationale is developed for ranking the buildings, a means of relating the effectiveness of proposed improvements and their costs should be evident. This project, along with the other student work, is unsponsored and functions primarily as a vehicle for student education. While the educational function is the principal focus, the techniques that are developed in the process become a base for future student projects and for the continued evolution of the engineering procedures.

7. DISCUSSION

The Engineering Method, as with all methods, has strengths and weaknesses. Rather than to identify the advantages and limitations in a concise listing, it is felt that a discussion in terms of the questions most frequently asked may provide a better description of the state of the art of the method.

Q1. What educational background is necessary to use the engineering method?

A1. The method is being developed for professional engineering analysis and design of buildings. The method will allow the firesafety of each building to be tailored to fit the needs of the building, consistent with professional standards of care. To do this, professional engineers knowledgeable in fire science and fire engineering are required.

Although efforts are not being directed at this time to the development of a simplified format, several years ago the feasibility for constructing short forms for rapid inspection screening or insurance evaluations were studied. It did appear feasible that paraprofessionals can inspect and rank existing buildings in a cost effective manner. However, the activity in this area was dropped because the time committment would detract from efforts to develop and quantify the engineering needs.

Q2. How can this method be used today?

A2. The engineering method can be used today for a detailed analysis of the building firesafety performance. The work with the U.S. Coast Guard on shipboard fire design illustrates that the method can provide a clear picture of the effectiveness of standards and specified systems when applied to specific problems. The performance evaluation of alternatives in a consistent manner is easier to understand with the structure of this method. However, the quantification is still based on engineering judgment. Consequently, the qualifications of the engineering team are important.

The evaluation of the hazards and the firesafety systems is the most important engineering activity. When these are incorporated into the computer model, the engineer can gain a good insight into the interaction of the complete firesafety system. The answers to "what if" questions allow the firesafety system to be tailored to the needs of the building to provide cost-effective solutions. The computer analysis can enable obscure, but important features to be recognized and ordered to address specific needs.

Q3. What does the computer model do?

A3. The computer model may be described as a "bookkeeper" at the present time. It will perform a variety of calculations on a temporal basis, as well as ordering the alternatives and their results. For example, the basic building response of fire growth hazard and barrier effectiveness can be evaluated for a fire starting in each room of the building. For example, if it is estimated that the fire department will be able to apply agent 23 minutes after ignition, the computer analysis can identify such factors as the order of the worst rooms of ignition and the number of rooms that have a probability of involvement at the time of agent application. In that way the capability of fire department response can be evaluated for the expected type of fire.

The computer model can incorporate a variety of alternatives, such as the fire department suppression or automatic sprinkler suppression, either separately or in combination. It can enable the engineer to ask a variety of "what if" questions from a design viewpoint and obtain the results in numerical or graphical form. Thus, cost effectiveness studies and graphical representations of results may be done.

The computer model also enables a variety of other studies to be conducted. For example, the trade-off of automatic sprinkler with fire resistance or exit access distance requirements is often questioned. The engineering method and its computer model can address questions of this type and provide comparative levels of risk so that the philosophical questions can be considered in a performance context.

Q4. What are the computer programs available for the method?

A4. Computerization of parts of the method have been under development for nearly a decade. Professor Ramon C. Scott of the WPI Computer Science Department has been the principal individual in the various computer models. Actually, there are several computer programs that are complementary, but not yet integrated. The earliest WPI model was a people movement simulation. From that initial model, a variety of programs have been written to simulate fires or to provide support to the engineering design needs for building firesafety. The most developed computer program is the flame movement analysis of the method. Recently, expert systems models have been started for evaluating the room fire growth hazard potential and the fire department extinguishing capability. As these expert systems are developed, it is envisioned that they will either be a basis for empirical quantification procedures or will provide a check for other scientific theories or models.

Q5. What are the computer requirements for the programs?

A5. Only the major program will be described here. It is modular in format and written in Pascal. The major parts of the program are listed below with the amount of memory required to run an executable code. The additional memory requirements for the data stored during execution can be large due to the exponential nature of fire path propagation.

		Memory Requirements
1.	Graphical Input (allows the building plans to be input on a graphical format)	64K
2.	Room connectivity (Identifies barrier connectivity between rooms in three dimensional space)	142K
3.	Calculation (Calculates a variety of components in three dimensional flame movement)	95K
4.	Data Base Structure (A data base was written to enable the design questions to be addressed and data to be stored for later recall)	64K
5.	Output (A variety of numerical and graphical descriptors are available for engineering analysis)	Included within other programs

The computer program has been under continual development for a number of years, and recognized, desirable enhancements will involve continued work for several more years. It is possible to use a personal computer, although the number of rooms is limited. The U.S. Coast Guard Hewlett Packard Computer was used for the analysis of the 405 room polar icebreaker.

Q6. How can one obtain a copy of the computer program?

A6. The computer program is a useful tool for use with this engineering method. However, it is only one part of the development of the method. A "users group" is being established for the organizations and individuals who are interested in developing the engineering method as an effective method for firesafety design. This group will periodically exchange information and experiences to foster general development of the method. Since the computer model is still under development and test, and it is so closely coupled to the framework and the quantification techniques, the computer program is not yet available for routine commercial use. computer program is, therefore, only a part of the engineering method development.

Q7. What are the major limitations of the engineering method?

A7. There are several major limitations that are obvious at the present time. One is that of completeness. Smoke movement and people movement analyses are very crude at the present time. A detailed decomposition framework for these analyses, where an engineer can feel confident that he is able to predict the behavior on the basis of judgment, has not yet been developed for these components.

A second major deficiency involves quantification. At the present time the quantification requires the engineer to predict the probability of success for selected firesafety building features. They reflect his belief in the performance success of the component. The basis for this subjective probability judgment may include theoretical behavior based on scientific and engineering principles, interpretation of deterministic computer model studies or of deterministic relationships obtained in the fire literature, and personal experiences. While the method encourages use of state of the art scientific resource results, this can be extremely time consuming for the practitioner and expensive for the client. Cost effective, semi-empirical equations relating design parameters are necessary for the quantification to have widespread use. Development of evaluative procedures where two engineers will obtain the same value for the same conditions is the next major thrust of the development effort. After that, for longer term planning, reliability studies will be conducted using classical load and resistance factor techniques to identify the level of risk and factors of safety for the design procedures.

Another major deficiency involves the lack of adequate documentation. Documentation is needed to explain the theory, practices, and illustrative examples to potential users. While existing documentation has been evaluated to some extent by others, a rigorous, critical examination for accuracy, completeness, and appropriateness is needed.

Another limitation relates to scope of use. Only relative levels of risk can be compared today. As more consistent techniques of quantification evolve, the results must be compared numerically to other benchmarks, such as the building code and statistical data. However, at the present time the method is limited to examining and evaluating the firesafety system for unique structures and for risk management for identifiable objectives.

Q8. What are the major advantages of the engineering method?

A8. The major strength of the engineering method is its organizational structure. The structure interrelates the many components in a manner that enables the building firesafety to be understood as an integrated system. Such diverse individuals as code officials, engineers, fire officials, equipment manufacturers, architects, and plant engineers are able to understand how the different parts of this complex system interact and how to evaluate, on a subjective basis, expectations of building performance. The structure enables communication between these groups so that a clear understanding of the problem and the likely effectiveness of the solution can be clearly comprehended.

The second advantage of the structure of the engineering method is its ability to incorporate a variety of evaluative techniques. On one end of the scale the quantification can be made by engineering judgment utilizing theory, empirical results, or experience as the basis fo the estimates. It would be possible to establish values and appropriate guidelines for selected conditions by loss experience statistics, Delphi procedures, or concensus. While these techniques may be useful for certain purposes, it is not appropriate for the engineering design envisioned as the principal goal for the method. Finally, the present structure can accommodate load and resistance factor probabilistic reliability analysis for deterministic design procedures without reorganization of the basic framework.

Q9. In what types of applications has the engineering method been used?

A9. Practical, commercial applications are very important to the development of the engineering method. While it has been used to a limited extent by a few individuals over the years, only in the past few years has the method matured enough that confidence in its use for special engineering applications is justified. The analysis and design of the polar icebreaker is the largest known application to date.

A number of building analyses have been and are continuing to be done as a part of our academic program. This work is developmental in nature and attempts to relate theory and computational methods to practical engineering problems using the method as the organizational framework. This work includes such activities as developing techniques of risk management or risk assessment, doing cost-benefit studies, relating the method to building codes and standards, and critical testing of the method and its quantification.

8. CLOSURE

The engineering method described in this paper has some distinct advantages, as well as recognized weaknesses. It may be noted that all methods used for firesafety analysis today have strengths and limitations that are unique to the procedures. This condition will continue until the discipline evolves from its infancy, through adolescence, to maturity. The growth of fire protection engineering capabilities clearly are beginning to mature. However, it appears that the process may experience some trauma during near term future.

Rather than to describe the advantages and limitations in the abstract, a frame of reference of conventional building design for firesafety is used. Today, fire protection engineers are rarely a part of the usual building design team. Building firesafety is incorporated by compliance with the local building code. The authority having jurisdiction makes the judgment of code compliance. As cited in "America Burning" [8], most designers assume the code provides adequate protection for fire. Rarely does a design professional knowledgable in fire protection become involved in the building process.

In this system, the building code assumes the responsibility for firesafety design, rather than a design professional who specializes in the field. The advantages of this system are that it is easy to use and administer, and involves relatively low design time costs.

The limitations of the present system involve both technical and operational factors. From a technical viewpoint, the level of risk established by a code is indeterminate, and cost-effectiveness relationships are meaningless. While the code provides a compilation of good practices, the technical basis for the requirements is weak. From an operational viewpoint several difficulties are evident. The code enforcement throughout the country is uneven, and design/construction control is difficult to attain. The sheer magnitude and complexity of regulatory requirements are overwhelming, and the designer often is placed in an adversary position with regard to compliance.

We may put these strengths and limitations of the existing system into perspective by tracing the enormous improvement in fire protection that has occurred in the built environment. This can be attributed to the evolution of the modern building code and to its enforcement by dedicated code officials. Today, the building code system and the fire service provide the principal protection for the citizen. In addition, regardless of the view of building codes, the code is the law.

The evolution of design and construction techniques and materials in this century has caused major changes in building construction. Technically, much is possible today that was inconceivable at the turn of the century, and even a generation ago. As buildings have become more complex, so have code requirements. The building code has grown during this same period, although its fundamental philosophy has not changed significantly. That philosophy is that the code, rather than a professional engineering specialist, assumes the responsibility for firesafety design.

Within this environment a number of other factors are beginning to interface with the building firesafety community. One is that buildings and their operation and use are becoming more complex, and economic analyses are more sophisticated. The cost and effectiveness of the fire part of a building code are coming under increased scrutiny by the non-fire community.

The gap between fire science and building design practice for fire is large and its rate of change is accelerating. The time commitment for a practicing professional to maintain currency with computational changes is enormous, and the expense cannot be borne only by clients.

The liability concerns are increasing with the advancement of fire research. Within the next decade we can expect a floodgate to open with more and more computer models used in building design and in civil litigation cases. These models will be used whether or not they are appropriate for the problem or have been validated and their limitations identified. Most practitioners have neither the background nor the skill to use these models effectively or appropriately. The building designer will need a more global knowledge at design time because they will be held accountable at trial time.

There are natural institutional conflicts between the traditional prescriptive consensus code and standard system and the predictive models. Both the codes and the predictive models have substantial limitations at the present time. An amount of trauma, uncertainty, and confusion lies ahead for the design community. It is important to find a rational means by which the new tools can be incorporated into the prevailing political and economic environment. It is far more important for the design professional than for the scientist to have a framework which allows standards of professional practice to reflect the knowledge base and engineering solutions.

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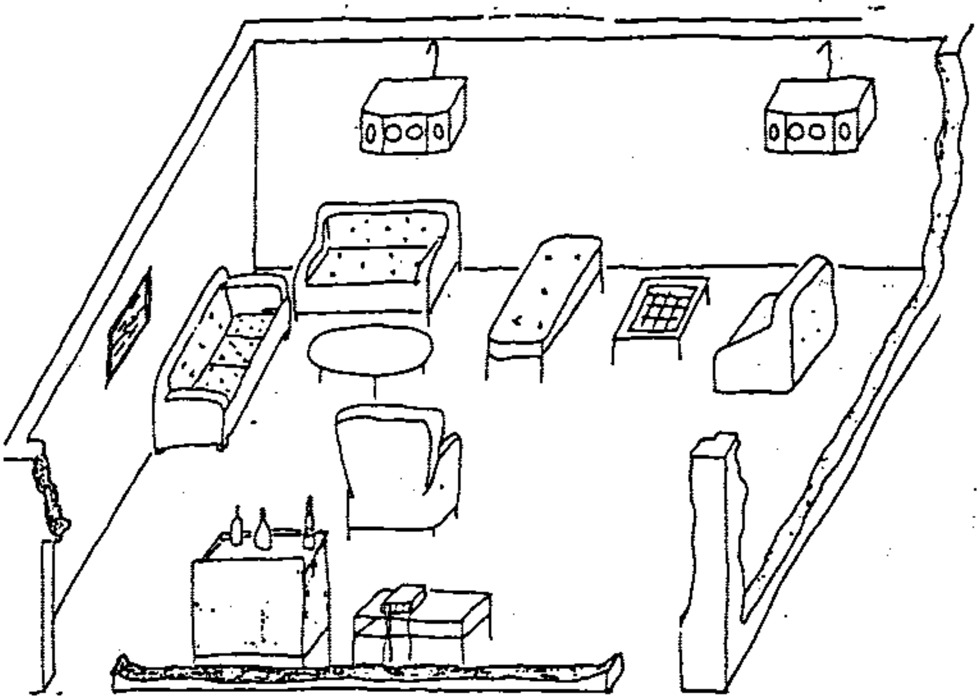


FIGURE 1

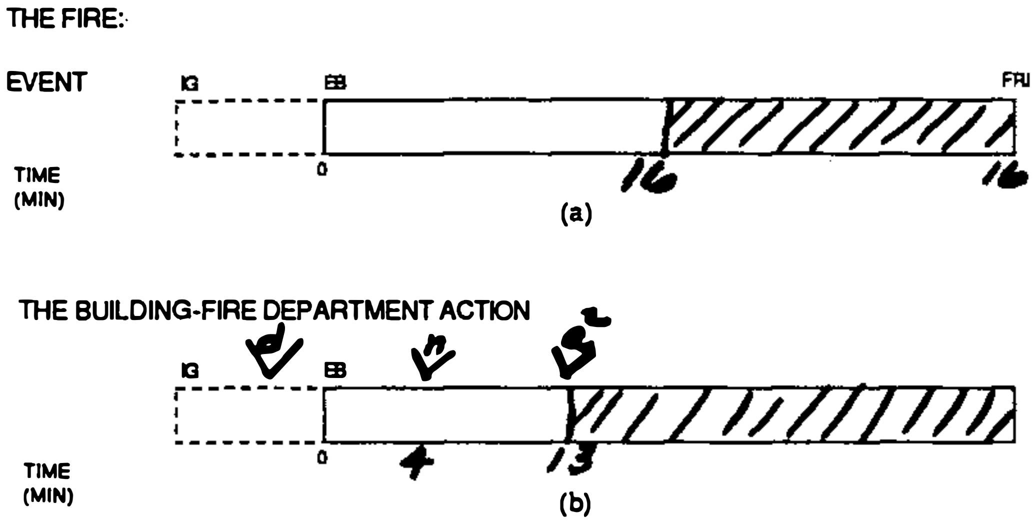
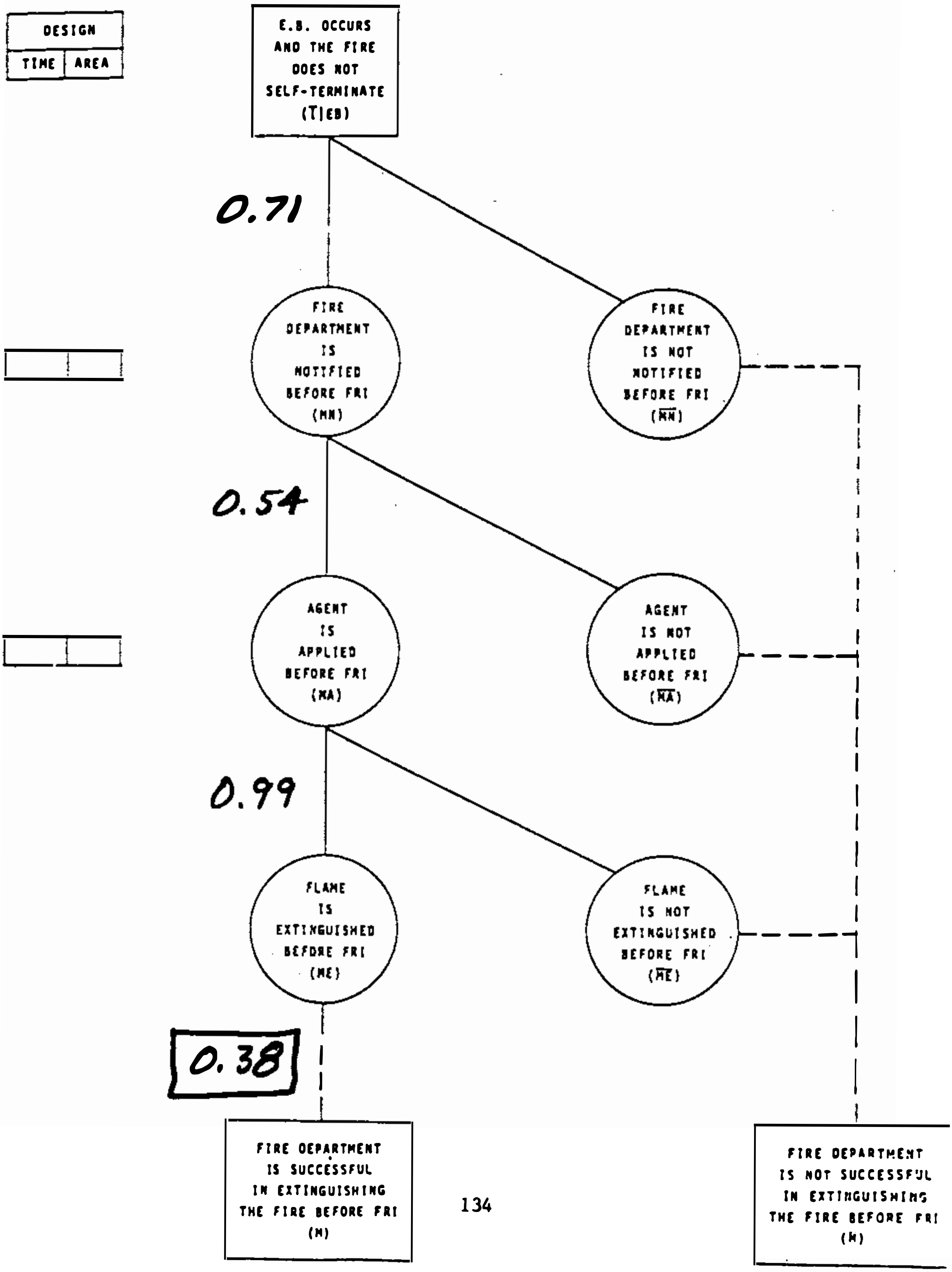

THE FIRE:
EVENT
IG
EB
FRI
0
16
16
TIME
(MIN)
(a)
THE BUILDING-FIRE DEPARTMENT ACTION
IG
EB
0
4
13
TIME
(MIN)
(b)

FIGURE 3

APPENDIX

FIGURE 14.1


DESIGN
TIME
AREA
E.B. OCCURS AND THE FIRE DOES NOT SELF-TERMINATE (T|EB)
0.71
FIRE DEPARTMENT IS NOTIFIED BEFORE FRI (MN)
FIRE DEPARTMENT IS NOT NOTIFIED BEFORE FRI ($\overline{MN}$)
0.54
AGENT IS APPLIED BEFORE FRI (MA)
AGENT IS NOT APPLIED BEFORE FRI ($\overline{MA}$)
0.99
FLAME IS EXTINGUISHED BEFORE FRI (ME)
FLAME IS NOT EXTINGUISHED BEFORE FRI ($\overline{ME}$)
0.38
FIRE DEPARTMENT IS SUCCESSFUL IN EXTINGUISHING THE FIRE BEFORE FRI (M)
FIRE DEPARTMENT IS NOT SUCCESSFUL IN EXTINGUISHING THE FIRE BEFORE FRI (M)

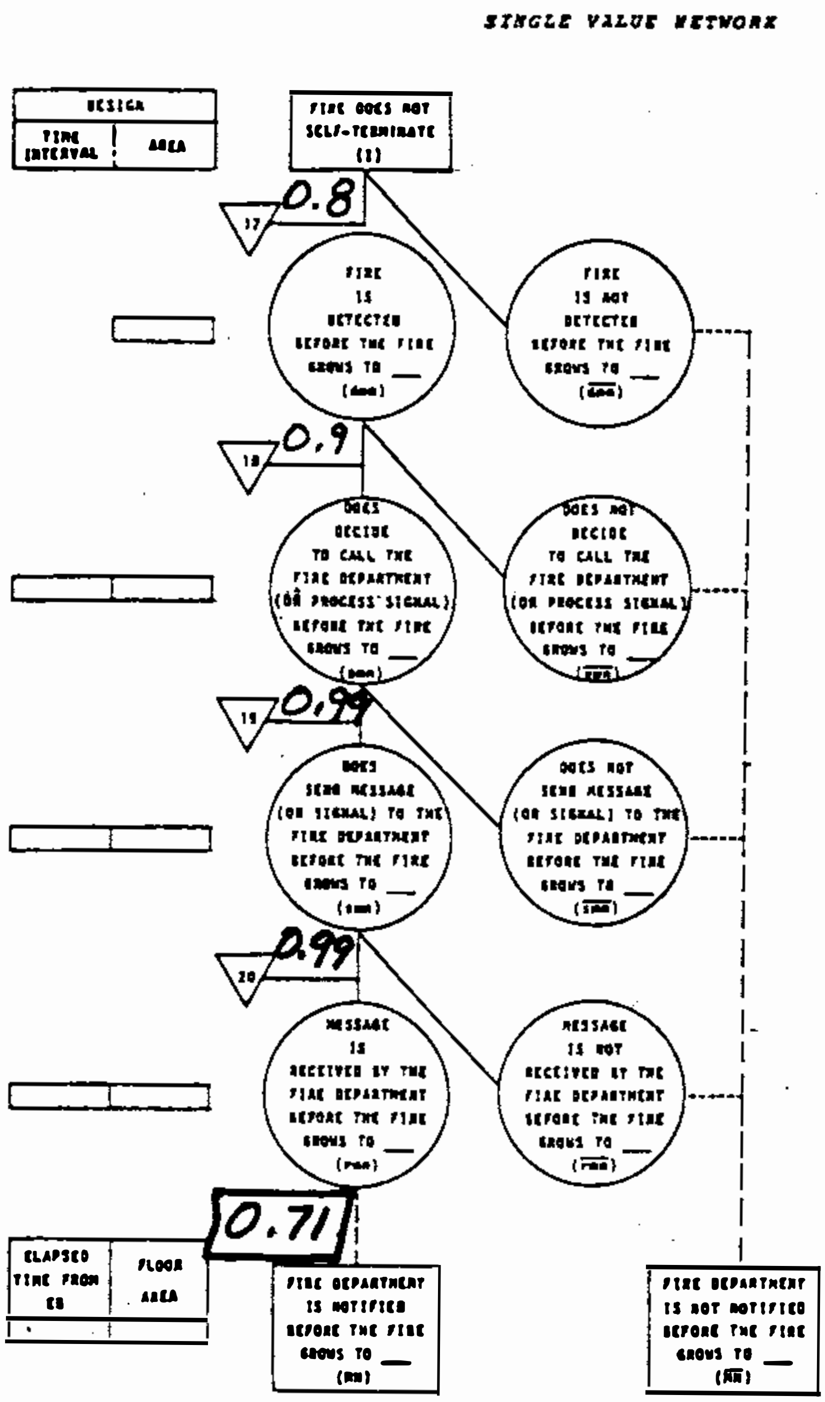


FIGURE C.12(a): NETWORK FOR FIRE DEPARTMENT NOTIFICATION

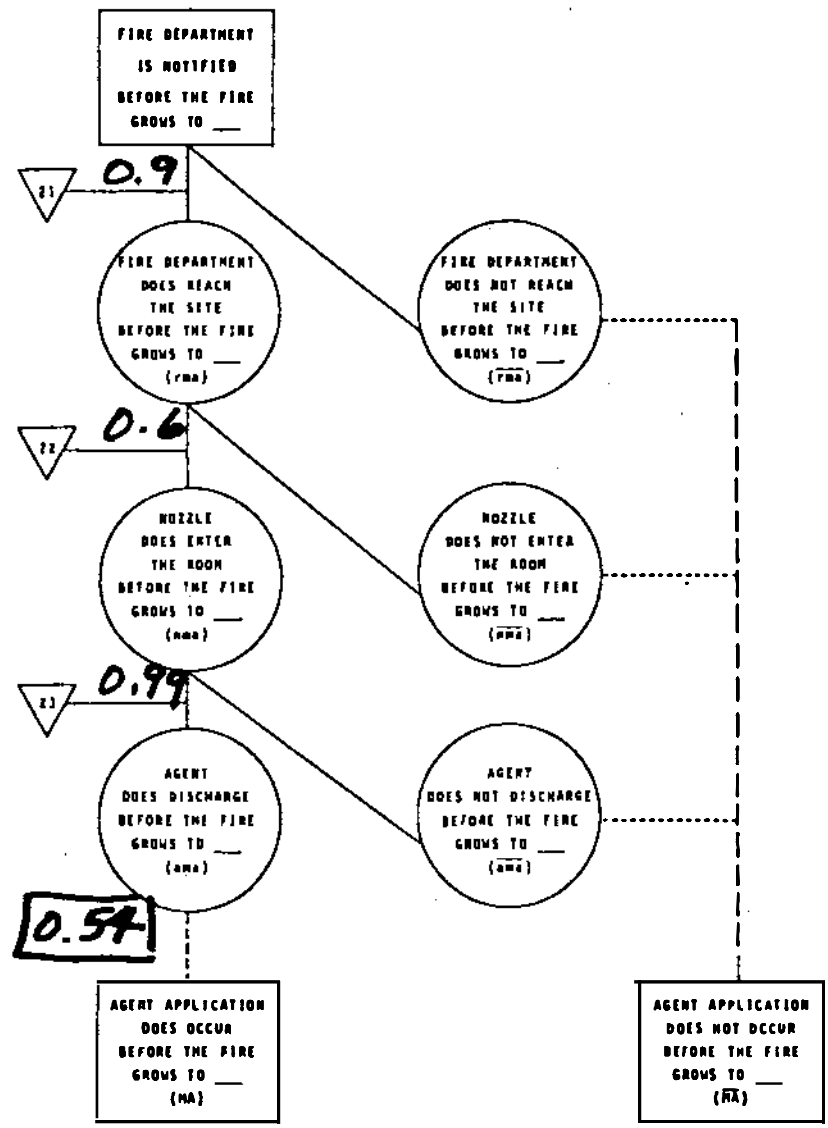


FIGURE C.13(a): NETWORK FOR AGENT APPLICATION

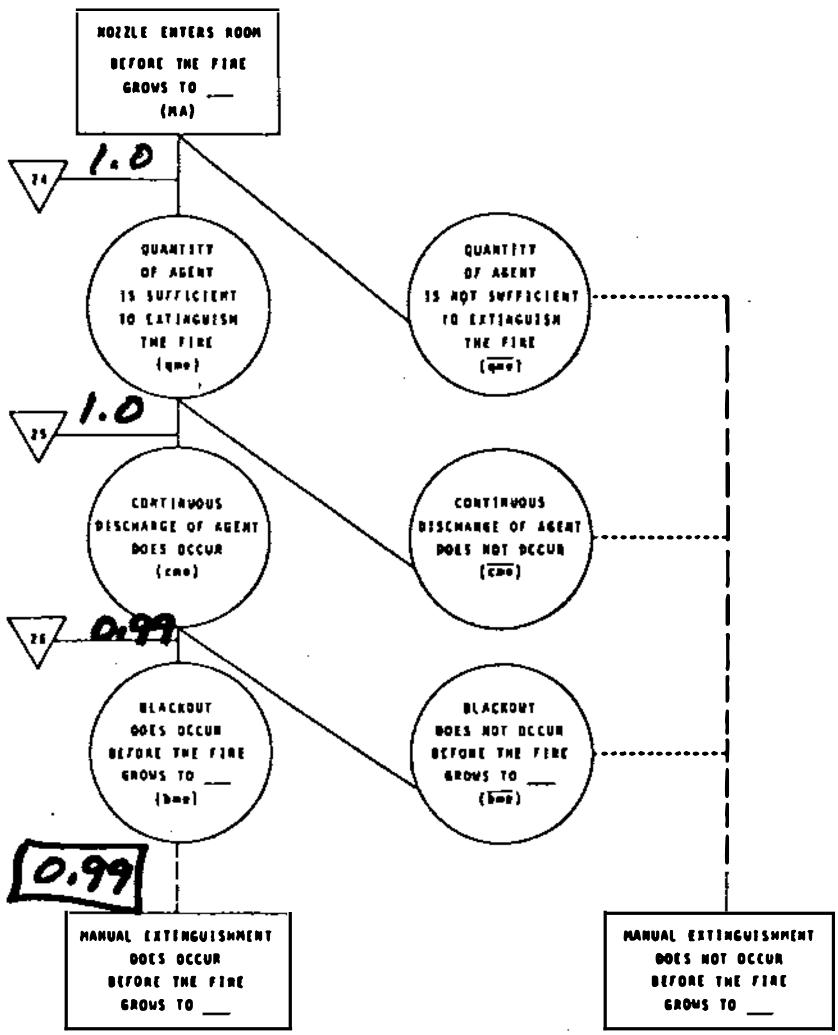
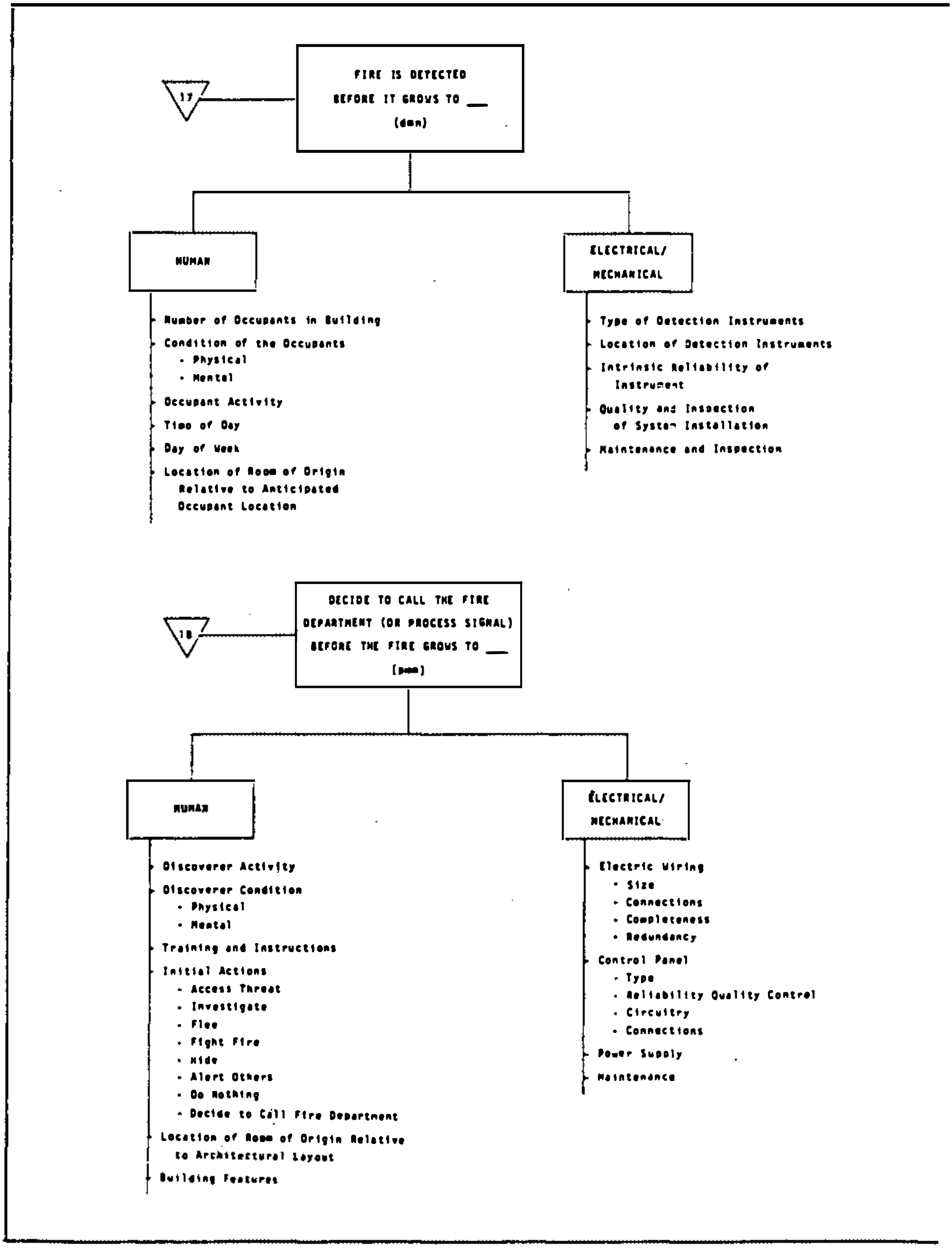


FIGURE C.14(a): NETWORK FOR MANUAL EXTINGUISHMENT


17
FIRE IS DETECTED BEFORE IT GROWS TO ___
HUMAN
ELECTRICAL/ MECHANICAL
Number of Occupants in Building
Condition of the Occupants
• Physical
• Mental
Occupant Activity
Time of Day
Day of Week
Location of Room of Origin Relative to Anticipated Occupant Location
Type of Detection Instruments
Location of Detection Instruments
Intrinsic Reliability of Instrument
Quality and Inspection of System Installation
Maintenance and Inspection
18
DECIDE TO CALL THE FIRE DEPARTMENT (OR PROCESS SIGNAL) BEFORE THE FIRE GROWS TO ___
HUMAN
ELECTRICAL/ MECHANICAL
Discoverer Activity
Discoverer Condition
• Physical
• Mental
Training and Instructions
Initial Actions
• Access Threat
• Investigate
• Flee
• Fight Fire
• Hide
• Alert Others
• Do Nothing
• Decide to Call Fire Department
Location of Room of Origin Relative to Architectural Layout
Building Features
Electric Wiring
• Size
• Connections
• Completeness
• Redundancy
Control Panel
• Type
• Reliability Quality Control
• Circuitry
• Connections
Power Supply
Maintenance

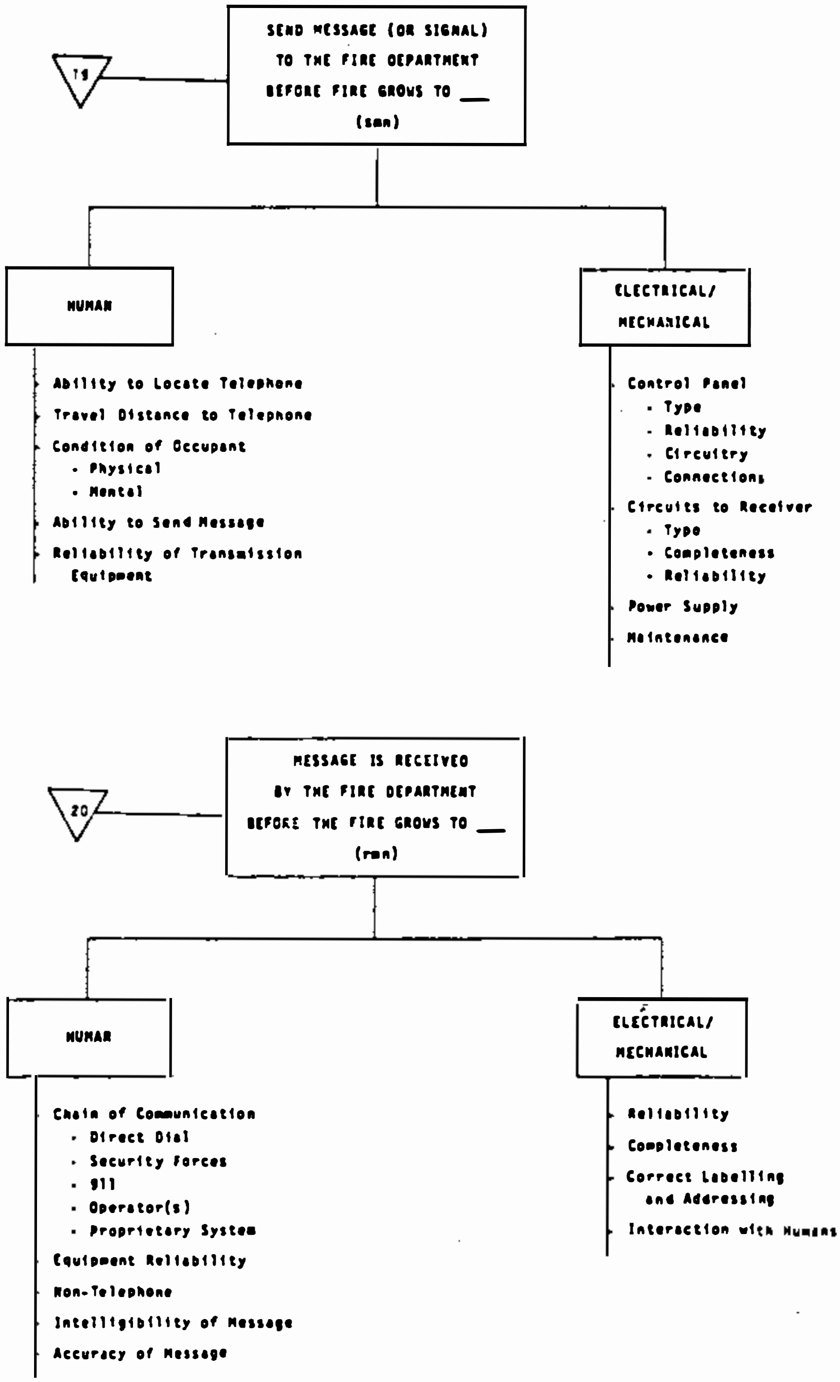


FIGURE C.12(b): FACTORS THAT INFLUENCE FIRE DEPARTMENT NOTIFICATION

21 FIRE DEPARTMENT REACHES SITE BEFORE THE FIRE GROWS TO ___ (rma)

- Alarm Handling Time
- Turnout Time
- Travel Time
  - Distance
  - Weather
  - Obstacles
- Site Access

22 NOZZLE ENTERS ROOM BEFORE THE FIRE GROWS TO ___ (nma)

- Building Access
- Locate the Fire
- Floor Access
  - Stairwell
  - Floor Level
  - Exterior Access
  - Elevator Operation
- Room Access
  - Stairwell Location
  - Architectural Layout
  - Smoke, Gas, and Heat Condition
  - Room Location
- Electric Power Supply
- Suppression Manpower
- Hose Connections
  - Hydrants
  - Pumpers
  - Standpipes

23 AGENT DISCHARGES BEFORE THE FIRE GROWS TO ___ (ama)

- Water Availability
  - Hydrant Location
  - Other Water Supply Sources
  - Weather Conditions
- Building Features
  - Floor Level
  - Building Pumps
  - Standpipes (wet or dry)
  - Reliability of Power Sources
- Fire Department Resources
  - Apparatus Pumps
  - Suppression Manpower
  - Portable Water Sources

FIGURE C. 13(b): FACTORS THAT INFLUENCE AGENT APPLICATION

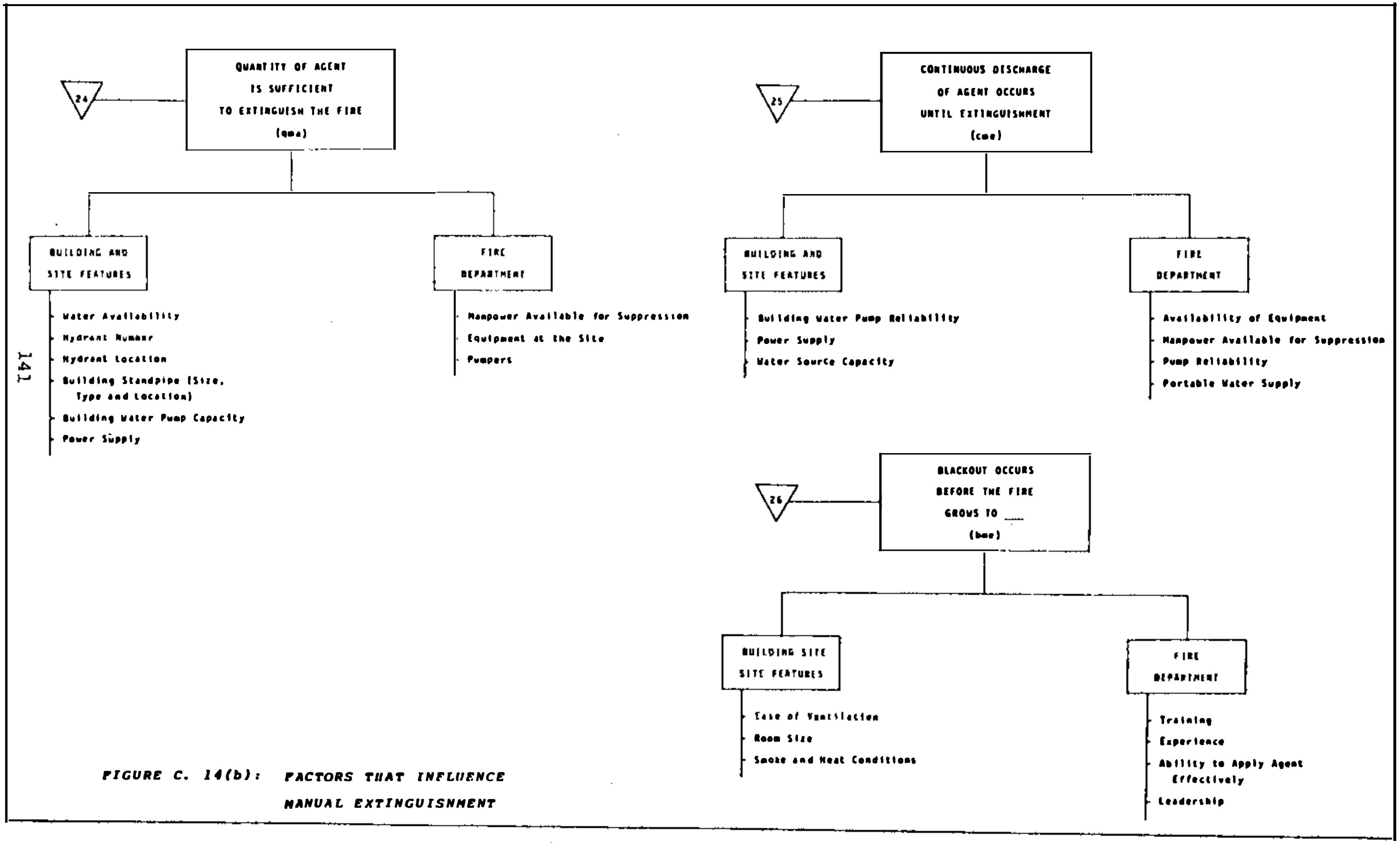


FIGURE C. 14(b): FACTORS THAT INFLUENCE MANUAL EXTINGUISHMENT

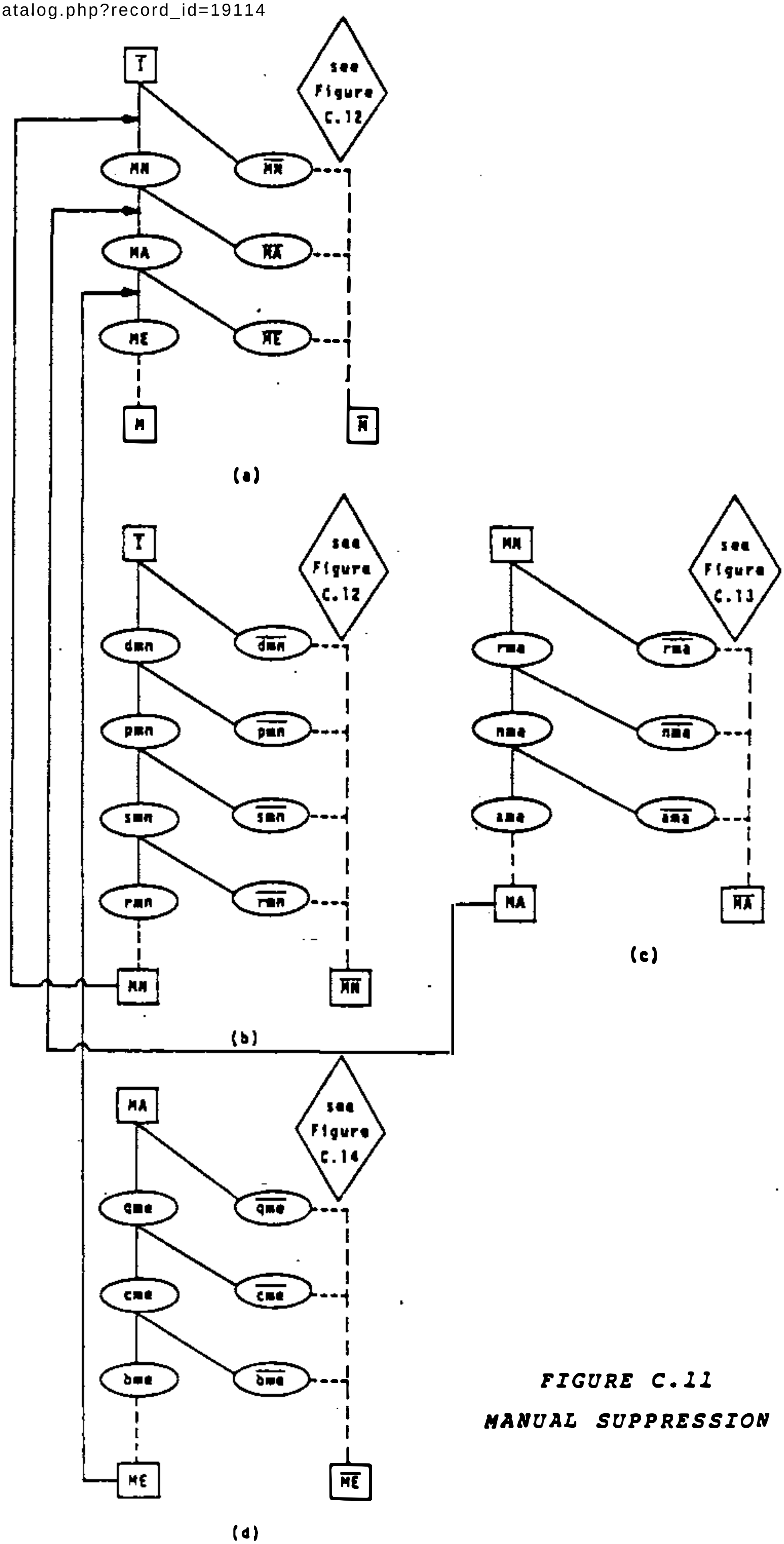


FIGURE C.11

MANUAL SUPPRESSION

APPENDIX 2

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