Evaluating Performance-Based Designs

EPBD-Student Manual

1st Edition, 7th Printing-April 2014

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U.S. DEPARTMENT OF HOMELAND SECURITY

UNITED STATES FIRE ADMINISTRATION

NATIONAL FIRE ACADEMY

FOREWORD

The U.S. Fire Administration (USFA), an important component of the Department of Homeland Security (DHS), serves the leadership of this Nation as the DHS's fire protection and emergency response expert. The USFA is located at the National Emergency Training Center (NETC) in Emmitsburg, Maryland, and includes the National Fire Academy (NFA), National Fire Data Center (NFDC), and the National Fire Programs (NFP). The USFA also provides oversight and management of the Noble Training Center in Anniston, Alabama. The mission of the USFA is to save lives and reduce economic losses due to fire and related emergencies through training, research, data collection and analysis, public education, and coordination with other Federal agencies and fire protection and emergency service personnel.

The USFA's National Fire Academy offers a diverse course delivery system, combining resident courses, off-campus deliveries in cooperation with State training organizations, weekend instruction, and online courses. The USFA maintains a blended learning approach to its course selections and course development. Resident courses are delivered at both the Emmitsburg campus and the Noble facility. Off-campus courses are delivered in cooperation with State and local fire training organizations to ensure this Nation's firefighters are prepared for the hazards they face.

This course is designed to provide fire professionals responsible for the review and/or approval of building and fire/life safety design in the regulatory process with the fundamental knowledge, skills, and abilities to assess performance-based designs. It introduces concepts and technologies that shift building design from traditional prescriptive-based building and fire regulations to strategies where engineers, architects, and designers employ a variety of options to meet specific performance goals.

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COURSE SCHEDULE

	SUNDAY	MONDAY	TUESDAY	WEDNESDAY	THURSDAY	FRIDAY
AM	NFA and Course Introductions Unit 1: Introduction	Unit 2: Introduction to Fire Dynamics	Unit 3 (cont'd) Module 2: Human Behavior Module 3: Risk/Probabilty Analysis	Unit 4: The process Method	Unit 5: Documentation	Final Project Examination
PM	Unit 1 (cont'd) Readings: Units 1, 2, and 3 in Student Manual Student Manual: Babrauksas article: Heat Release Rate Fleming, et al., article O'Hara and Bierwerth article Begin reading final project information: *Performance-Based Design Analysis for a Shopping Mall*	Unit 3: Introduction to Fire Effects and Egress Models Module 1: Fire Effects Models LRC--Scheduled Orientation Readings: Review Unit 3 in Student Manual Babrauksas article: Fire Modeling Bryan article Bukowski article McGrattan, et al., article Mower article Paulsen article	Unit 3 (cont'd) Module 3 (cont'd) Test: Units 1, 2, and 3 (closed book) Readings: Chapter 3 in SFPE *Engineering Guide* Unit 4 in Student Manual Final project information: *Performance-Based Design Analysis for a Shopping Mall*	Unit 4 (cont'd) Test: Unit 4/ Debrief (closed book) Readings: Units 5 and 6 in the Student Manual Chapter 12 in SFPE *Engineering Guide* Final project information: *Performance-Based Design Analysis for a Shopping Mall*	Unit 6: Testing, Inspection, and Maintenance Reading: Final project information: *Performance-Based Design Analysis for a Shopping Mall*	Final Project Debrief Graduation

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FIREFIGHTER CODE OF ETHICS

Background

The Fire Service is a noble calling, one which is founded on mutual respect and trust between firefighters and the citizens they serve. To ensure the continuing integrity of the Fire Service, the highest standards of ethical conduct must be maintained at all times.

Developed in response to the publication of the Fire Service Reputation Management White Paper, the purpose of this National Firefighter Code of Ethics is to establish criteria that encourages fire service personnel to promote a culture of ethical integrity and high standards of professionalism in our field. The broad scope of this recommended Code of Ethics is intended to mitigate and negate situations that may result in embarrassment and waning of public support for what has historically been a highly respected profession.

Ethics comes from the Greek word ethos, meaning character. Character is not necessarily defined by how a person behaves when conditions are optimal and life is good. It is easy to take the high road when the path is paved and obstacles are few or non-existent. Character is also defined by decisions made under pressure, when no one is looking, when the road contains land mines, and the way is obscured. As members of the Fire Service, we share a responsibility to project an ethical character of professionalism, integrity, compassion, loyalty and honesty in all that we do, all of the time.

We need to accept this ethics challenge and be truly willing to maintain a culture that is consistent with the expectations outlined in this document. By doing so, we can create a legacy that validates and sustains the distinguished Fire Service institution, and at the same time ensure that we leave the Fire Service in better condition than when we arrived.

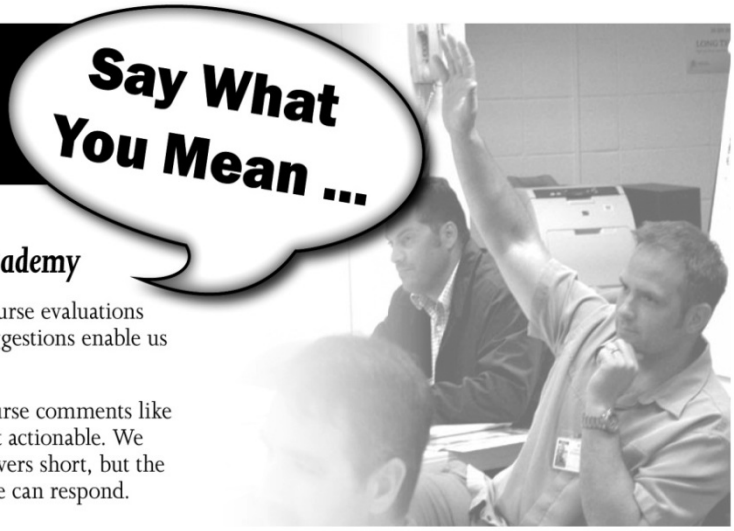
FIREFIGHTER CODE OF ETHICS

I understand that I have the responsibility to conduct myself in a manner that reflects proper ethical behavior and integrity. In so doing, I will help foster a continuing positive public perception of the fire service. Therefore, I pledge the following…

- Always conduct myself, on and off duty, in a manner that reflects positively on myself, my department and the fire service in general.
- Accept responsibility for my actions and for the consequences of my actions.
- Support the concept of fairness and the value of diverse thoughts and opinions.
- Avoid situations that would adversely affect the credibility or public perception of the fire service profession.
- Be truthful and honest at all times and report instances of cheating or other dishonest acts that compromise the integrity of the fire service.
- Conduct my personal affairs in a manner that does not improperly influence the performance of my duties, or bring discredit to my organization.
- Be respectful and conscious of each member's safety and welfare.
- Recognize that I serve in a position of public trust that requires stewardship in the honest and efficient use of publicly owned resources, including uniforms, facilities, vehicles and equipment and that these are protected from misuse and theft.
- Exercise professionalism, competence, respect and loyalty in the performance of my duties and use information, confidential or otherwise, gained by virtue of my position, only to benefit those I am entrusted to serve.
- Avoid financial investments, outside employment, outside business interests or activities that conflict with or are enhanced by my official position or have the potential to create the perception of impropriety.
- Never propose or accept personal rewards, special privileges, benefits, advancement, honors or gifts that may create a conflict of interest, or the appearance thereof.
- Never engage in activities involving alcohol or other substance use or abuse that can impair my mental state or the performance of my duties and compromise safety.
- Never discriminate on the basis of race, religion, color, creed, age, marital status, national origin, ancestry, gender, sexual preference, medical condition or handicap.
- Never harass, intimidate or threaten fellow members of the service or the public and stop or report the actions of other firefighters who engage in such behaviors.
- Responsibly use social networking, electronic communications, or other media technology opportunities in a manner that does not discredit, dishonor or embarrass my organization, the fire service and the public. I also understand that failure to resolve or report inappropriate use of this media equates to condoning this behavior.

Developed by the National Society of Executive Fire Officers

A Student Guide to End-of-course Evaluations



Ten Things You Can Do to Improve the National Fire Academy

The National Fire Academy takes its course evaluations very seriously. Your comments and suggestions enable us to improve your learning experience.

Unfortunately, we often get end-of-course comments like these that are vague and, therefore, not actionable. We know you are trying to keep your answers short, but the more specific you can be, the better we can respond.

Actual quotes from student evaluations:	Examples of specific, actionable comments that would help us improve the course:
1 "Update the materials."	• The (ABC) fire video is out-of-date because of the dangerous tactics it demonstrates. The available (XYZ) video shows current practices. • The student manual references building codes that are 12 years old.
2 "We want an advanced class in (fill in the blank)."	• We would like a class that enables us to calculate energy transfer rates resulting from exposure fires. • We would like a class that provides one-on-one workplace harassment counseling practice exercises.
3 "More activities."	• An activity where students can physically measure the area of sprinkler coverage would improve understanding of the concept. • Not all students were able to fill all ICS positions in the exercises. Add more exercises so all students can participate.
4 "A longer course."	• The class should be increased by one hour per day to enable all students to participate in exercises. • The class should be increased by two days so that all group presentations can be peer evaluated and have written abstracts.
5 "Readable plans."	• The plans should be enlarged to 11 by 17 and provided with an accurate scale. • My plan set was blurry, which caused the dotted lines to be interpreted as solid lines.
6 "Better student guide organization," "manual did not coincide with slides."	• The slide sequence in Unit 4 did not align with the content in the student manual from slides 4-16 through 4-21. • The instructor added slides in Unit 4 that were not in my student manual.
7 "Dry in spots."	• The instructor/activity should have used student group activities rather than lecture to explain Maslow's Hierarchy. • Create a pre-course reading on symbiotic personal relationships rather than trying to lecture on them in class.
8 "More visual aids."	• The text description of V-patterns did not provide three-dimensional views. More photographs or drawings would help me imagine the pattern. • There was a video clip on NBC News (date) that summarized the topic very well.
9 "Re-evaluate pre-course assignments."	• The pre-course assignments were not discussed or referenced in class. Either connect them to the course content or delete them. • The pre-course assignments on ICS could be reduced to a one-page job aid rather than a 25-page reading.
10 "A better understanding of NIMS."	• The instructor did not explain the connection between NIMS and ICS. • The student manual needs an illustrated guide to NIMS.

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UNIT 1: INTRODUCTION

TERMINAL OBJECTIVE

Given examples of a performance-based design and a prescriptive-based design, the students will be able to describe the differences, based on criteria outlined in the Society of Fire Protection Engineers (SFPE) Guide *and in Unit 1.*

ENABLING OBJECTIVES

Given examples of performance-based and prescriptive-based designs, the students will:

1. *Identify the defining characteristics of each design type.*

2. *Identify differences between prescriptive group/division occupancy classifications and "performance groups."*

3. *Identify legal issues in transitioning from prescriptive to performance-based designs and how they are resolved.*

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PRESCRIPTIVE AND PERFORMANCE-BASED DESIGN

In Unit 1, we discuss prescriptive and performance-based designs and codes. We also discuss the major requirements of the

- International Code Council (ICC) *Performance Code for Buildings and Facilities*;
- ICC *International Existing Buildings Code*;
- National Fire Protection Association (NFPA);
- NFPA 1, *Fire Prevention Code*;
- NFPA 101®, *Life Safety Code*;
- NFPA 101A, *Guide to Alternative Approaches to Life Safety;*
- NFPA 5000, *Building Construction and Safety Code*; and
- "smart" building codes.

Prescriptive Design

For years, American architects and engineers have operated within a "prescriptive" environment when designing structures. Design and construction freedom is limited by building and fire codes that "prescribe" exactly what the architect and engineer must do to meet the code.

Among other things, building heights, areas, fire protection systems, egress plans, and subsystems (electrical, mechanical, and plumbing) fall within the rules of State or local legislation that occasionally stifles creativity in both design and construction. Building owners, architects, designers, and engineers must comply with these regulations to get their projects completed, and to meet the public goal of life safety and fire protection.

Prescriptive design enjoys a long history in the United States. In many ways, it establishes a "culture of design" where buildings and structures assume standardized--and often bland--design elements from one community to another. Due to both marketing decisions and building code limitations, covered shopping malls assume a surprisingly similar look and feel. Highrise office buildings begin to look alike. National chains of fast food restaurants, motor vehicle service stations, and business service centers share common themes and features.

One complaint about prescriptive design is that due to code-mandated redundancies (i.e., fire resistive separations and automatic fire suppression equipment), increased construction and operational costs occur without a concurrent increase in occupant or building safety. Local amendments to building and fire codes also may restrict designs to meet local conditions and further increases development costs.

But what about those circumstances and projects where it is impossible to meet current prescriptive codes? How does an architect express himself or herself aesthetically while fulfilling a client's special need? How can old or historically significant buildings be salvaged for re-use while improving their life safety and fire protection features? How do we encourage creativity in design and materials to compete in an increasingly competitive global marketplace?

One answer is to enable flexible "performance" techniques in building design and operations.

Performance-Based Design

In "performance-based" design, many of the old ideas and prescriptive rules are set aside in favor of establishing mutually agreed upon design, construction and safety goals and objectives. This method allows the widest possible design and construction latitude while assuring a reasonable level of safety for the occupants and structure.

By definition, performance-based design is an engineering approach to design elements of a building or facility based on performance goals and objectives, engineering analysis, scientific measurements, and quantitative assessment of alternatives against the design goals and objectives, using accepted engineering tools, methodologies, and performance criteria.

Performance-based design provides a new set of challenges for the Authority Having Jurisdiction (AHJ). Rather than requiring the building to meet a list of prescriptive requirements, the AHJ must evaluate how the structure and its occupants will perform under fire conditions. This means the AHJ must be familiar with principles of fire behavior, structural performance, human response, and integrated life safety and fire protection systems.

While this course emphasizes the fire protection elements of performance-based design, it is important to remember that other challenges exist: wind, earthquake, flooding, ventilation, sanitation, occupant comfort and convenience, communications, security, and visitor access are among the issues the architect or engineer must address in a performance-based design. We can expect to see more of these enterprises as the design community responds to yet another environmental threat, that of terrorist infiltration or attack. So-called "target hardening" is a predominant concern in the design community as building owners and occupants want to protect their assets from these risks. Many of these counterterrorist strategies--such as stand-off distances, explosion- and bullet-resistant glazing, and security locking systems--will create an entirely new set of challenges for the fire service.

Some characteristics of performance-based designs are

- their ability to deal with unique design and engineering challenges;
- their reliance on "stakeholder[1]" participation and goals;
- their aim to reduce construction costs while maintaining safety;
- their use of "bounding conditions[2]" to restrict a buildings' use and, perhaps, invalidate its performance design; and
- their dependence on critical design assumptions developed early in the design process.

The performance-based design approach allows the comparison of safety levels provided by various alternative designs. Performance-based design also provides a mechanism for determining what level of safety is acceptable to the stakeholders, and at what cost. Performance-based codes require the use of a variety of tools for proper analysis. Such tools

[1] "Stakeholders" are those individuals or groups that have an interest in successful project results. See discussion below.

[2] "Bounding conditions" from the ICC *Performance Code for Buildings and Facilities* will be discussed later in the course.

might include deterministic analysis techniques, probabilistic analysis techniques, application of the theory of fire dynamics, application of deterministic and probabilistic fire effects modeling, use of actual fire tests or test data, and application of human behavior and toxic effects modeling.

Probabilistic analysis and models deal with the statistical likelihood or chances of the occurrence of a fire and its outcome, based upon the random nature of fire and the likelihood of its occurrence. Deterministic analysis and models are based on physical laws, or correlations developed as a result of fire test data, to predict fire outcomes. These concepts will be discussed in more detail in Unit 3: Introduction to Fire Effects and Egress Models.

Stakeholders

The performance-based design concept involves a wide range of "stakeholders." Stakeholders include all individuals or their representatives who have an interest in the successful completion of the specific project. Clearly, stakeholders include not only the members of the design team, the building owner, and the developer, but the code enforcement officials as well. In the broadest sense, stakeholders are not, and should not, be limited only to those who have a financial interest in the project. The design team is a subgroup of "stakeholders" which includes individuals such as representatives of the architect, building owner, developer, and any other pertinent engineers and designers. AHJ early participation in a performance-based design is important. Performance-based design can be used on any project, but because of its cost, it is usually used for unusual projects--especially when prescriptive codes do not exist. Performance designs also are the only designs that include fire service capacity and capability.

Experience in other countries' buildings in performance-based design suggests that performance-based designs can result in equal or better fire safety, more functional buildings, and more cost-effective construction. However, most buildings are based on prescriptive codes because of the high cost of performance-based designs.

CODE ORGANIZATIONS

The following organizations publish the codes discussed in this course.

- International Conference of Building Officials (ICBO);
- Southern Building Code Congress International (SBCCI);
- Building Officials and Code Administrators International (BOCA);
- ICC; and
- NFPA.

Prescriptive Codes

The traditional approach used to achieve life and property protection in the United States has been that of prescriptive building and fire codes. Prescriptive codes are quantitative: they rely on fixed values prescribed in the codes to achieve life safety and fire protection. Prescriptive codes establish code requirements based upon broad or generic classifications of buildings or

occupancies. We all are familiar with Groups A, E, B, M, and S occupancies, but are all educational occupancies alike? Do all storage occupancies contain the same type and array of materials, thereby creating common fire hazards?

Most of our fire protection equipment installation standards also are prescriptive: giving the design and installation team very specific guidance in the selection and placement of equipment and materials.

Existing prescriptive codes and standards use a "one occupancy category fits all" approach to problem-solving. For example, when a fire sprinkler contractor designs a protection system for an office building, the design is "in compliance" if the system meets the "light hazard" requirements in accordance with NFPA 13, *Installation of Sprinkler Systems*. What if the office has only noncombustible steel chairs and desks on a concrete floor? Or, what if the office is full of highly combustible upholstered furniture, medical gases and patient records storage? Under a prescriptive code, either scenario would be considered "light hazard," although intuitively we would recognize the second one as a greater fire challenge.

Requirements in prescriptive codes and standards typically are stated in terms of fixed values such as travel distance, fire resistance ratings, allowable area and height, number of plumbing fixtures, minimum ventilation rates, number and capacity of exits, fire alarm and detection system requirements, and fire suppression system demands.

Prescriptive codes cover buildings and systems, and they tend to provide only one method for addressing various design and construction issues. As an example, the prescriptive codes establish limits on travel distance; e.g., a maximum travel distance of 150 feet to an exit in a nonsprinklered building, or 200 feet in a sprinklered one. From where did this limit come? Upon what is it based? Why is it 150 feet, not 140 feet or 200 feet?

Another example occurs where the building codes limit the floor area and height based on the construction and occupancy types. One of the current prescriptive building codes limits the area of a wood-frame office building to 9,000 square feet Why is this building considered acceptable and its occupants considered reasonably safe at 9,000 square feet, but unacceptable or "unsafe" at 9,100 square feet? These threshold limits need to be re-examined in light of current scientific knowledge.

The foundation of our prescriptive codes is based on our fire loss experiences from the 19th century when major conflagrations were a major concern. Historically, our first attempt was to confine the size of fires "to the block of origin". Subsequent code revisions have shrunk that size successively to the "building of origin," to the "floor of origin," and, finally, to the "room of origin."

While fire research techniques in the 19th century were not nearly as sophisticated as they are today, many early researchers worked hard to identify materials and construction techniques that would prevent fires from spreading. Their research led to the development of masonry fire walls of various thickness to achieve horizontal fire resistance, hollow clay tile floor/ceiling assemblies

to prevent vertical fire spread, fire resistive roof designs to minimize flying brands, and analysis of steel and cast iron columns to identify issues of structural integrity in fire conditions.

In the early 1920's, for example, the Federal National Bureau of Standards[3] (NBS) conducted some of the first significant studies on fire behavior in buildings. NBS built some full-scale test apparatus for fire growth or what they called "burnout" studies.

Tests were also conducted in actual buildings scheduled for demolition, the most notable being an old five-story building in Washington (DC) in 1928 in an area being cleared for the Federal Triangle. The spectacular collapse of this building convinced city officials to ban further experimentation in the downtown area. Steven Inberg's landmark 1928 article relating to the severity of fire with magnitude of the combustible contents or "fire load" still forms the underlying basis for the building code requirements which are prescribed in terms of hourly ratings according to the standard fire endurance test exposure[4].

Research with these materials and methods was translated into early building and fire codes that matched the success of their tests. If a successful test revealed that a 4-inch thick masonry wall resisted fire spread for a specific period of time, the codes included that detailed construction method. Over time, the specific requirements for masonry, block, concrete, tile, or other materials were replaced by a "performance" requirement that walls, ceilings, floors, and roofs resist fire for a measured period of time. The methods and materials to achieve that goal were left up to the building designer and contractor, as long as they were approved by the local building and fire officials or--in some cases--insurance underwriters.

A number of famous, tragic fires resulted in changes to the building and fire codes as show in Figure 1-1.

[3] Renamed the National Institute of Standards and Technology (NIST) in 1988.

[4] Gross, Daniel. "Fire Research at NBS: The First 75 Years." National Institute of Standards and Technology, Gaithersburg: 1991

Fire Incident	Date	Lives Lost	Predominant Code Issue
Iroquois Theater Chicago, IL	12/30/1903	602	• Exit doors swing in direction of egress • Fire retardant decorations
Triangle Shirtwaist Factory New York, NY	3/25/1911	145	• Inadequate and locked exits • Accumulations of combustibles
Cleveland Clinic Cleveland, OH	5/15/1929	125	• Storage of cellulose nitrate films
Ohio State Penitentiary Columbus, OH	4/21/1930	320	• Inadequate egress supervision • Lack of fire protection equipment
Cocoanut Grove Boston, MA	11/28/1942	492	• Number of exits • Exit door swing • Combustibility of decorations
LaSalle Hotel Chicago, IL	6/5/1946	61	• Corridor protection • Enclosure of vertical openings
Winecoff Hotel Atlanta, GA	12/7/1946	127	• Enclosure of vertical openings • Early notification (fire alarm) • Recognition that "fire proof" does not exist
GM Transmission Plant Livonia, MI	8/12/1953	3	• Concealed combustible spaces • Unprotected steel columns • Lack of fire separations • Lack of sprinklers • Large quantities of heated combustible liquids
Hartford Hospital Hartford, CT	12/8/1961	16	• Combustible ceiling tile and glue • Delayed fire reporting • Open doors onto corridors
Golden Age Nursing Home Fitchville, OH	11/23/1963	63	• Lack of fire separations • Lack of fire protection equipment

Figure 1-1
Some Famous Fires and Related Code Issues

Even when less famous tragedies occur, fire and building officials often are motivated to initiate local changes to their codes. It may be as simple as a retrofit law for the installation of fire doors or fire alarm systems, or as comprehensive as the installation of fire sprinkler systems in all high-rise hotels as occurred in Nevada after the MGM Grand and Hilton Hotel fires in 1980.

Finally, whether or not we like to admit it, some code changes occur simply in a political environment. Many of these national and local changes occur without any specific evaluation of their adequacy, excessiveness, or conflicts with other requirements. This has resulted in many code provisions that are based primarily on empiricism (observed events), experience and judgment, or past results rather than on current scientific understanding of the principles of fire and life safety.

Once adopted, these prescriptive codes effectively establish the minimum level of risk that we are willing to accept as a community. Building designers, contractors, and AHJ's place great emphasis on "code compliance." If it meets the code, they argue, it must be safe.

However, not all buildings constructed under the mantle of prescriptive codes meet absolutely every detailed fire protection and life safety requirement. We know people still die or are injured in these structures, so sometimes it is difficult to describe them as "safe."

The prescriptive code writers have recognized for a long time that there may be specific circumstances that arise in a project design or construction that cannot meet the mandates of prescriptive design, so the codes allow "equivalencies" or "alternate designs" when approved by the local building or fire official. As you look around at your community and identify historic structures, architecturally unique buildings, and designs that are creative, exciting, and new, you realize they cannot always meet requirements outlined in currently adopted prescriptive codes. "Equivalencies" or "alternate designs" give architects and code officials the latitude to explore alternate ways to solve complex code problems as long as the solution meets some agreed-upon minimum standard of life safety and fire protection, and the intent of the code.

The principal challenge with "equivalencies" or "alternate designs" is that they put the burden on the code enforcement official to define the criteria by which the equivalency will be considered "successful." While the codes require that the proponent submit the design solution and supporting documentation, the final decision rests with the code official as to its effectiveness. Unfortunately, the prescriptive codes give us no tools or evaluative methods to assess proposed alternates to determine if they provide equivalent levels of safety.

Performance-Based Codes

Performance-based codes, on the other hand, offer a solution to this equivalency dilemma by providing a **process** by which life safety and fire protection goals and objectives are established, acceptable performance criteria are agreed upon, and successful performance can be measured objectively.

Performance-based codes cover structures, operations, and processes. They are not based on assigning broad or generic occupancy classifications, but focus on measurable, scientific life safety and fire protection goals and objectives. They establish by a consensus process among project participants acceptable or tolerable levels of hazard or risk for a variety of health, safety, and public welfare concerns.

As part of the development of the new family of "International Codes," the ICC has developed the *Performance Code for Buildings and Facilities*.

Additionally, beginning with the 2000 edition, the *NFPA* 101®, *Life Safety Code* contains a revised Chapter 5, entitled "Performance-based Design." Similar requirements also will be contained in NFPA 5000 Chapter 5, entitled "Performance-based Design".

NPFA 101A also can be used in a performance-based design approach, although it is limited to life safety matters only.

While having extensive or detailed requirements for "performance" is relatively new to the building and fire codes used in the United States, the concept is not. The *BOCA National Building Code, Standard Building Code, Uniform Building Code, International Building Code* and NFPA 101® all have provisions for "alternative methods and materials" or "equivalencies." These code provisions allow for the use of methods, equipment, or materials not specified or prescribed in the code, provided the alternative is approved by the AHJ. The provisions also allow the AHJ to approve the alternative or equivalency if it can be shown to be equivalent in quality, strength, effectiveness, fire resistance, durability, and safety.

The proponent of the alternative method or equivalency is responsible for providing all necessary documentation to the AHJ. Based on the ability of the AHJ to permit alternate methods and materials in the existing prescriptive codes, performance-based codes offer the AHJ a system to accept alternative designs based on performance. In other words, this is nothing new to the AHJ, just a formal way to review designs.

NFPA 1 does not contain specific performance requirements but sets forth that, when a performance design is used, the submitter must document, in an approved format, each performance objective and applicable scenario, as well as any calculation methods or models. The AHJ is identified as the final approval authority for any performance-based design.

The code also clearly requires that the building must be maintained in accordance with all documented assumptions and design specifications. Any proposed changes to the original design must be approved by the AHJ prior to the change actually occurring.

NFPA 1 requires the property owner to certify to the AHJ on an annual basis that the design features and systems are being maintained in accordance with the approved performance-based design and assumptions.

The Movement to Performance-Based Codes

There has been, and continues to be, a strong movement in the United States to move our building and fire codes towards the performance-based concept. This movement began even before the development of the International Codes. At least part of the justification for this movement is the use of such codes by other countries. Countries that have implemented or are in the process of implementing the performance-based concept include England, New Zealand, Australia, Wales, Sweden, Canada, Japan, Poland, Romania, and China. While performance-based codes have been used successfully in other countries, it is important to consider all of the cultural, social, technological, and economic variables or differences between these countries and the United States.

The effectiveness of performance-based codes also is affected by conditions outside of the design profession and code enforcement agencies. The overall attitude of a society toward fire or safety in general also must be considered. When a society has little tolerance for the occurrence of fires or other accidents, this has a direct effect on what is considered to be a reasonable or acceptable level of risk.

The Rationale for Performance-Based Codes

Unlike prescriptive codes, performance-based codes address an individual building's unique aspects or uses; specific "stakeholder" needs; and in some instances, the broader community's needs. They provide the basis for the development and selection of alternative fire protection options, based upon the needs of the specific project, rather than the broad occupancy classification. Performance-based design, the implementation or application of performance-based codes, results in a fire protection and life safety strategy in which fire protection systems are integrated, rather than designed in isolation.

ICC PERFORMANCE CODE FOR BUILDINGS AND STRUCTURES

Note: The major elements of the ICC *Performance Code* and the NFPA 101® are summarized in Job Aid 1.1 at the end of this unit.

The overall purpose of the ICC *Performance Code for Buildings and Facilities* is to provide appropriate health, safety, welfare, social, and economic value while promoting innovative, flexible, and responsive solutions that optimize the expenditure and consumption of resources. This code contains both "building" and "fire" sections.

The Building Section

The intent of the building section of this code is to provide a reasonable level of heath, safety, and welfare, and to limit damage to property from events that are expected to affect buildings and structures.

The code intends buildings to provide for

- an environment free of unreasonable risk of death and injury from fires;
- a structure that will withstand loads associated with normal use and of the severity associated with the location in which the structure is constructed;
- means of egress and access for normal and emergency circumstances;
- limited spread of fire, both within the building and to adjacent properties;
- ventilation and sanitation facilities to maintain the health of occupants;
- natural light, heating, cooking, and other amenities necessary for the well being of the occupants; and
- efficient use of energy.

The Fire Section

The intent of the fire section of the code is to establish requirements necessary to provide an acceptable level of life safety and property protection from the hazards of fire, explosion, or dangerous conditions, in all facilities, equipment, and processes.

Performance-based codes generally follow a five-part format, beginning with a goal statement that establishes the intent. Next are one or more functional objectives that set out the functions necessary for achieving the goal. Third is the performance criteria, which is used to judge or evaluate compliance with the objectives. Finally, verification methods and acceptable solutions are addressed in the administrative requirements.

Example of Performance-Based Code Elements

- **Goal statements,** e.g., "Safeguard people from injury due to structural failure."
- **Functional objectives**, e.g., "A building is to be provided with safeguards to prevent fire spread, so that occupants have time to evacuate to a safe place."
- **Performance criteria**, e.g., "The deflection of reinforced concrete structural members shall not exceed that permitted by American Concrete Institute 318."
- **Verification methods**, e.g., test methods, fire effects models, previous acceptance.
- **Acceptable solutions** "deemed to satisfy" approaches, usually prescriptive approaches from prior codes.

Building Owner Responsibilities

Under the provisions of the ICC *Performance Code for Buildings and Facilities*, the building owner is responsible for retaining and furnishing the services of the design professionals and for the costs of any special services, including contract or third-party reviews and inspections required by the AHJ. The building owner also must retain all required documents and reports on the premises, and is required to operate the building in accordance with the approved design throughout the life cycle of the building.

Design Professional Responsibilities

The design professional is an individual who is registered or licensed to practice his or her respective design profession as defined by the statutory requirements of the professional registration laws of the State or jurisdiction in which the project is to be constructed. The design professional must possess the required knowledge and skills to perform design, analysis, and verification in accordance with the code requirements and applicable standards of practice.

Design professionals may include architects, civil engineers, mechanical engineers, and fire protection engineers.

The design professionals and special experts must be able to apply performance requirements; provide appropriate analysis, research, computations, and documentation; use authoritative documents and design guides; and review the completed construction elements to verify compliance with the prescribed design.

Design Documentation

All design documentation must be prepared by the design professional. Required documentation includes a concept report, design report, and an operations and maintenance manual. Details of these documents will be discussed later in this course. The design professional must coordinate all plans and documents for consistency, compatibility, and completeness, and submit them to the AHJ for review and approval.

The AHJ is obligated to perform a "knowledgeable" review of the proposed design and is permitted to use a third-party or peer review. When such third-party or peer review is used, the cost for that service may be passed on to the submitter. Once the plans and specification have been reviewed and approved, a permit may be issued for the start of construction. During the construction process, inspections and tests must be conducted in accordance with the design documents, AHJ procedures, and applicable codes. Upon completion, acceptance testing must be undertaken prior to occupancy.

Upon completion of the project and acceptance testing, the design professional must prepare and submit to the AHJ documentation that verifies that all performance and prescriptive code provisions have been met. The AHJ is permitted to require a third-party or peer review of this documentation as well. Upon completion of construction, final inspection, and testing and submission of all required documentation, the AHJ must issue the certificate of occupancy. A temporary certificate of occupancy may be issued for a limited timeframe with specified conditions, provided all life safety items are accepted. The AHJ also may require that a temporary certificate be issued for a specific period of time and/or be "renewable" on a periodic basis.

The owner is responsible for proper maintenance and operation of the building, in accordance with the "Operations and Maintenance Manual," throughout the life of the building. Unfortunately, this important requirement often is overlooked.

The building owner also is responsible for verifying compliance with the approved design at a frequency approved by the AHJ. Documents verifying that the building, facilities, premises, processes, and contents are in compliance with the approved design documents must be filed with the AHJ. The requirements for the development of this "owner's manual," and the inspections necessary for continued maintenance and operation of a performance-based design building will be discussed in more detail later in this course.

Design Changes

When a building that was designed and constructed using a performance-based design is remodeled or altered, or its use changes, a design professional must evaluate the existing building and applicable documentation. Any change that results in an increase in hazard or risk must undergo a full evaluation of design. The review and evaluation must be documented in a written report and submitted to the AHJ for review and approval. Such written review must be submitted to the AHJ even when the proposed changes do not exceed the original conditions. Changes in use or occupancy of a performance-based design building will be discussed in more detail later in this course.

Building Use

Under the provisions of the *ICC Performance Code for Building and Facilities*, the development of the acceptable level of design is based upon the building use (use or occupancy group), risk factors, and magnitude of events. The primary use of a building is based upon the principle purpose or function and the hazard-related risks to the users. The use and occupancy groups employed in the traditional prescriptive codes (A, E, I, M, H, etc.) may be used as a basis for assessing principal purposes or functions under the performance code.

Performance Groups

Use group and hazard-related classifications are then combined into a "performance group." The performance group classifications reflect the relative importance to the community of protecting the building or facility.

The performance groups follow.

- Group I--Buildings and facilities that represent a low hazard to human life in the event of failure. This group includes agricultural facilities, certain temporary facilities, and minor storage facilities.

- Group II--All buildings and facilities except those classified as Group I, III, and IV.

- Group III--Buildings and facilities that represent a substantial hazard to human life in the event of failure. This group includes buildings where more than 300 people congregate in one area; schools or day care centers with a capacity greater than 250; jails and detention facilities; and public utility facilities.

- Group IV--Buildings and facilities designed as essential facilities. This group includes fire, rescue, and police stations, power generation facilities, and buildings and facilities containing highly toxic or explosive materials.

Tolerated Damage

Each building also must be evaluated in terms of how the building is expected to perform under varying load conditions. Each magnitude of event must be based upon realistic event scenarios and not exceed the maximum level of damage to be tolerated, based upon the performance group classification.

There are four maximum levels (impacts) of tolerated damage.

Mild Impact

At the mild impact level, there is no structural damage and the building is safe to occupy; injuries are minimal in number and minor in nature; damage to the building and contents is minimal in extent and minor in cost; and minimal hazardous materials are released to the environment.

Moderate Level Impact

At the moderate level, there is moderate, repairable structural damage, and some delay in re-occupancy can be expected; injuries may be locally significant, but generally moderate in numbers and in nature; there is low likelihood of a single life loss and very low likelihood of multiple life loss; and some hazardous materials are released to the environment, but the risk to the community is minimal.

High Impact

At the high impact level, it is expected that there will be significant damage to structural elements, but with no falling debris. Significant delays in re-occupancy can be expected. Nonstructural systems needed for normal building use also are damaged significantly and inoperable. Emergency systems may be damaged, but remain operational. Injuries to occupants may be locally significant with a high risk to life, but are generally moderate in numbers and nature. There is a moderate likelihood of a single life loss, with a low probability of multiple life loss. Hazardous materials are released to the environment with localized relocation required.

Severe Impact

With severe impact, there will be substantial structural damage, and repair may not be technically possible. The building is not safe for re-occupancy, as re-occupancy could cause collapse. Nonstructural systems for normal use may be completely nonfunctional, and emergency systems may be substantially damaged and nonfunctional. Injuries to occupants may be high in number and significant in nature. Significant hazard to life may exist. There is a high likelihood of single life loss and moderate likelihood of multiple life loss. Significant hazardous materials are released to the environment, with relocation needed beyond the immediate vicinity.

The magnitudes of events to be considered are classified as small, medium, large, and very large. No specific definitions of these terms are provided in the ICC *Performance Code for Buildings and Facilities*. The stakeholders themselves must define and agree upon these terms.

International Code Council Parts

Part II of the ICC *Performance Code for Building and Facilitie*s addresses building issues. These chapters include Stability, Fire Safety, Pedestrian Circulation, Safety of Users, Moisture, Interior Environment, Mechanical, Plumbing, Fuel Gas, Electricity, and Energy Efficiency.

Part III addresses fire issues. These chapters include Fire Prevention, Fire Impact Management, Means Of Egress, Emergency Notification, Access and Facilities, Emergency Responder Safety, and Hazardous Materials. Each chapter contains objectives, functional statements, and performance requirements. Remember that the verification methods and acceptable solutions criteria are established in the administrative chapter.

Part IV contains various appendices, risk factors of occupancies, worksheets, and minimum qualifications of design team members.

Summary of International Code Council Performance Code Provisions

The application of the provisions of the ICC *Performance Code for Buildings and Facilities* can be summarized in the following procedural steps:

1. Concept report development.
2. Design preparation.
3. Coordination and verification with other stakeholders.
4. Submission of plans and supporting documents to the AHJ.
5. Plan review by the AHJ and/or third party.
6. Verification that applicable prescriptive and performance-based objectives are met.
7. Permit issuance.
8. Construction in accordance with approved plans and documents.
9. Inspections during construction by AHJ and/or third party.
10. Acceptance testing and fire protection system commissioning.
11. Issuance of a Certificate of Occupancy.
12. Continual maintenance, inspections and verification of conditions.

THE NFPA 101® *LIFE SAFETY CODE* AND NFPA 5000, *BUILDING CODE*

Unlike the ICC *Performance Code for Building and Facilities*, which addresses all types of building issues, the provisions of NFPA 101®, Chapter 5, "Performance-based Option," address only those issues related to "life safety systems." The provisions of NFPA 5000, Chapter 5 also apply to life safety issues.

This design approach is based upon a life safety evaluation which is a written review dealing with the adequacy of life safety features relative to fire, storm, collapse, crowd behavior, and other related safety considerations.

The performance-based design must be prepared by a person with qualifications acceptable to the AHJ. The AHJ is permitted to require an approved, independent third-party review of the proposed design, and to be provided with an evaluation of the design. All data sources are required to be identified and documented. The AHJ is empowered to make the final determination as to whether the performance objectives are met.

Both design specifications and other conditions used in the performance-based design must be clearly stated and shown to be realistic and sustainable. The characteristics of the building or its contents, equipment, or operations that are not inherent in the design specifications, but that can affect occupant behavior or the rate of hazard development are required to be identified explicitly. The anticipated or expected performance of a fire protection system and building features also must be documented.

In addition, the "occupant characteristics" selection must be approved by the AHJ and must reflect the expected population of building users. Response characteristics of the occupants shall include their sensibility (sensory awareness), reactivity, mobility, and susceptibility. Sources of data for these characteristics must be documented. It also must be assumed that in every normally occupied room or area, at least one person will be located at the most remote point from the exits. The design also must reflect the maximum number of people contained in every occupied room or area.

In those instances where the ability of trained employees (occupants) is part of the overall performance design concept, the number of employees, their training, and ability shall be identified and documented.

Under the provisions of NFPA 101® and NFPA 5000, the availability, speed of response, effectiveness, roles, and other characteristics of emergency response personnel may be considered. When such factors are part of the performance design, these factors must be specified, estimated, or characterized sufficiently for the evaluation of the design.

Design Fire Scenarios

A fire scenario is a set of conditions that define the development of fire, the spread of combustion products throughout a building or portion of a building, the persons' reactions to fire, and the effects of combustion products on people and facilities. A design fire scenario is one that is used for the evaluation of a proposed design.

NFPA 101® and NFPA 5000 require that all design fire scenarios be approved by the AHJ. Each design fire scenario must be evaluated using a method acceptable to the AHJ. Further, each scenario must be challenging but realistic, with respect to at least one of the following: initial fire location, early rate of growth of fire severity, and smoke generation. The scenario specifications must be as challenging as any that could realistically occur in the building.

NFPA 101® and NFPA 5000 provide eight design fire scenarios that are to be considered, unless the scenario is demonstrated by the design team to be inappropriate for the building and use conditions. The designs to be considered are

Design Fire Scenario #1 is an occupancy-specific design representative of a typical fire for the occupancy. The scenario must account explicitly for the occupant activities, number and location of occupants, room sizes, furnishings and contents, fuel properties and ignition sources, and ventilation conditions.

Design Fire Scenario #2 is an ultra-fast developing fire in the primary means of egress with all interior doors open at the start of the fire. The scenario must address the reduction in the number of available means of egress.

Design Fire Scenario #3 is a fire that originates in a normally unoccupied room and that has the potential to endanger a large number of occupants in a large room or area.

Design Fire Scenario #4 is a fire that originated in a concealed wall or ceiling space adjacent to a large occupied room. The scenario must address a fire originating in such space that is not equipped with either a detection or suppression system, and the spread of such fire into the room within the building that can hold the greatest number of occupants.

Design Fire Scenario #5 is a slowly developing fire that is shielded from fire protection systems and is in close proximity to a high occupancy area. The scenario must address the concern regarding a relatively small ignition source causing a significant fire.

Design Fire Scenario #6 is the most severe fire resulting from the largest possible fuel load characteristic of the building. This scenario must address a rapidly developing fire with occupants present.

Design Fire Scenario #7 is an outside exposure fire which addresses concerns of a fire originating at a location remote from the area of concern and either spreading into the area, blocking escape from the area, or developing untenable conditions within the area.

Design Fire Scenario #8 is a fire originating in ordinary combustibles in a room or area with each passive or active fire protection system rendered ineffective. This scenario must address the concern regarding each fire protection system or fire protection feature, considered individually, being unreliable or becoming unavailable.

Selection of design fire scenarios also must be acceptable to the AHJ. The selection of appropriate design fire scenarios will be discussed in more detail later in this course.

The Operations and Maintenance Manual

Like the ICC *Performance Code for Building and Facilities*, the provisions of the NFPA 101® and NFPA 5000 provide for the continued use and maintenance of a performance-based design facility. Each building or facility designed and constructed using a performance-based design relies on certain conditions remaining stable throughout the life of the building.

The Operations and Maintenance (O&M) Manual documents agreements with stakeholders and clearly states that the building owner must ensure that the components of the performance-based design remain in place and in proper operating condition.

The Manual provides instructions that restrict building operations, and communicates to the building tenants and occupants their responsibilities and the limits of building use. The Manual provides a guide to tenant renovation, and documents what actions are to be taken if a fire protection system is impaired or removed.

The Manual also will specify the requirements for the periodic recertification of the performance-based design. A sample O&M Manual is shown in Job Aid 6.2.

Fire Effects Models

One tool that might be used in performance-based design is fire modeling. Fire modeling, by definition, is a structured approach to predicting one or more effects of a fire. Fire effects models can involve an interdisciplinary consideration of physics, chemistry, fluid mechanics, heat transfer, biology, toxicology, and human behavior. Each model requires the specification of a complete fire scenario. Fire modeling may be either hand or computer calculated, or involve actual fire testing. Additional information regarding fire modeling review and approval will be covered later in this course. This course will **not** teach you how to perform fire effects modeling.

NFPA 101A, *GUIDE ON ALTERNATIVE APPROACHES TO LIFE SAFETY*

NFPA 101A was developed in 1988 to provide alternative approaches to **life safety** only. It evolved from, and must be used with, NFPA 101®.[5]

Instead of the phrase "alternate methods and materials," NFPA 101® allows "equivalency concepts" when the AHJ approves the equivalency. The design professional can use NFPA 101A assessment methods as part of the technical documentation submitted to the AHJ for evaluating "equivalency concepts." NFPA 101A provides an alternate to fire effects and evacuation models as a means of achieving life safety in various occupancies.

The evaluation process is known formally as Fire Safety Evaluation System (FSES). It is a method to quantify (count) safety features in a building to compare them to the level of life

[5] For alternative building fire protection features, NFPA 101A recommends using the "Systems Concept for Building Firesafety" found in the 18th Edition of the NFPA *Fire Protection Handbook*, and "Hazard Calculations" and "Fire Risk Ranking" in the SFPE *Handbook on Fire Protection Engineering*.

safety mandated in NFPA 101®.

Values for different "risk parameters" and "safety parameters" are tallied on worksheets or inserted into a computerized database, and the product is compared to a similar type of occupancy that meets the requirements of NFPA 101®.

Within NFPA 101A separate evaluation procedures are established for health care, detention and correctional, board and care, and business occupancies. The document also provides guidance on the uses of computerized fire safety evaluation system for business occupancies.

The following provides a sample of the risk and safety parameters evaluated in a health care facility:

Risk Parameter Factors	Safety Parameter Factors
• Patient mobility status • Location of smoke zones • Ratio of patients to attendants • Patient average age • Number of patients per smoke zone	• Types of construction • Interior finishes • Fire protection/detection systems • Smoke control • Vertical opening protection

Figure 1-2
NFPA 101A Sample Risk and Safety Parameters

In the first item, patient mobility status, patients are "scored" in one of four categories: mobile, limited mobility, not mobile, not movable. As the risk increases from mobile to not movable, the corresponding "deficiency" points are assigned.

Likewise, in the fire protection safety category, scores are assigned based on no sprinklers, corridor and habitable space sprinklers only, and complete fire sprinkler protection. All things being equal, as the level of sprinkler coverage increases, the risk decreases.

While NFPA 101A provides an organized method for evaluating life safety, it should not be considered a substitute for a complete fire and life safety analysis as part of a performance-based design.

"SMART" CODES

Another method of alternative design is the so-called "smart" building code. Smart codes began in New Jersey, were adopted in Maryland, and are being considered in other cities and States as a means to rehabilitate existing buildings without requiring compliance with the latest editions of building and fire codes. Smart codes are prescriptive, and very detailed.

The New Jersey "smart code"--the Rehabilitation Subcode of the Uniform Construction Code--was an *Innovation in American Government* 1999 national award winner with three major organizations: The Ford Foundation, The John F. Kennedy School of Government at Harvard University, and The Council for Excellence in Government.

Smart codes appeal to policymaking bodies because they help minimize costs when restoring older buildings. Legislators are anxious to rehabilitate existing building stock and make it viable. Since the model building codes are intended primarily for new construction, the cost of retrofitting or remodeling an old structure to meet current building codes often is prohibitive and may result in abandoning a project. Costs increase when applying energy conservation or barrier-free requirements to existing structures.

Smart codes are intended to allow a certain amount of repair, renovation, alteration, or reconstruction without requiring full compliance with the current building code. Based on the type of occupancy, they provide specific requirements--and exceptions--without lessening life safety and fire protection below a legally established minimum.

Unlike the model building codes, a proposed change of occupancy does not trigger full compliance with the current edition of the adopted building code. In New Jersey, for example, if a structure has been occupied for more than one year, it may comply with change of use requirements of the "Rehabilitation Subcode" rather than the entire Uniform Construction Code that applies to new buildings[6].

The "Subcode" employs a "Relative Use Group Hazard" table to assess requirements. If an occupancy moves **up** from one use group to another, it must comply with all of the so-called "basic requirements" of the subcode. If it stays within the same level, or goes **down**, no changes are necessary except those specifically listed in the subcode. The figure below is from the New Jersey "Rehabilitation Subcode." The occupancy classifications in the right hand column are the same as those found in the model building codes.

Relative Use Group Hazard	
1 (highest)	H-1, H-2, H-3
2	A-1, A-2, H-4, F-1, I-3, M, S-1
3	A-3, A-5, B, F-2, I-2, R-1, S-2
4	A-4, E, I-1, R-2 more than two stories in height or more than four dwelling units
5 (lowest)	R-2 two stories or fewer in height and four dwelling units or less, R-3, R-4, U

Figure 1-3
Relative Use Group Hazard
New Jersey "Rehabilitation Subcode"

[6] "Uniform Construction Code, Rehabilitation Subcode." Title 5, Chapter 23, Subchaper 6.31--Change of Use.

LEGAL ISSUES IN PERFORMANCE-BASED CODES AND DESIGNS

The legal implications of performance-based designs and codes cannot be ignored. Given our society's current litigious ways, it is reasonable for an AHJ to be concerned about both the jurisdictions' and individuals' personal liability exposure.

As with the enforcement of prescriptive codes, there is nothing the AHJ can do in the performance-based environment that will insulate him or herself--or the jurisdiction--from tort liability lawsuits. If a person feels aggrieved and wants to sue, there is nothing to stop him or her. However, the risk of successful prosecution and the collection of damages can be managed effectively, especially if the AHJ follows nationally recognized procedures for evaluating performance-based designs. Risk increases substantially when someone deviates from professional standards: by sticking to those review and approval steps that have been recognized by a consensus process, the AHJ is less susceptible to be found negligent.

When States or municipalities adopt one of the existing model prescriptive building code packages (building, fire, mechanical, and plumbing), the opportunity exists for approving alternate materials and methods of design. Responsibility for that approval lies with the AHJ.

It is important to realize what "approval" really means. It does not mean the official agrees the alternate design will work. It may not even mean the official has made an independent judgment that the alternative complies with the code. Generally it implies the building or fire official is satisfied that the proponent has conducted a reasonable investigation and put forth a reasonable explanation of how and why the alternative meets the code requirements.

A governmental agency may choose to adopt the ICC *Performance Code for Buildings and Facilities* as an adjunct to its prescriptive code, thereby giving the community a nationally recognized procedure by which it will evaluate both performance-based designs and alternate methods and materials.

Unfortunately, in the United States, the widespread understanding, use, and recognition of performance-based design and codes has not yet been achieved. Therefore, there is little "case law" by which the courts can establish precedent and define the bounds of professionally responsible conduct or decisionmaking.

Suing building officials over the building code does not seem to be a big industry, but there is some useful case law that applies directly. For example, a survey of Massachusetts from 1937 through 1995 (published in 1996) found 117 building code cases where a building inspector was a party to the case. In 81 of those examples (69 percent), the inspector was a defendant. Of the 117 cases, 104 involved zoning. That leaves only 13 where the building code was part of the dispute, a rate of about one case every 4-1/2 years. Some of those nonzoning cases involved administrative issues (like granting or denying a building permit) rather than interpretations or applications of the codes. Often the litigated denial was based on something other than technical provisions of the code[7].

[7] Elovitz, Kenneth M., P.E., Energy Economic, Inc., Foxboro, Massachusetts. Mr. Elovitz also is in-house counsel for the firm.

Building inspectors who rightfully denied applications for building permits on technical grounds have been upheld. For example, see *Karl V. Wolsey Company, Inc*. v. *Building Inspector of Bedford*, 324 Mass 419, 86 NE2d 644 (1949).

Courts also have legitimized performance-based alternatives and an inspector's acceptance of them. The case of *Krupp* v. *Building Commissioner of Newton*, 325 Mass 686, 92 NE2d 242 (1950), addressed a challenge by neighbors of three proposed steel framed houses. The building inspector accepted the design as adequate even though the steel to be used in the houses was not so thick as specified by city ordinances. The plaintiffs claimed that permitting the alternative design undermined the ordinance and should not be allowed. The court disagreed, effectively legitimizing equivalency provisions in building codes.

Building and fire officials must remember that legal liability is established only by the courts, and then only after all the facts are heard. Code enforcement officials should not be so "hung up" by liability concerns that they render themselves ineffective. Generally, the courts have held that as long as code officials act within the scope of their training and authority, they cannot be found liable unless they allow something entirely outside the realm of reasonableness.

Likewise, unless provided by a court, legal opinions are just that: one person's opinion of how a code or law is interpreted. Many of the points discussed below will reveal there are at least "two sides to every issue." Don't confuse "technical" issues with "legal" issues. Technical issues include those matters that are the responsibility of the AHJ: interpreting and enforcing the codes. If an issue arises that involves legal interpretations, the AHJ should seek competent legal counsel.

Some of the potential concerns the AHJ might want to consider:

- Until a history of case law becomes established, legal "liability" may be more loosely defined. In a prescriptive environment, it's generally easy to point to a section of a building or fire code and prove whether the requirement was met or not. For example, if a building code prescribed that the maximum rise for interior stairs shall not exceed 7 inches--and a code official allowed 8-3/4-inches--the code official likely would be hard pressed to justify that decision. Performance-based codes, by their nature, do not employ those specific requirements and therefore are open to broader interpretation.

  However, there is plenty of case law that says violations of regulations and statutes are either negligence **per se** or evidence of negligence (depending upon the jurisdiction). In either case, the plaintiff must show that the violation was the cause of the injury. There is no code or statute that says the building official must find all the construction errors in a building.

  This example illustrates how performance-based codes are more flexible for everyone. To prove violation of a performance-based code, the plaintiff would have to show that the 8-3/4-inch rise actually was a problem that impeded egress. To find the building official liable, the plaintiff also would have to show that the building official either ignored the 8-3/4-inch rise, or was aware of it and failed to apply appropriate judgment in accepting or rejecting it.

- Unethical, uninformed, or inexperienced design practitioners who do not understand performance-based design or intentionally manipulate test or model results to achieve their desired outcome may create confusion for the AHJ. It is easy to imagine how a AHJ who has never seen the product of a sophisticated evacuation model might be overwhelmed by the reams of data and mathematical calculations submitted to justify it. The code official is not expected to be able to design such a system. The code official also is not necessarily expected to understand all the sophisticated ins and outs of the modeling. The code official is expected to ask enough questions and require enough explanation from the proponent to be satisfied that the proponent understands the proposed design and that the proponent's reasoning makes sense. In any type of professional liability situation, professionals (designer or code official) legally are not required to be "correct." They are expected only to exercise reasonable judgment in evaluating the situation.

- Uninformed or inexperienced AHJ's may not have adequate skills to assess the design philosophy, engineering documentation, and performance outcomes expected in the modern design. Regular, continuing education on performance-based design, fire effects and evacuation modeling, alternate means of design and construction, and legal expectations must be part of every AHJ's career path. This is the same for performance-based codes or prescriptive codes.

- The AHJ should not feel pressured to accept a design or construction detail about which he or she has doubts. Simply because something is a "performance-based design" accompanied by glossy drawings and thick booklets of calculations does not mean it necessarily provides an improved level of life safety and fire protection.

  The AHJ does not need to have a full understanding of all the details of the design. The AHJ simply needs to be satisfied that the project proponent has thought through the process, applied reasonable judgment, and reached sensible conclusions. If someone is proposing a new material that uses plywood half as thick as that used conventionally, the AHJ only has to ask how it can be justified. The AHJ does not have to understand all the calculations or be able to repeat them independently. The AHJ simply must be satisfied that the proponent's approach makes scientific sense.

  Another big consideration here is the possibility that courts will consider questions like these unresolved or more than extensions of existing law. In that case, courts should look for guidance on what the industry thinks the liability is. Industry practice is a common yardstick by which unresolved legal questions are answered.

- Performance-based construction requires a substantial amount of sophisticated understanding of the goals and objectives included in the design. Assuring that the final construction elements comply with the intended outcome can be a daunting task. If the AHJ does not want to accept that responsibility, he or she can require third party "verification" of design and construction details. The administrative chapter of the ICC *Performance Code for Buildings and Facilities* describes the code official's authority to obtain contact or peer review. This may reduce some of the jurisdictions' and individuals' liability exposure--as long as the third party service is qualified.

- The AHJ may not be "authorized" to grant alternative schemes or construction features often employed by performance-based designs. In some jurisdictions, only the legislative body (i.e., council, commission, board, legislature) may adopt or amend building and fire codes. If the AHJ is left to assess each permit against some nonprescriptive options, this may be construed as exceeding his or her scope of authority.

  Likewise, if the AHJ wants to use third-party verification or inspection services, local legislation may have to be created to allow this practice. In both the United Kingdom and New Zealand, laws allow "private building surveyors" or "building certifiers" to act on behalf of the jurisdiction.

  Cities and towns need not be reluctant to hire architects and engineers as consultants in situations where their code officials need outside expertise. Another approach is for the code to require project proponents to submit independent engineering review of sensitive aspects of performance-based designs. Some building codes already require independent structural review of certain building designs.

- Failure to require an operations and maintenance plan or manual that makes it clear the conditions established during the design and construction must be maintained by the owners and occupants for the life of the building might affect liability. Ongoing protective inspections of performance-based occupancies will require specialized knowledge and training. This may be another opportunity for the jurisdiction to consider the use of third-party inspection or verification services to lessen municipal liability exposure.

  (It is interesting that in the United Kingdom, some third party services originally had a difficult time obtaining their own liability insurance to cover their risks in inspection services[8]. This may be a consideration for AHJ's in the United States who want to take advantage of third-party services.)

- Uninformed or inexperienced dispute resolution bodies, such as the Board of Code Appeals, may render interpretations and decisions contrary to professional engineering or good fire safety standards. The dispute resolution procedure must be careful to achieve the "correct" decision in terms of life safety and fire protection, and not look for one that simply is a "compromise." The AHJ should make an effort to educate these groups before they must review a complex performance-based design and make decisions on its future.

- The "statute of limitations" for liability may be a problem until case law and precedent are established. The courts will have to decide how long after approval and construction an owner or jurisdiction are liable for the decisions their representatives make. In Australia, building owners are liable only during a 10-year period after initial occupancy of the building.[9] The long-term liability of the permitting authority is not decided yet.

[8] "Report of the Second Workshop on Legislative and Liability Issues." May 26, 1997, National Research Council, Ottawa, Canada, p. 2.

Every State already has a statute of limitations. Courts have little problem applying them. The usual issue is trying to figure out when the plaintiff "knew or should have known" of the defect to start the statute of limitations clock running. Most States have "statutes of repose" that cut off all tort liability after a certain period of time. Courts in 35 of those States have upheld the statutes, and eight had been overturned. Statutes of limitation and repose need not be a big concern.

- "Sovereign immunity," the legal concept that a jurisdiction is immune from liabilities when performing a governmental function, also may be in jeopardy with performance-based designs. Generally, jurisdictions are protected from liability because the governmental unit does not have a "special duty" to a protected class or group of individuals. In other words, the government is there for **everyone**, not a select few.

  However, with performance-based designs, the jurisdiction may be creating a "special relationship" with one or more stakeholders in a project when it accepts a final design, especially if it involves a strategy that includes fire department service levels as a key component of the overall design. Once a special relationship exists, the courts may insist that the jurisdiction has a special duty to act on behalf of the property owner in an emergency.

  Additionally, this special duty may prevent a jurisdiction from closing, moving, or re-assigning companies and personnel from a fire station if the performance-based design relies on these features.

  Municipalities are given wide latitude in their governmental powers. Moving or reassigning personnel may be the type of planning or policymaking discretionary function that is exempt from tort liability in almost every jurisdiction.

  The 1992 case of *Harry Stoller & Co.* v. *Lowell*, 412 Mass. 139 (1992) made a big splash in the trade press, and the firefighting community roundly criticized the Massachusetts court for holding that certain decisions made on the fireground are **not** the type of discretionary functions that the public duty doctrine protects.

  The firefighting community protested that the court had taken all protection away from firefighters. That's not what happened. The holding was rather narrow. "The jury decided that, in exercising their discretion not to use the buildings' sprinkler systems, the Lowell firefighters were negligent because they failed to conform to generally accepted firefighting practices."

  The court also stated, "There are aspects of firefighting that can have an obvious planning or policy basis. The number and location of fire stations, the amount of equipment to purchase, the size of the fire department, the number and location of hydrants, and the quantity of the water supply involve policy considerations, especially the allocation of financial resources. In certain situations, firefighting involves determinations of what property to attempt to save because the resources available to combat a conflagration are or seem to be insufficient to save all threatened

[9] Ibid, p. 7

property. In such cases, policydeterminations might be involved, and application of the discretionary function exception would be required."

It is important to remember that even when the case turns on the ministerial/discretionary function question, the liability cap that many States impose on charitable or municipal organizations remains in place. The original $850,000 jury verdict in this case was cut to $100,000 because of that limit.

It is well to remember that the special relationship situations are fairly narrowly carved-out exceptions in many States. Performance-based designs are not so uncontrollable or so sophisticated that they create a special relationship between the municipality, the code official, or any individual member of the public. Performance-based codes and designs are fundamentally no different from existing prescriptive-based codes (which almost all contain equivalency provisions) so do not create a special relationship where none exists under present practice.

- How might construction deviations from the approved plans and design documents affect the agency's liability? In the time between plan approval and the issuance of the certificate of occupancy, many changes might occur in the structure, layout, operations, and performance of the building's or facility's fire protection features. This is a common event, even under prescriptive codes, as architects and general contractors juggle the work of their subcontractors to get a project done.

  If a change in the project's details affects the final outcome, who is liable for approving the alteration or verifying its compliance with the overall performance-based design? Ideally, the fire protection engineer is charged with the responsibility for overseeing the project and evaluating the changes, but what if it is something seemingly inconsequential at the time of the change, or if it occurs without the engineer's knowledge?

- Adequate recordkeeping may be an issue for some jurisdictions. The detail and length of time that records must be maintained vary from State to State, and local community to community. Owners and other stakeholders might not maintain detailed records of all correspondence, plans, design briefs, construction details, operations and maintenance manuals, and related documents. Is it the jurisdiction's responsibility to do so? If "yes," in what form should those records be maintained, and for how long? Are they public records open to scrutiny, or a private "contract" between the owner and the community?

  Some legal authorities argue the records would **not** be a private contract between the owner and the community. Many cities and towns maintain copies of filed plans, and people who want them can get copies for a fee. Depending upon the jurisdiction, it may be an obligation or just a convenience.

Like the prescriptive codes, the provisions of the performance-based codes place the ultimate burden of compliance on the building owner. The performance-based code also clearly places the burden for the development and proper documentation of any performance-based design on the design professional. The AHJ has the responsibility of conducting a "knowledgeable

review." Given this, it is incumbent upon the AHJ to employ, either in-house or by some other means, qualified individuals to review performance-based designs.

Performance-based codes and designs are here to stay. AHJ's are obligated to entertain and evaluate any and all designs using performance-based codes, and treat them just as they would buildings designed in accordance with the traditional prescriptive code requirements.

Because the limits of liability exposure for public officials vary substantially from State to State, the AHJ should ensure that designs are reviewed by a knowledgeable professional and should discuss any specific questions with legal counsel. Sources of third-party reviewers can be

- consultants;
- peers;
- code reviewers;
- colleges and agencies; and
- code and standard organizations.

Whether a design is prescriptive or performance-based, the AHJ must ensure that it meets fire protection system standards.

SUMMARY

The development and proper evaluation of a performance-based design is time consuming, expensive, and extremely technical. Because of this, the application of the provisions of a performance-based code is going to be limited to those projects where compliance with prescriptive code provisions is difficult. The majority of ordinary projects will continue to be built using the traditional approach of the prescriptive codes.

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Activity 1.1

Introductions

Purpose

To introduce you to each other and to the instructors.

Directions

1. Select a partner you do not know.
2. Introduce yourself and ask your partner:
   a. What do you like to do in your life away from work?
   b. Where do you live/work?
   c. What experience have you had with building codes and with reviewing building designs and performance-based designs?
   d. What do you expect from this course?
3. In the space provided below, make notes on your partner's responses.
4. Reverse roles with your partner and repeat steps 2 and 3.
5. You will have 5 minutes for these introductions. Then you and your partner will introduce each other to the class.
6. Include in the introduction the information your partner provided.

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Activity 1.2

Examining Differences in Prescriptive and Performance Language

Purpose

1. To explore the ambiguities in the language of prescriptive and performance code requirements.

2. To demonstrate that performance requirements already exist in the model codes.

3. To lessen student anxiety regarding perceived differences between prescriptive and performance language.

Directions

Ten building or fire code requirements or statements are listed on the following page.

1. Based on the language in which the requirement is written, mark in the appropriate column whether you believe it is from a **prescriptive** or **performance-based** code.

2. Identify whether the requirement is **prescriptive** or **performance-based**.

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Activity 1.2 (cont'd)

	Prescriptive Code	Performance Code	Prescriptive Requirement	Performance Requirement
1. Open flames and high-temperature devices shall not be used in a manner which creates a hazardous condition.				
2. A barrier shall be provided where people could fall 30 inches or more from an opening in a wall or floor.				
3. Adequate illumination shall be provided appropriate to the use and occupancy of the habitable spaces and means of egress served.				
4. Fire alarm systems; fire hydrant systems; fire-extinguishing systems; standpipes; and other fire-protection systems and appurtenances thereto shall meet the approval of the fire department as to installation and location and shall be subject to such acceptance tests as required by the chief.				
5. Adequate safeguards shall be provided to minimize the risk of exposing combustible hazardous materials to unintended sources of ignition.				

	Prescriptive Code	Performance Code	Prescriptive Requirement	Performance Requirement
6. Live loads of 100 pounds per square foot or less shall not be reduced in public assembly occupancies.				
7. Means of egress shall be illuminated at all times the building is occupied with light having a minimum value of one footcandle at floor level.				
8. Fire alarm, suppression, and smoke management systems shall undergo commissioning testing when first placed into service or following any substantial alteration.				
9. Facilities shall be designed, constructed, and maintained to limit the fire impact to people and property.				
10. An automatic sprinkler system shall be provided in Group H occupancies.				

Activity 1.3

Selecting a Performance-Based Design

Purpose

To identify examples of and reasons for selecting a performance-based design.

Directions

1. Take 15 minutes to work as a group and brainstorm the following exercise.

2. You will identify five specific construction or fire protection projects that might employ performance-based design, and list reasons why.

   Example: The Minnesota Wild **arena** used a performance-based design because of its **unique characteristics** and **multiple uses**.

3. Use your imagination to think of potential projects. Your instructor has some suggestions to get you started.

4. Select a spokesperson and share your list and reasons with the class.

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Activity 1.4

Alternate Materials and Methods of Design

Purpose

To explore examples of "alternate methods and materials" (equivalencies) that might be permitted under prescriptive codes.

Directions

1. Take 30 minutes to work as a group and brainstorm the following exercise.

2. You are to propose at least two alternate materials or methods of design to achieve equivalent levels of protection for each of the scenarios provided where strict compliance with the prescriptive codes cannot be achieved. Use your imagination to think of potential solutions.

3. Select a spokesperson and share your list with the class for discussion.

Scenario 1

A property management firm owns a vacant 75,000-square-foot heavy-timber building that was constructed as a mill in the late 1880's. The exterior walls are tongue-and-groove wooden planks 1 inch thick and 8 inches wide. They are covered by beveled cedar siding. One exterior wall has about 10 percent of its surface area in the form of single-pane glass.

As part of a renovation project, the company wants to rehabilitate the building, and create "incubator suites," small spaces where fledgling companies can build their businesses. The spaces are separated from one another by 1-hour fire rated construction. The building will be sprinklered, and modernized to meet current fire and life safety codes.

During a site survey prior to building permit application, the owner learns that the wall with the windows is within 2 feet of the nearest property line. Under modern building codes, this would require a 4-hour rated firewall. This discovery could result in abandonment of the project if full compliance is required.

You are to suggest two alternate materials or methods of design to achieve equivalent levels of protection for this project.

Scenario 2

A local aluminum boat manufacturing firm has been highly successful, and is growing to meet the demand of your area's burgeoning commercial fishing fleet. Last year, the company won the mayor's "Up-and-Coming Business" Award.

The owners want to quadruple the size of their existing building. Currently, it is 38,000 square feet on a single level. The building is 40 feet from the slab floor to the underside of the roof. The building is entirely noncombustible: steel columns and trusses are covered by corrugated sheet metal walls and roof.

The boat-building process involves no flammable or combustible liquids, and only a small amount of compressed gases. The floor plan must be "wide open," however, to allow the boats in various stages of completion to be moved through the plant. The boats are fabricated on large, wheeled carts for ease of moving, and their size prevents the construction of fire separation walls.

During a survey, the design engineer discovers that the structural elements of the existing building are unable to support the loads imposed by a fire sprinkler system, which would be required because of the building's increased area.

Furthermore, the neighborhood's water supply lacks adequate pressure to support a sprinkler system.

You are to suggest two alternate materials or methods of design to achieve equivalent levels of protection for this project.

Activity 1.5

Assigning Performance Groups

Purpose

To examine how existing occupancy groups and divisions from the model building codes might be assigned into performance groups in the ICC *Performance Code For Buildings and Facilities.*

Directions

1. Take 15 minutes as a group and work on this activity.

2. Given the level of detail provided, you are to assign the 10 listed occupancies into one of the four building and facility performance groups identified in Table 303.1 of the ICC *Performance Code For Buildings and Facilities.* An example has been provided to get you started.

3. Write your answers in the column at the right.

4. Select a spokesperson and share your list with the class for discussion.

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Activity 1.5 (cont'd)

	Occupancy Description	Group Division	Performance Group
	Example: Hospital having surgery and emergency treatment facilities.	I-1	IV
1.	Two-story commercial laundry using less than the exempt amounts of flammable and combustible solvents.	F-1	_____
2.	Correctional facility operating 24 hours per day, but housing fewer than 25 inmates.	I-3	_____
3.	Theater with an occupant capacity of 1,923 persons and a legitimate stage.	A-1	_____
4.	1 million square-foot (92 900 m^2) warehouse for paper records storage, a Class III commodity, in cardboard boxes on racks 46 feet (14.02 m) high.	S-1	_____
5.	Explosives manufacturing plant with daily output of 10,000 pounds. (4536 k) of Division 1.2 explosives.	H-1	_____
6.	Six million gallon (22 710 000 l) potable and fire protection water storage tank for a community of 87,326 persons.	U	_____
7.	A 17,000 square-foot (15 793 m^2) office building that is entirely non-combustible, fully sprinklered with automatic smoke detection, and that is used as a winter weather shelter for itinerant families.	B	_____
8.	800,000 square-foot (74 320 m^2) covered shopping mall with no food court.	M	_____
9.	College classroom building with 40 classrooms, each capable of seating 65 students.	B	_____
10.	645,000 square-foot (59 920 m^2) noncombustible warehouse for storing mixed commodities (Class I and II) on pallets not more than 15 feet (4.57 m) high.	S-2	_____

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APPENDIX A

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Job Aid 1.1

Code Summaries

The ICC Performance Code for Buildings and Facilities	
Elements	**Objective**
Overall Purpose	Provide a reasonable level of health, safety and welfare, social, and economic value. Promote innovative, flexible, responsive solutions. Optimize the expenditure and consumption of resources
Building Section	
	Provide a reasonable level of health, safety, and welfare. Limit damage to property. Provide an environment free of unreasonable risk of death/injury from fire. Provide a structure that will withstand loads associated with normal use and of the severity associated with the location. Provide means of egress and access for normal and emergency conditions. Limit spread of fire within building and to adjacent properties.
Fire Section	
Overall Purpose	Provide an acceptable level of life safety and property protection from fire.
Owner Responsibility	Retain and furnish the services of the design professional. Provide costs of any third party reviews required by the AHJ. Retain required documents and reports on the premises. Operate the building in accordance with the approved design.
Design Professional Responsibility	Be registered or licensed to practice design profession as defined by statutory requirements of the State or jurisdiction. Possess skills to perform design, analysis, and verification in accordance with code requirements and applicable standards of practice. Review completed construction to verify design compliance. Prepare all design documentation for AHJ approval. During construction, ensure that inspections and tests are conducted according to the design documents. If the building is remodeled, altered, or its use changes, evaluate the existing building and documentation and submit a written report to the AHJ for approval.
AHJ Responsibility	Review documents, or have review conducted by a knowledgeable third party. After final inspection and testing and submission of required documents, issue certificate of occupancy.
Building Owner Responsibility	Maintain and operate building in accordance with the O&M Manual. Periodically verify compliance with the approved design. File with the AHJ documents verifying that the building, facilities, premises, process, and contents are in compliance.

Job Aid 1.1

Code Summaries (cont'd)

NFPA 101A, *Guide on Alternative Approaches to Life Safety*	
Code Elements	**Code Provisions**
Overall Purpose	Provide a formal, written procedure for the evaluation of alternative approaches to life safety in new and existing occupancies. Intended to be used in conjunction with NFPA 101®, *Life Safety Code.*
Design Review	Review of design by qualified professional approved by AHJ.
Data Sources	Data sources identified and documented.
Specifications and Conditions	Design specifications and conditions used in the design clearly stated and shown to be realistic and sustainable. Building characteristics, contents, equipment, or operations that can affect occupant behavior or the rate of hazard development explicitly identified. Expected performance of the fire protection system and building features documented.
Occupant Characteristics	Selection of occupant characteristics approved by AHJ. Response characteristics reflect sensibility, reactivity, mobility, susceptibility. Design assumes that at least one person in every normally occupied room or area will be at the most remote point from exits. Design reflects the maximum number of people each room or area will contain.
Training	If trained employees are part of the design concept, designers will identify and document • Number of employees. • Employees' training and ability.
Fire Scenarios	Evaluated using method acceptable to AHJ. Must be as realistic and challenging as any that could occur. Eight fire scenarios are suggested. (See Job Aid 3.1.)
Occupancies	Health Care, Detention and Correctional, Board and Care, Business.
Safety Parameters	Values are assigned for various building features, fire protection systems, and other life safety considerations.
Acceptability	Minimum values are established for containment, extinguishment, people movement, and general safety.
NFPA 5000, *Building Construction and Safety Code*	
Overall Purpose	Provide a formal, written procedure for the evaluation of alternative approaches to life safety in new and existing occupancies. Intended to be used in conjunction with NFPA 101®, *Life Safety Code.*

Job Aid 1.1

Code Summaries (cont'd)

Code Elements	Code Provisions
Design Review	Review of design by qualified professional approved by AHJ.
Data Sources	Data sources identified and documented.
Specifications and Conditions	Design specifications and conditions used in the design clearly stated and shown to be realistic and sustainable. Building characteristics, contents, equipment, or operations that can affect occupant behavior or the rate of hazard development explicitly identified. Expected performance of the fire protection system and building features documented.
Occupant Characteristics	Selection of occupant characteristics approved by AHJ. Response characteristics reflect sensibility, reactivity, mobility, and susceptibility. Design assumes that at least one person in every normally occupied room or area will be at the most remote point from exits. Design reflects the maximum number of people each room or area will contain.
Training	If trained employees are part of the design concept, designers will identify and document • Number of employees. • Employees' training and ability.
Fire Scenarios	Evaluated using method acceptable to AHJ. Must be as realistic and challenging as any that could occur. Eight fire scenarios are suggested. (See Job Aid 3.1.)
Occupancies	Health Care, Detention and Correctional, Board and Care, Business.
Safety Parameters	Values are assigned for various building features, fire protection systems, and other life safety considerations.
Acceptability	Minimum values are established for containment, extinguishment, people movement, and general safety.
NFPA 1, *Fire Prevention Code*	
Overall Purpose	Provide a formal, written procedure for the evaluation of alternative approaches to life safety in new and existing occupancies. Intended to be used in conjunction with NFPA 101®, *Life Safety Code*.
Building Owner Responsibility	Building must be maintained in accordance with approved design. Owner must certify to the AHJ on an annual basis that the building is being used in accordance with the performance-based design and all assumptions.

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Job Aid 1.2

Comparison of Prescriptive Designs and Performance-Based Designs

Prescriptive	Performance-Based
Based on empiricism and experience.	Based on fire science.
May result in redundancy, increasing cost.	Seek to reduce cost, without reducing safety.
Reflect legally prescribed fire safety standards.	Reflect stakeholder fire safety goals in conjunction with legally adopted code.
Most appropriate for design of structures that are not complex or unusual in terms of scope or use.	Most appropriate for design of complex structures with unique architectural features, but can be used for any building.
Describe solutions in quantitative terms.	Describe risk in qualitative terms.
Construction safety requirements are specific.	Construction safety requirements are stated in terms of the specific structure, its use, and the stakeholder goals.
Building is designed to meet generic fire safety standards related to building use over its expected life cycle.	Future use of building must be restricted in accord with design assumptions.
Fire safety construction requirements are specific.	Fire safety goals are performance based.
Liability issues are relatively straightforward due to already evolved case and tort law, and quantitative analysis of prescriptive requirements.	Liability issues are more complex and can depend on interpretation of the performance-based design.

SFPE Book #	ICC Perf. Code #	Name	Work Telephone

APPENDIX B

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Code Officials and Performance Based Fire Safety

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ABSTRACT

This paper will discuss some of the concerns that the Boston Fire Department has concerning Performance Based Codes and Performance Based Fire Safety Designs. There will be four areas of concern discussed: 1. Need for prescriptive rules on methodology; 2. Acceptable level of safety problem; 3. Maintenance/Enforcement problem; 4, Training and Education problem. For each area of concern, the problem will be introduced, examples will be provided, and possible solutions will be proposed.

THE LACK OF PRESCRIPTIVE RULES PROBLEM

The Problem

Performance based designs appear to rely on three sources of information: 1. A set of objectives (possibly from a performance based code); 2. A design guide (general rules on documentation and methodology); 3. Reference material (an engineering handbook). The problem with the use of this material is that it allows too much flexibility in the selection and use of critical items used in designs. A code official trying to use these documents to insure the safe design of buildings is analogous to a police officer trying to enforce a safe society by using books on philosophy and theology. These books may contain valuable information as to how one should conduct affairs but are also useless as a set of enforceable rules. These books might also be adequate in a society where everyone is well intentioned and are less useful in a society where human nature is less than perfect.

For example, performance criteria. Like many of the issues before us, are a troubling one for a code official. This is due to the fact that there is no consensus; the designer has the freedom to choose almost any tenability limits for which they can find a reference source. In fact, almost every design that we have seen has utilized different tenability criteria. The obvious reason why this becomes important is because by changing the tenability criteria, the time until untenable conditions may be changed to suit the engineer's needs with respect to the design. In doing so, one can artificially increase or decrease the available safe egress time.

Example

The two different criteria that were used in the "draft" and "final" version are listed below:

Table 1: Comparison of Tenability Criteria

Draft Boston High-Rise Tenability Limits	**Final Boston High-Rise Tenability Limits**
Upper layer at breathing height, 1.67 m	Temperature of 150ºC - less than 2 min.
	Radiant Flux of 25 kW/m^2
	CO of 2,000 ppm - less than 5 min. Visibility - 0.5 OD m"'

The reason for this change was never made clear by the designer but a consequence of the change was a drastic increase in the time available to exit the apartment. The need to increase the time available to egress the apartment was probably due to the fact that, in the final version, "reaction time" was taken into account. In the original "draft" report the Total Evacuation Time (Time to Detection + Egress Time) was less than the ASET (Available Safe Egress Time). Once a reaction time of 25 seconds was incorporated, at our insistence, into the Total Evacuation Time (Time to Detection + Reaction Time + Egress Time) the Total Evacuation Time often exceeded ASET. To get around this dilemma, the designers changed the assumptions. This type of flexibility is convenient for designers but as code officials, we find it troubling.

The engineer used his judgment and- considered all the correct factors as recommended by various design guides. So, what basis would I have to reject this criteria selection? No rules were broken. This is important due to the fact that traditionally, when we review plans, we are trying to find out if any rules were broken. What power do we have to insure safe building if there are no rules?

The proper use of safety factors is another area where there seem to be only general guidelines, as opposed to rules. It does not appear that any designs or models that we have reviewed are 100% accurate. As a consequence, it would seem prudent to utilize safety factors to offset the uncertainty. In actuality, many designs I have seen have not utilized any safety factor. Others have used safety factors of 1.5. All of these selections were based on "Engineering Judgment." In the SFPE Handbook, Pauls recommends that "...in relation to the Life Safety evaluation, there should be a factor of safety, especially in view of the incomplete technical grasp of both egress and fire issues at the present." For example, in a conservative approach, the "time available" should be at least twice as long as the "time required." [3] Despite this documented recommendation, one of the designs we reviewed stated: Jake Pauls method of doubling the occupant egress time is not commonly accepted or used for fire engineering analysis. For almost any engineering analysis you could find someone with an opposite analysis or result. [4] Do we have the right as a code official to reject this design based on this document?

Solution

We are willing to give designers freedom to choose different designs to achieve the same goal. However, we see no reason to allow freedom to pick any criteria and make any assumption that they can find a reference for in a technical handbook or peer reviewed journal. We understand that the occupant characteristics such as egress speed and reaction time as well as hazard criteria selected for an elderly housing complex will differ from the occupancy characteristics and hazard criteria for a high-rise office building. What we do not understand is why designers have the freedom to choose different occupant characteristics and hazard criteria for the same occupancy. It would seem to limit designers' freedom to create a prescriptive set of occupant characteristics and hazard criteria for different occupancy classifications. A guideline such as this would let us know when the assumptions made "break the rules."

We believe that a set of rules can also be developed for the selection of safety factors to deal with the uncertainty inherent in fire models. Several sources have estimated the accuracy of current methods at 10 to 30 per cent, when used with conservative inputs and within the limitations of the model. [5,6,7] The problem for code officials is to know when the designer has used the models correctly and even then, the code official does not know if the uncertainty is as low as 10 or as high as 30 per cent. Fortunately, the ASTM Standard Guide for Evaluating the Predictive Capability of Fire Models - 1994, has a standard to measure this predictability. This predictability is express as a percentage. In this guide it has been suggested that the predictive capabilities of a fire model may be expressed as percent accuracy. Other methods for presenting results of a sensitivity analysis are equally acceptable. [8]

Utilizing ASTM 1355-92, 1994, the predictive capability of models is suggested to be represented as % accuracy. This suggestion can be combined with an assumption that a typical safety factor should be approximately 2. The results are shown in Tables 2 and 3. Using these charts along with the documentation required by ASTM 1355 provides the code official with a much higher level of comfort than a safety factor whose sole justification is "Engineering Judgment" that is not typically peer reviewed.

Table 2:
Boston Fire Department Safety Factor Chart
Due to Uncertainty for Deterministic Timed Egress Analysis for
Moderate Hazard Occupancies, i.e. Business, Industrial

Potential		**10%**	**20%**	**30%**
in Egress Time	10%	1.5	1.75	2.0
Calculations	20%	1.75	2.0	2.25
	30%	2.0	2.25	2.5

***Uncertainty Safety Factor = (1+(potential error in ET)/(1-potential error in ASET).**

Table 3: Boston Fire Department Safety Factor Chart Due to Uncertainty for Deterministic Timed Egress Analysis For High Risk Occupancies. i.e. Nursing Homes Day Care

Potential Error in Egress Time Calculations		**Potential Error in ASET Calculations**		
		10%	20%	**30%**
	10%	2.0	2.25	2.5
	20%	2.25	2.5	2.75
	30%	2.50	2.75	3.0

***Uncertainty Safety Factor = (1+(potential error in ET)/(1-potential error in ASET).**

The actual rules that are eventually developed could differ from the examples provided here. The point is that a set of prescriptive rules, that a plans examiner can use in checking the validity of a design will make it much easier for a code official to review designs.

LEVEL OF SAFETY PROBLEM

Many code officials are concerned that without having a given "prescribed level of safety" designers will feel free to submit their own assumptions as to what constitutes an acceptable level as part of their design. The designer will not only produce a design, the designer would be able to set the criteria against which it will be measured, as well as the level to which those criteria are met. When a code official disagrees with the designer's choice as to what constitutes an acceptable level of safety, the official will be forced to argue the legal and political concepts as opposed to design issues. More than once we have found ourselves before state appeals boards facing arguments that had more to do with whether or not the code requirement(s) in question were appropriate, rather than facing arguments on whether the design met the intent of the code. In fact, after a presentation of a case study at a local chapter of the SFPE, by the designer on several designs reviewed by the Fire Prevention Division, a couple of audience members commented that one area that was never discussed was whether or not the code requirement should have been there in the first place. The reply was the issue was not raised because it was not a valid issue to raise during a plans review or an appeal of a given plans review.

Examples

The performance codes that I am aware of contain language similar to the following.

Objective. To protect occupants from injury or illness when evacuating a building during a fire…

Functional Statement. Buildings shall be designed with safeguards against the spread of fire so that: 1. Occupants have sufficient time to escape without being overcome by fire and smoke...

Performance Requirements. Automatic fire suppression systems, when provided as a means to controlling fire growth shall deliver sufficient suppression to suppress a fire (Many other performance requirements are typically listed).

The problem that a code official has in trying to enforce language of this type is that not only are there many different designs that can achieve these objectives, there are many different levels at which the objectives can be met. Battery powered smoke detectors protect occupants to one level of safety. Quick response sprinklers and interconnected alarm systems also protect occupants. On what basis do we reject one level of safety over another? All levels meet the objectives; they do not meet the objectives to the same extent. This is not a hypothetical concern. We recently had to argue a case in court in which one of the main arguments being used against us was that a design which relied primarily on detectors was claimed to be equivalent to a prescriptive requirements of the installation of an automatic sprinkler system. This was due to the interpretation that the design met the same objectives that the prescriptive code was meant to address.

Solution

To provide the flexibility in design with the minimum and prescribed level of safety we would like to propose the following language:

DEFINITION OF REASONABLE LEVEL OF SAFETY

A facility taking a performance approach to meeting the code requirements has reached a "reasonable level of safety" when, at a minimum, the design meets the objectives of the code for all of the people, including fire fighters and property to the same overall level[b] that the prescriptive approach intends to protect them.

Exception: In the case where the facility is utilizing a design or approach that is not anticipated by the prescriptive code, the performance approach must meet the objectives of the code providing the level of safety that is intended by the most applicable nationally recognized standard for similar occupant, process or hazard.

a. In cases where the design analysis identifies areas where the prescriptive code do not meet the objectives of the code by providing a reasonable level of safety, the performance approach must exceed the minimum level prescribed by the code. This is anticipated to achieve the reasonable level of safety.

b. For portions of a design that are deterministic, an alternative design will be determined to meet the same overall level of safety when the results or prediction of the analysis produces at least as safe a result as the prescriptive code. For portions of a design that probabilistic or deterministic design will be determined to meet the same overall level of safety when the result of prediction of the analysis produces an estimate of risk that is lower than the prescriptive code. Redundancy and reliability of the design options must be analyzed.

Designers seem to be concerned that any text that implies equivalency is merely the "alternative but equivalent" option allowed by the prescriptive codes. They argue that this text does not encourage alternative designs. I would argue that it is not the "equivalency" requirement that discourages designs but it is how equivalency is demonstrated and interpreted. In the past there has been a lack of tools that would demonstrate "equivalency" in a convincing manner. This is

rapidly changing. In cases where they are designing a building or a process that is anticipated by the prescriptive code, we believe the "alternative but equivalent" approach is adequate. The new "performance based design" techniques provide plenty of freedom of design within a given approach. This freedom of design is particularly apparent if one views equivalency as an *overall intended level of safety equivalency. This* overall equivalency is different from an item-by-item equivalency that might be required by some code officials.

By defining the acceptable level of safety as the level of safety provided by the prescriptive code, the freedom of the designer to design facilities where this equivalency doesn't exist or where it cannot be demonstrated. We do not view this as negative since this type of freedom should not be available to the designer. On the other hard, if by limiting the designers choice of options to ones where equivalency can be demonstrated, the code official has some documented assurance that the intent of the prescriptive code is being met. This requirement, instead of discouraging innovation could actually encourage it by facilitating the approval of these designs.

The exception is needed to provide the flexibility that new and unanticipated designs or processes need while requiring the final proposed level to have some rational basis to justify it. The burden to justify why a different level of safety, from the level implied by the prescriptive code should be placed on the, designer. The designer must also make it clear what the basis is for the level that is proposed.

MANINTENANCE/ENFORCEMENT PROBLEM

Problem

The question that arises as a fire official is: How are the assumptions that are made in an objective based design enforced? Our experience in Boston has shown that these types of designs are connected to a set of assumptions with no redundancies or room for error. Some of these assumptions are made with respect to people movement and fuel loading with little or no scientific background or statistical analysis. Furthermore, many times assumptions are made and used outside of the boundaries with which they were derived. This becomes an issue when managing the use of buildings on a day-to-day basis. In fact the day-to-day uses, repairs to fire protection equipment and owners’ interests may act retrograde to the engineer's initial design assumptions. In recognition of these constraints, the Fire Prevention Division of the Boston Fire Department has outlined some issues that we believe must be discussed to illustrate some past failures and propose a path that the engineering, construction and code enforcement community can take.

Examples

In order to outline the concerns clearly, two actual cases will be used. The first will be a description of the assumptions that were made about an 18,000 seat arena and a high rise residential building and how future use negatively impacted the engineer's original design assumptions. Although the issues brought forth by these cases are indeed complex, a small cross section of the assumptions will be used to illustrate our case. It should be noted that none of the

assumptions in this paper were taken out of context of the boundaries of the argument proposed by the engineer. In fact, they were critical in their relevance and nature of the overall project.

A submittal for the arena detailed the use of a "fast-fire" (see NFPA 72, Appendix B for explanation) in the ASST-BX model for a design fire. In part, the modeling was performed to show that an increase in seating and the deletion of an automatic sprinkler system could be allowed. This was based on the information from the model with respect to untenable conditions. Setting aside the issue of the use of the model, there were issues raised with the use of a fast-fire. The result was that the ownership capitulated and proposed the limitation of combustibles in the arena. Furthermore, the area was to be used for sporting type events and those with a low fuel load only. During the first weeks of operation of the arena, a concert event was held. The stage consisted of decorations consisting of 4 stories of flexible polyurethane material. In addition, there have been other events that use pyrotechnic displays. This type of use would seem to fall outside the boundaries of the solution that the engineer and owner proposed in order to obtain an increase in occupants and the deletion of an automatic sprinkler system. In the cases of the polyurethane decorations, no one from the arena notified the fire department nor the building department to determine if this particular use violated the appeals agreement

In the high rise residential building case. A proposal was made to omit the installation of an automatic sprinkler system at the time of construction. Instead of an automatic sprinkler system, the ownership proposed that an open balcony be constructed to connect adjacent units so that passage from one to another could be easily accomplished, fire extinguishers be installed in every kitchen and an automatic door closure be installed on the kitchen door. Over 30 years of use, the fire extinguishers are gone, the kitchens have been remodeled to look modern and the balconies have been enclosed so that passage from either one is impossible. No one consulted the fire department or the building department to determine if this type of construction and removal of fire protection features were legal modifications.

There are 5 questions and solutions we would like to propose that stem from our experiences and relate directly to the enforcement of assumptions used in an objectively based design. The questions are:

1. Where should documentation of assumptions used in an objective based design be kept? We believe that the owner and his agents are ultimately responsible for the maintenance of the documentation used in a performance based design. This information must remain on site and accessible for use. In addition, any conditions on the Certificate of Occupancy should be kept at the municipal building department as part of the legal documentation.

2. Who should review and approve modifications prior to building permit application? Due to the fact that these types of designs are so assumption driven, any deviations or proposed modifications should be approved by the original engineer of record. The ramifications of this statement are wide ranging. However, if an engineer cannot determine if a modification will not adversely impact his assumptions why should the authority having jurisdiction be responsible for the decision.

3. Who is responsible for maintaining the records and that all the assumptions used in a design are followed? A concept like a Fire Safety Director would seem like a logical choice. This person would be on site to determine if events or modifications impact the design assumptions used by the engineer. If the documentation on the design is on site and the individual is qualified to make judgments of this magnitude, we believe that incidents like the arena and the high-rise can be avoided. These type of events must be avoided if we are to use objective based designs. We have had experiences with other major property owners in the city that are similar to the fire safety director concept. These people are onsite to determine if the day to day operation complies with the requirements of the building code and legally sanctioned variances. However, questions remain if this concept is used. What level of training is required for this type of person? There is a definite void of information on this topic. The final issue on this subject is: how does an AHJ site someone for not being qualified?

4. What happens if the assumptions must be violated due to repair of a fire protection system? We presently manage this type of situation by requiring the owner to make provisions such that an adequate level of protection is provided if a required or non-required fire protection system is impaired. Many times this requires removal of all combustible material and fire watches that an owner supplies while other cases require temporary water supplied be made with fire department personnel and apparatus. In any case of severity, the impairment issue is great and must be dealt with as much care as is taken in the initial design phases of construction.

5. Who submits a status report to the AHJ on the state of the assumptions used in the design? We believe that a status report should be submitted on a frequent basis. The content of the report would indicate that all assumptions are being followed and include all test data of all the fire protection systems used. This would range from automatic sprinkler systems to the status of doors with automatic door closures.

It is important that a systems approach be used in objective based designs. What is ever more important is that a systems approach be take to maintain and determine if compliance exists on a system wide basis. It is important to explain to individuals that will be using the built environment the importance of the assumptions and how they will impact on occupant safety if they are not followed. By empowering the user of the built environment with this information, the intentions of the original design and overall level of safety will be realized. Due to the size and scope of objective based designs, the maintenance of the assumptions by the code official cannot be done alone. The concept and importance of the fire safety director should be embraced by the fire protection community as a whole.

TRAINING AND ESUCATION PROBLEM

Problem

A problem, which will impede the use of performance-based fire protection design methodologies, is that many code officials, engineers, and architects lack proper training and

education about the use of these methodologies. There are both short and long term implications concerning the training and education problem. Short-term problems will arise when one tries to obtain the code official's acceptance to use performance-based fire protection design methodologies within the official's jurisdiction and is met with stiff resistance. As a minimum, if the use of performance-based fire protection design methodologies is permitted, the review process could be very slow as many designs will be subjected to a lengthy appeal and review process due to the code official not being qualified to properly review submitted performance-based designs. It is worth mentioning that long review periods, in many instances, are attributable to insufficient, inadequate, or misleading information being submitted for review. Long-term problems will arise due to changes that will occur over time to a building's use, function, and built in fire protection characteristics. These changes to the building will necessitate a re-review of the original performance-based fire protection design's, objectives, assumptions, and performance criteria.

An improperly trained code official, engineer, or architect will not recognize that the originally approved performance based fire protection design requires additional evaluation because of the changed conditions. However the long-term problem is also an enforcement problem which is covered in another part of this paper. Additionally, inadequately trained code officials may also approve unsafe performance-based fire protection designs quickly without rigorous and adequate analysis because the code official would not know the appropriate questions to ask of the designer or even where to go to seek additional information regarding performance-based fire protection designs. This situation opens up the question as to why a designer is submitting an unsafe design in the first place for a code official's approval.

Another problem area related to training and education is the necessity of a code official, engineer, or architect to exercise judgment when deciding upon the acceptability of a proposed performance based design--in other words what makes a design safe or even more simply stated what is safe design. Performance based designs utilize many assumptions, performance criteria, and design methodologies, which are many times subjectively chosen by the designer. For example, a designer may select that a design be deemed safe if the time for occupants to egress a building is less than the time for a hazardous condition to develop such as the height of the bottom of a descending smoke layer to reach a pre-determined level. Upon thorough analysis the designer may then discover that given the pre-selected design fire scenario and original performance criteria the available safe egress time is not achievable and proceeds to abandon the objective of obtaining a safe egress time using the concept of a descending smoke layer.

The designer then proceeds to use the same design fire scenario in the same building, yet changes the performance criteria to new threshold levels using radiant heat flux, maximum layer temperature, carbon monoxide concentration, and visibility. Upon re-calculation, the designer now determines that the building occupants will egress prior to the onset of unsafe levels using the new performance criteria. How can the same building design be deemed unsafe for occupants in one design scenario but safe in another when the only change was different performance criteria? When designers make final selection of their assumptions, performance criteria, and design method and submit them for review to the code official, the code official is obligated to judge their acceptability. The design and review process is fraught with subjectivity for both the designer and the code official.

Proper training and education of both code officials and designers will address only part of the judgment and subjectivity dilemma. A prescriptive review methodology for use by code officials could also solve part of the problem concerning a code official and designer's proper use of judgment and design subjectivity.

Examples

Recently, the owner of a high-rise building submitted a performance-based design as an alternative to installing a complete NFPA 13 sprinkler system within the building. The owner's design team, during the course of review with the code official, made approximately six major changes to their design fire assumptions, two major changes as to the selection of their performance criteria, three major changes concerning their assumptions about human behavior and egress from hazardous conditions, and numerous other changes to the overall design including fire department response times. Reviewing all of the changes and the final proposal required over 250 hours of review time by the code official. In this instance, the code official was left with the question of how to accept a proposed performance-based design, which involved such subjective establishment of assumptions, design fires, and performance criteria, by the design team. A considerable amount of review time was spent by the code official getting educated on the engineering material that was requested of the design team in order to substantiate the analysis and conclusions of their design proposal.

A performance based fire protection design was submitted for an 18,000-seat arena. The original design was not properly documented or justified by the designer concerning the manual activation of the arena smoke control system and the timed egress analysis of the arena occupants. In addition, the designer submitted documentation that the arena's stage and floor fuel load would never exceed a certain quantify and hence a certain size fire would never develop based on this fuel loading. This limitation and its implications were not known by the building owner and were not directly made a condition of the building's certificate of occupancy. Upon discovery of this matter by the code official at a later date, the arena owner must either eliminate a large portion of his trade show business or take expensive measures in order to ensure occupant safety.

Solution

It is obvious that code officials must obtain some formal type of certification in order to ensure proper evaluation of performance-based fire protection designs. Many code officials are presently career employees who are qualified by a combination of experience and education. It is imperative that the instructive portion of a code official's qualifications incorporate training in the review of performance-based designs. Unfortunately, until this training is more universally, uniformly, and inexpensively provided by inspector associations, universities, model building code groups, SFPE, and the like there is little that can be done on a large scale to help solve the training and education dilemma faced by code officials

Architects and engineers are more uniformly schooled in traditional university settings and the availability of engineering and architectural programs perhaps puts these occupations in a better

position to respond to the lack of available training in performance-based fire protection design. Not everyone in the building design professions can be a truly qualified fire protection engineer but neither should the traditional engineering and architectural schools offer so little on performance based fire protection design. Again until more faculty are provided with training in fire protection engineering within mainstream engineering/architectural programs the option of the traditional engineer/architect to seek advanced training in fire protection engineering will be limited to a small cadre of universities offering fire protection engineering program. Technology today does offer the opportunity for distance learning on a much larger scale than ever before. It is worth mentioning that the Society of Fire Protection Engineers has offered numerous short programs about performance based fire protection design.

Presently, the best option for overcoming the lack of training and education in performance-based fire protection design is to require peer review of proposed designs upon submittal to the code official. A suggested format for peer review selection could go as follows:

1. The code official provides a list of qualified fire protection engineers to the owner.

2. The owner is given a set of ground rules by the code official as to the expected extent of the code officials review--this could be the prescriptive review methodology used by the code official described elsewhere in this paper.

3. The owner could then select a fire protection engineer from the list after the prospective engineers have reviewed the proposed design documents and the prescriptive review methodology developed by the code official. The owner should now have a variety of bids and price ranges to select from.

4. Once the owner has selected the peer reviewer it shall be a requirement that the peer reviewer be ethically bound to work for the code official in determining the adequacy of the performance-based fire protection design.

5. A peer review report is generated and is used by the owner and the code official as the basis of discussion during the approval process. This sets the ground rules so to speak.

While not perfect solution it does address the immediate needs of the performance-based fire protection designer and their code official counterparts.

SUMMARY

Although this paper is entitled Code Officials and Performance Based Fire Safety, we believe that the items that have been discussed are also valuable to many others in the process. The prescriptive rules of design will make it easier for the designers to select assumptions and set criteria. They could also have less liability in the event an assumption or criteria leads to an unsafe design, since the assumption or criteria was agreed to by some consensus process. These benefits are also derived by defining the acceptable level of safety as the level implied by the prescriptive code.

Another benefit of tying the acceptable level to the prescriptive code is that it automatically allows a single national model to be adopted by different jurisdictions that have different levels of "acceptability". If indeed a jurisdiction does have a different level of acceptability than a national model prescriptive code, it should be reflected in the prescriptive code for that jurisdiction. This allows one model code to take into account the different level of safety that different areas of the country accept.

The requirements for training code officials will enhance a jurisdiction's ability to adequately review performance-based designs. However, if our experience is typical, an added benefit is an enhanced ability to provide consultative services to the applicant as well as an increased ability to review prescriptive based designs. We have found that the questions that are raised during performance based reviews apply to all designs. In particular, the importance of maintenance, safety during phases of construction, and qualifications of on-site personnel. In discussing these concerns with property management people they recognize these shortfalls. They are asking us to help train their in-house personnel to deal with these issues.

We believe that the solution to these problems will accelerate the acceptance of performance-based codes. Although these requirements will make it harder for poor designs to get approved, they will simultaneously make it easier for good designs to get approved. In society, people give up a small percentage of their freedoms to protect the rest. We are asking the designers to give up a small amount of freedom, such as the freedom to use unjustified safety factors, so that code officials feel comfortable dealing with the freedom to utilize different design options. We believe these recommendations will have a practical affect to provide designers more freedom by making it easier for code officials to accept these designs for review.

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APPENDIX C

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Heat release rate: a brief primer	by: Dr. Vytenis Babrauskas, Fire Science and Technology Inc. This article ©Copyright 1996 vyto@doctorfire.com

Background

When the aftermath of a serious fire is being investigated, one of the most common questions is: *Why did the fire get so large?* Until relatively recently, the 'large' questions could only be answered qualitatively, since means of quantifying a fire size in engineering units did not exist. Eventually, it was recognized that since heat is the energy output of the fire, and scientific means exist for measuring energy, the problem may be soluble. The principles are clear. Heat is measured in units of Joules. What is usually more of interest is the rate at which heat is released, not the total amount. The heat release rate (HRR) can thus be measured in Joules per second, which is termed Watts. Since a fire puts out much more than 1 Watt, it is usually convenient to quantify the HRR in kilowatts (1000 W) or megawatts (a million watts).

Bench-scale measurement of HRR

Prior to the 1970s, such ideas, while theoretically accessible, were not usable, since actual means of measuring HRR from fires were not available. The first instruments for HRR measurement started being available in the 1970s and they were bench-scale devices. (One specialized unit had been already built in the 1950s in one lab.) Bench-scale means such instruments can measure samples on the order of a few inches or a few centimeters in size, but not real objects that could be man-sized (or even warehouse-sized). The early HRR instruments (OSU apparatus, developed by Prof. Ed. Smith; NBS-I calorimeter, developed by Alex Robertson and Bill Parker; etc.) suffered from normal first-generation issues of usability and cost. The NBS-II calorimeter, for instance, cost NIST $250,000 to build in 1977-78 (actual 1977 dollars). Shortly after joining NIST in 1977, I was tasked to find a better way. Several years of exploration elapsed, and by 1982 I had invented the Cone Calorimeter, in its first iteration. This has since become the world standard, available at test laboratories around the globe.

Furniture calorimeters (large-scale products calorimeters)

Having a bench-scale HRR apparatus is not enough for

comprehensive studies of fires. In many cases, it is necessary to study the HRR of objects in their full scale, or at least nearly full-scale. This development was also started around 1979, and by 1982 two different apparatuses were independently invented. The NIST furniture calorimeter was developed by myself, along with Doug Walton, Randy Lawson, and Bill Twilley. The FMRC products collector was developed by Gunnar Heskestad. These have also now become used around the world and are the basis of numerous standards of ASTM, NFPA, and other organizations.

Room calorimeters

The final HRR measuring apparatus which was needed was a room calorimeter. Furniture calorimeters can measure the HRR of discrete objects, able to support themselves on the floor. This does not include such products as ceiling tiles nor wallboard. Also, special measuring issues arise when one wants to measure a whole burning room, fully furnished. For such studies, room calorimeters were needed. Room calorimeters were developed in a parallel effort between Fred Fisher and Prof. Brady Williamson at UC Berkeley and by Billy Lee and Jin Fang at NIST. This effort was also largely completed in 1982, meaning that instruments of all three needed scales became available nearly simultaneously in 1982.

Which scale to use?

It is costlier and more difficult to test in larger-scale instruments, thus it would seem that preference would always go towards running a bench-scale test. This is not necessarily true, since to make intelligent use of the bench-scale data one needs a **predictive model**. In other words, it is not of much interest to know what a 10 cm size sample would do; what is of interest is the full-scale behavior of a piece of furniture, appliance, wall covering, or even a whole room. For some categories of objects, such models have been developed. These include upholstered furniture, wall linings, carpets, and some others. But the available categories are few, while the types of objects which can potentially be of interest in fire reconstructions are numerous. Thus, one of the things which must first be determined is whether it is reasonable to run bench-scale tests or whether full-scale testing is needed. We may note that for polymer manufacturers and others developing new materials, it is often sufficient to only use bench-scale testing. This is because they mainly wish to find the relative differences in fire behavior, while actual product performance may not be relevant to them since they do not even make the end product.

The overwhelmingly important role of HRR in fires

HRR is not just 'one of many' variables used to describe a fire. It is, in fact, the single most important variable in describing fire hazard. (The only notable exception is for explosions). There are three main reasons for this.

1. HRR is the driving force for fire.

The HRR can be viewed as the engine driving the fire. This tends to occur in a positive-feedback way: heat makes more heat. This does not occur, for instance, with carbon monoxide. Carbon monoxide does not make more carbon monoxide.

2. Most other variables are correlated to HRR

The generation of most other undesirable fire products tends to increase with increasing HRR. Smoke, toxic gases, room temperatures and other fire hazard variables generally march step-in-step with HRR as HRR increases.

3. High HRR indicates high threat to life.

Some fire hazard variables do not relate directly to threats to life. For instance, if a product shows very easy ignitability or high flame spread rates, this does not necessarily mean that fire conditions are expected to be dangerous. Such behavior may merely suggest a propensity to nuisance fires. High HRR fires, however, are intrinsically dangerous. This is because high HRR causes high temperatures and high heat flux conditions, which may prove lethal to occupants.

If HRR is so important, why are regulators not regulating it?

In the US, over the last decade, HRR has shown up in various regulations and specifications, but this has been in specialized areas. Where it has not yet shown up in is in the building codes. The US model building codes still regulate products according to the Steiner Tunnel Test. This test was developed during the late 1930s and early 1940s and, of course, predates all of modern fire protection engineering knowledge. The test controls flame spread which is not, as noted above, a primary factor in determining human untenability. Over the years, a number of research projects documented various shortcomings of this test. The basic reason why we have not yet progressed beyond 1940s technology in the building codes has to do with the inertia of the process and of the lack of funding resources necessary to propel a building code change. In the US, there is no public-interest organ with specific funding to conduct

research leading to building code improvements. Changes, instead, are usually originated by commercial entities. As of now, no commercial group has decided that it would be advantageous for them to sponsor a change, intended to introduce improved engineering methods in this area. In fire litigation however, HRR testing is well established, and eventually it is also certain to become utilized in building codes.

Some common misconceptions

- *We have taken measures to control the ignitability, so we don't have to worry about HRR*

It is certainly wise to always control ignition sources and also to use less ignition-prone materials, when possible. Such a strategy, however, can never be **relied upon** to avoid an ignition. Neither HRR nor any other consequences of fire will come into play as long as there is no ignition. However, when an ignition does occur, limiting the HRR means that the fire has a chance to be controllable and not disastrous.

One must also realize that if the application is not in aircraft safety, military or NASA areas, the affordable, commercial materials that are available are not very ignition resistant. Studies have shown that even small ignition sources normally apply about 35 kW m^2 heat flux to their target. If one then seeks materials able to resist an ignition flux of 35 kW m^2, one finds that these are rare and costly.

- *Coroners tell us that inhalation of toxic fire gases is the main cause of fire deaths, so we should control toxicity, not HRR*

This fallacy rests on the imprecise definition of the term 'toxicity.' Regulatory officials sometimes presume that this means that 'toxic potency' is the root problem and that this is what must be controlled. Toxic potency is the toxicologist's term for defining **how toxic is the substance when you inhale 1 gram of it**. But of course the victim will inhale something other than 1 g of it. **How much** of the substance will be inhaled is governed by the fire's **mass loss rate**. The mass loss rate is closely proportional to the HRR of the fire. Now, what is important to realize is that studies at NIST and elsewhere have shown that for commercial products, burned under realistic fire conditions, toxic potencies vary only within a narrow band. By contrast, mass loss rates (same as HRR) vary over an enormous range among products of any given type. Since both toxic potency and mass loss rate affect the total impact of the fire on the victim, it is clear that effective control can be mounted by limiting mass loss rates, but there is little that can be achieved by attempting to control toxic potencies.

For further reading, see the textbook Heat Release in Fires.

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APPENDIX D

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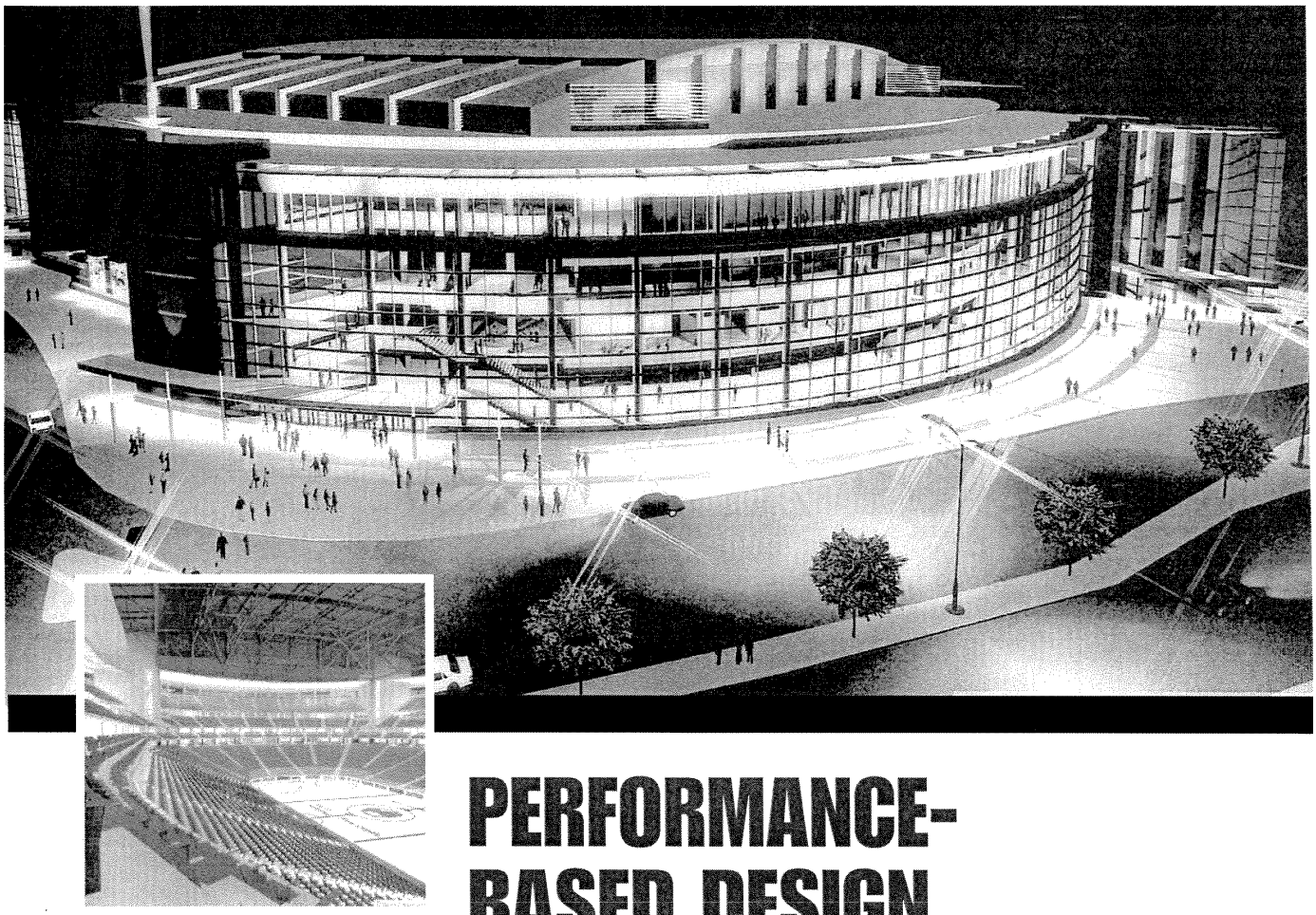


PERFORMANCE-BASED DESIGN OF A PROFESSIONAL HOCKEY ARENA

By Michael A. O'Hara, P.E., with Ryan Bierwerth

The MountainStar Group, Inc., developed a performance-based design (PBD) to meet the Uniform Building Code intent for the smoke-protected seating concept in a 19,000-seat multipurpose indoor arena, the new home of the National Hockey League franchise Minnesota Wild. The arena is still under construction with a planned opening of September 2000.

The performance-based fire safety plan essentially followed the process delineated in the draft copy of *The SFPE Engineering Guide to Performance-Based Fire Protection Analysis and Design of Buildings*.[1] The overall PBD approach used on this project is a fire-hazard analysis as opposed to a probabilistic assessment. Specific fire scenarios were identified and trial designs applied to them and compared to performance criteria.

The fire/life safety systems being implemented in this complex are a result of a combination of performance-based fire protection technology and application of prescriptive building and fire code requirements. Design solutions reflect the collaborative efforts of the design team, jurisdictional authorities and the owner.

Table 1 - Goals, Objective and Criteria

Fire Protection Goal	Objectives	Performance Objectives	Performance Criteria
Minimize fire-related injuries and prevent undue loss of life	■ Adequate time for egress prior to smoke involvement and structural failure ■ Protect firefighters by employing active systems ■ Provide credible building systems to support fire-fighter tactics	■ Detect and control a fire early in its developmental stage ■ Maintain tenable egress ■ Manage smoke movement ■ Prevent flashover in the area of origin ■ Maintain fire attack locations	■ Egress within 23 minutes, assuming a 4-minute delay ■ Tenability values addressed CO, visibility and temperature ■ Preclude flashover in confined and open spaces 1100°F (600°C) at the ceiling and a radiant heat flux of 20 kW/m² ■ Provide smoke detection in under 4 minutes ■ Provide sprinkler response precluding flashover in confined spaces ■ Evacuating occupants before the descending smoke layer reaches 10 ft (3 m) above the highest level of general public egress (upper deck), a UBC requirement ■ Permit each event
Minimize downtime	■ Meet the life and property objectives	■ Safeguard contents and procedures	■ Fire department prefire planning ■ Site access on at least three sides ■ Permit each event
Minimize property damage and structural collapse	■ Provide aggressive fire detection and control systems ■ Reduce the chance of structural collapse ■ Limit fire development to maintain structural integrity for 2 hours	■ Detect a fire early in its developmental stage ■ Prevent flashover in the area of origin ■ Prevent flame impingement on steel	■ Detect a fire at less than its design basis for smoke control ■ Keep upper layer fire temperature below 1000°F (540°C) per UBC Standard 7-1 within proximity of the critical structural framing components ■ Restrict flame impingement upon the steel trusses ■ 10-minute fire department response time ■ Permit each event

The St. Paul Arena is located in downtown St. Paul, Minnesota, and will be home to the National Hockey League's Minnesota Wild, an expansion team beginning play during the 2000-2001 season. The arena was designed by Hellmuth, Obata & Kassabaum, Inc., Sports Division (HOK Sport) under state-amended versions of the 1997 Editions of the Uniform Building and Fire Codes (UBC and UFC, respectively)[2,3].

The primary use of the St. Paul Arena is for National Hockey League games. However, other possible uses include basketball games, trade shows, boxing events, concerts, conventions and exhibitions. The building gross floor area is approximately 650,000 ft² (60,000 m²). The building has a height of 142 ft (43.3 m) from the floor to the roof. The arena is attached on its east side to a skyway and convention center. Public streets border to the north, west and south. The predominant occupancy classification is A-2.1 (assembly), but other accessory occupancies are A-3, S-1 (storage) and B (business). Fire protection strategies address the multiuse and architectural focus, which is best described as an "open environment" between the spectator "bowl" area and the concourses.

DEFINE PROJECT SCOPE

The scope included compliance with the code provisions for smoke-protected seating and eliminating sprinklers over the bowl area. The St. Paul Arena project included 3 different authorizing agencies and 14 different firms, all of whom made up the design team.

Smoke-Protected Seating: UBC Section 1002 defines smoke-protected assembly seating as "seating served by a means of egress and is not subject to blockage by smoke accumulation within or under a structure." Smoke-protected seating allows for reductions in spacing of seats, aisleways and egress components provided the building is equipped with an engineered smoke control system and a life safety evaluation is undertaken.

NFPA 101, the Life Safety Code[4], provided guidance as to the composition of a life safety evaluation given the lack of clarity in the UBC. Specific stakeholders were identified to execute the evaluation. This organizational framework required stakeholders to understand their primary responsibilities. The life safety evaluation incorporated key aspects of the PBD.

UBC provides guidance for design calculations for smoke control; however, NFPA 92B[5], *Society of Fire Protection Engineers Handbook*[6] and *Design of Smoke Management Systems*[7] were also utilized. UBC calculations for smoke control using the "exhaust method" provided the primary guidance.

Sprinklers over the bowl: The necessity of sprinklers over the bowl was evaluated, considering fire scenarios and fire department operations.

PROJECT GOALS/OBJECTIVES AND CRITERIA

Table 1 summarizes the relationship between goals and objectives, and they were translated into performance criteria.

Performance criteria came from published literature primarily extracted from the *SFPE Handbook*,[6] NFPA 92B,[5] DD240[8] and *Design of Smoke Management Systems*[7]. From an enforcement perspective, permitting each event became a critical perfor-

Continued on p. 37

mance criterion as a quality-assurance tool to assure compliance with the design parameters and assumptions of the PBD.

DESIGN FIRE SCENARIOS AND DESIGN FIRES

Attaining stakeholder agreement regarding the credible fire scenarios was the most challenging part of the process because the scientific literature provides a broad and sometimes conflicting range of data.

Probable design fire scenarios considered inherent characteristics of the building: people, use, construction and fixed in-place fire protection. Critical information was researched regarding the space such as ignition sources, nature and configuration of the fuel, ventilation, as well as characteristics and locations of occupants.

To determine the design fire size, MountainStar and the City of St. Paul researched fire tests, like facilities and methods found in *The SFPE Handbook of Fire Protection Engineering,* published fire test reports and results of the large-scale fire tests conducted in the former St. Paul Civic Center[10].

Four primary building fire scenarios assumed steady-state conditions and specified locations within the facility:

1. Spectator Event: Any event where the fixed seating is used throughout the bowl to accommodate the general public. This scenario, for example, includes hockey games, sporting events and entertainment, but does not include occupancy of the arena floor. [10,000 BTU/s (10 MW) design fire in the bowl and 5,000 BTU/s (5 MW) to 7,000 BTU/s (7 MW) in the concourse areas]

1A. Spectator Event/Concert: All the criteria of Scenario 1, but also including the occupation of the bowl floor space using nonfixed seating and a stage. This event, for example, includes concerts and stockholder meetings. [10,000 BTU/s (10 MW) design fire]

2. Consumer/Trade Show Event: Any event where the fixed seating above the suite level is restricted from general public use. Occupants are concentrated in the lower bowl and arena floor. Displays, salable goods, boats, vehicles and similar temporary structures are concentrated on the arena floor. [50,000 BTU/s (50 MW) design fire in the bowl area]

3. Unoccupied: This scenario implies that any of the above scenarios may be occurring yet it is during non-event hours and the general public is not present (i.e., late night or early morning).

Additional research assisted in establishing the fire loads anticipated. BSI DD 240, "Fire Safety Engineering in Buildings",[8] suggests a rate of heat release per unit area of 500 kW/m² for retail spaces (Table 11 in DD 240). Supplemental guidance in DD 240 suggests a medium t^2 fire as a design basis. Australia's *Fire Engineering Guidelines,*[9] yields like results (See Table 2 above).

Table 2 - Summary of Fire Load Data

Summary Australia, DD240 & UBC			
Fire HRR	UBC (kW/m²)	DD 240 (kW/m²)	Australian Code (kW/m²)
Office	284	250	250
Retail	567	500	500

RESULTS OF LARGE-SCALE FIRE TESTS BY THE STAKEHOLDERS[10]

Prior to demolition on June 6, 1999, a series of full-scale fire tests were conducted at the 15,000-seat St. Paul Civic Center Arena, St. Paul, Minnesota, to assist the stakeholders in conceptualizing the magnitude of different fire sizes and their effects on large spaces. This aspect is what made the St. Paul Arena project unique, because it allowed the design team to compare empirical and engineering calculations with actual experimental data that were obtained on a large scale.

Test results indicated:

- Calculations tracked with empirical results.
- Sprinklers at the heights in this structure did not activate at the fire sizes tested.
- Temperatures drop off significantly in large spaces as height and distance from a fire increase.
- Smoke stratifies as it cools yet remains relatively high in a large space with typical ambient conditions for an occupied space.
- Structural integrity was not threatened.
- Axis-symmetric fire smoke production volumes are readily inflated by the introduction of makeup air. The UBC calculations appear conservative.

DEVELOPING AND EVALUATING TRIAL DESIGNS: FINAL DESIGN SELECTION

The trial designs applied against the four specified fire scenarios encompassed fixed, in-place protection, management practices and fire department response times. An understanding of the sprinklers in confined spaces and areas with low ceilings achieved group agreement that those spaces were well protected. Smoke-protected seating required a close look at tenability and smoke production given the expected fire scenarios. Structural performance over the bowl was studied against the steady state fire sizes.

Fire Department: A letter written by the city fire department to the design team indicated a three-minute response time based upon historical data; MountainStar added time to this given the need to determine the fire location, setup and apply water. Fire department access includes site access from all sides, as well as strategic placement of standpipes within the arena and hydrant location outside. Arena management is implementing a traffic management plan fostering the historical response times.

The steady-state fire conditions of four scenarios were compared to the anticipated fire department response based on different t^2 fire growth rates to ascertain a better understanding of fire sizes and conditions upon fire department arrival. Figure 1 outlines expected fire sizes vs. time based on t^2 fires in anticipation of fire department response negating any effects of fixed, in-place fire suppression or the operational plan that affects content spacing and use. The shaded region indicates expected fire department response

ranges.

Egress/Tenability: Two approaches estimating egress times were used based on the operational scenarios: one based upon calculations outlined in both the *SFPE Handbook*,[11, 12] the *NFPA Handbook*,[13] and other references[8, 9]; and the second using the egress subroutine of FPETool.[14] Calculations considered delay factors, recognition times and speeds typical of smoke-protected seating. Queuing at the stair towers doors of the upper deck posed what was the governing criterion given the smoke movement in the structure and tenability.

The stakeholders agreed to a study comparing tenability to egress times of the most vulnerable areas within the arena. Tenability of performance-based design can be formulated to meet the objectives of a smoke exhaust system designed for life safety. This can be accomplished by analyzing the impact of the smoke management system based on the hazard parameters. The hazard parameters used for this project were temperature, light obstruction and carbon monoxide concentration based upon polyurethane and red oak. Klote and Milke give examples of this method.[7] Temperature of the smoke layer became the governing factor as CO levels in the smoke layer remained low given the smoke dilution in a space of over 4,500,000 ft³ (130,000 m³) in the upper reaches of the bowl.

Smoke-fill rates were simplified and calculated at a defined smoke layer height in accordance with UBC provisions. Smoke layer heights varied with the scenario analyzed. The quality of the smoke can be approximated. Assuming the 10,000 BTU/s (10 MW) steady-state fire, a temperature rise of 34°F (18.9°C) is expected due to the large volume of space. Most of the heat is lost to the large volume surroundings. CO concentrations again remained low, considering 50 ppm is the allowable 8-hour exposure in a parking ramp per UBC requirements. With the smoke layer height 10 ft (3 m) above the highest point occupied by the general public, a 500,000 cfm (236 m³/s) exhaust rate was calculated. Tenability data based upon data calculations from *Design of Smoke Management Systems*[7] are summarized in Table 3.

The viable trial design resulted in 500,000 cfm (236 m³/s) of exhaust at the roof level of the bowl with selected exhaust via specified fans and openings in the concourse with makeup air introduced primarily at the floor and main concourse of the arena. Smoke detection at the roof level or in designated concourse areas triggered the smoke exhaust system, as well as addressed the city's concern of a fire when the building is unoccupied. Smoke detector response times were calculated using FPETool[14] at an RTI of 1 (ft/sec)$^{1/2}$ [0.5 (m/sec)$^{1/2}$] and at a spacing per the listing of the detector. Trial designs that resulted in smoke detection in greater than four minutes, as calculated by FPETool, were modified until that design criterion was achieved.

Confined spaces pose the greatest threat given flashover, yet are well protected with sprinklers to preclude this condition. Large open spaces pose the least threat because the shear volume dissipates the smoke and precludes the likelihood of flashover.

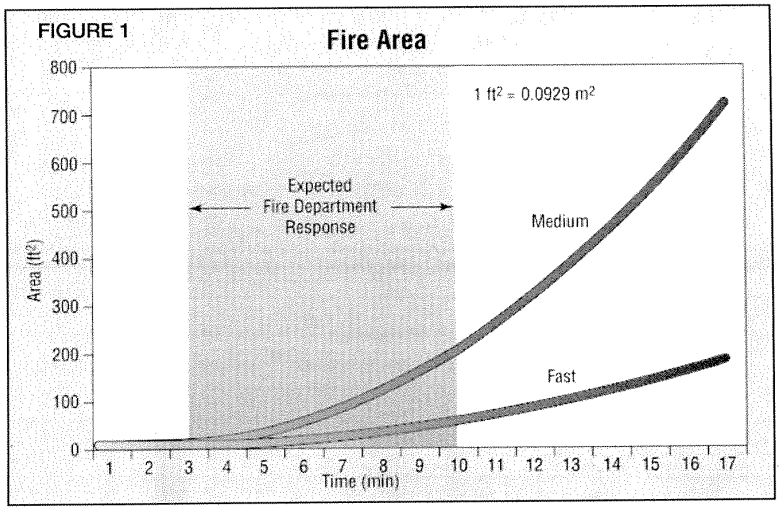
For example, given the 50,000 BTU/s (50 MW) design fire, the stakeholders agreed that this condition might exist in a consumer trade event, such as a car show. The general public is typically on the floor of the arena viewing the displays. Maintaining the smoke layer height to the level of public access, which is the lower portion of the bowl in this case, provided for realistic smoke exhaust capacity. The smoke layer, along with most all other fire physics parameters, was calculated using the equations and methodologies outlined in Section 905.5 of the UBC.

Sprinklers over the bowl: Test results[10] in addition to the calculations support the conclusion that sprinklers over the bowl would not activate due to elevated height.

Analysis indicates flame impingement on the trusses, based upon calculating the effective flame height per calculations found in UBC Section 905, did not occur as long as displays in the bowl were limited in height. This was done for each design fire scenario.

In design fire scenarios that were not protected by automatic sprinklers (i.e., under the bowl), the heat release rate of the steady-state design fires

FIGURE 1



were used in calculating flame heights. These flame heights were shown not to reach the 92 ft (28.0 m) required to impinge on the structural steel of the St. Paul Arena. Furthermore, these calculations were consistent with visual observation of the large-scale fire tests performed at the former Civic Center.

Using FPETool calculations, a 50,000 BTU/s (50 MW) fire produces a flame height of 36 ft (11.0 m), and the critical members are at a height of 92 feet (28.0 m). Conservatively assuming a flat ceiling at the truss, placing a fire directly below the truss at floor level produces ceiling plume temperatures of 280°F (138°C), if the fire is 92 feet (28.0 m) vertically below. Ceiling plume temperatures are calculated within the impingement zone. Further calculations fostered a use limit of displays or equipment no higher than 30 ft (9.1 m) in height above the bowl floor.

DESIGN DOCUMENTATION

Reports generated included the resulting fire protection design, performance-based analysis and building/fire code review. Close coordination with the design and construction team improves effectiveness of PBD implementation. Reviews of applicable shop drawings and schematics, along with consistent communications, are critical. Contractors with numerous requests for information are typical. This became a critical conjuncture because this is where the PBD analysis meets the reality of application.

The city and building management requested a summary operational plan that describes the fire protection features and operational plan in concise and comprehendible terms for use after the Certificate of Occupancy is obtained. This reference guide is useful for field enforcement, event permitting and event planning.

Operational plans address compliance with the PBD assumptions. The fuel packages in each scenario were nonpermanent structures and equipment such as vehicles, trade booths, displays and temporary stages. These fuel packages were converted into heat-release rates as outlined in Section 905.6 of the UBC[2]. A heat-release rate per area of 570 kW/m² was used, which is representative of mercantile and residential occupancies. This calculation determined operational limits and

Table 3 - Smoke, Egress And Tenablity

Event Scenario	Bowl Fire $\dot{Q}$	Bowl Smoke Layer	Smoke Temp. & CO	Smoke Volume Exhaust Provided	Egress Upper Deck	Tenability
Smoke Exhaust Design I & IA	10,000 BTU/s (10 MW)	95 ft (29.0 m)	104°F (40°C) <15 ppm	500,000 cfm (236 m³/s)	15 minutes	60 minutes

Table 4 - Fire Scenarios and Associated Operational Limits

Use/ Area	Design Fire	Example Fuel Load Clusters	Operational Limits
Consumer Event	50,000 BTU/s (50 MW)	Multilevel Trade Show Booths, Boats, Recreational Vehicles, Cars and Trucks (e.g., consumer shows) in the Bowl	Maximum 1000 ft² (93 m²) per cluster with a minimum horizontal separation between the clusters of 5 ft (1.5 m), per Figure 2, and maximum height of 30 ft (9.1 m). No general public allowed above the suite level. Submit event plan to city. Implement a one-person fire watch during setup of the event.
Sporting Event	10,000 BTU/s (10 MW)	Hockey and Sporting Events, Concerts in the Bowl	Maximum 200 ft² (19 m²) per each cluster with a minimum horizontal separation distance between the clusters of 5 ft (1.5 m), per Figure 2, and a maximum height of 12 ft (3.7 m). Submit event plan to city. Implement a one-person fire watch during setup and during the event.
Displays	5,000 BTU/s (5 MW)	General Displays of Any Kind throughout Concourses	Displays are unlimited in area and spacing, but not to be located under stairs or in an area defined having draft stops or closed-space sprinklers (e.g., escalators). Submit event plan to the city. Figure 2 does not apply. Maintain exit widths.
III	7,000 BTU/s (7 MW)	Single-Level Booths, Cars, Boats under 18 ft (5.5 m) long, and Kiosks in the Atrium Concourses	Maximum 200 ft² (19 m²) of area per cluster with a minimum horizontal separation between clusters of 5 ft (1.5 m), per the enforcement guide and a maximum height of 12 ft (3.7 m). Submit event plan to the city.

parameters such as separation distances to preclude nonpiloted ignition of nearby combustibles.

In line with these operational limits, each event must receive a permit and comply with the intent of the PBD. Configurations of contents representing the design basis fires are translated into field enforcement and building/event management guides. Areas of the building are identified with specific area, use and spacing requirements. (See Figure 2.)

A cluster is defined as a single item or group of items, structures or displays that take up a given area. There can be more than one item in a cluster as long as it does not exceed the area restrictions. The city emphasized that even if a use falls outside the boundaries of the limits, it does not necessarily mean the use is unacceptable. Rather, the city will require closer review and may request supplemental fire defenses for that specific event.

Figure 2 provides guidance to the fire inspector if the need arises to verify display or cluster spacing. It illustrates the relationship of area versus separation distance required to prevent nonpiloted ignition of combustibles using a 20 kW/m^2 threshold. This establishes spacing requirements given specific heat-release rate values. The 20 kW/m^2 appears to provide a nominal target for the diverse range of materials to be found. Enforcement of the fire prevention aspects of the Minnesota Uniform Fire Code for materials control will assist.

CONCLUSION

PBD requires intense involvement of all stakeholders. The time and energy expended by all stakeholders on the PBD exceeds the traditional prescriptive approach. The body of fire science knowledge to defend specific design-basis fire scenarios still requires improvement. PBD requires a combination of fixed, in-place fire safety and continual building fire safety management including fire prevention review, inspection and maintenance.

Educating the stakeholders as to the limits of a performance-based design is essential. The limits are based upon fire design assumptions. Translation of the limits into pragmatic owner use and field enforcement is a challenge, yet essential.

The City of St. Paul jurisdictional authorities spent countless hours with the design team to come to closure on design objectives and implementation. The project is still under construction with a September 2000 grand opening. Continuous communications coordination with field personnel remains essential. The Minnesota Wild management and all the stakeholders have an outstanding commitment to a fire-safe facility. When all stakeholders come to the table to resolve the performance-based design issues in earnest, the performance-based design approach works well.

Michael O'Hara and Ryan Bierwerth are with the MountainStar Group.

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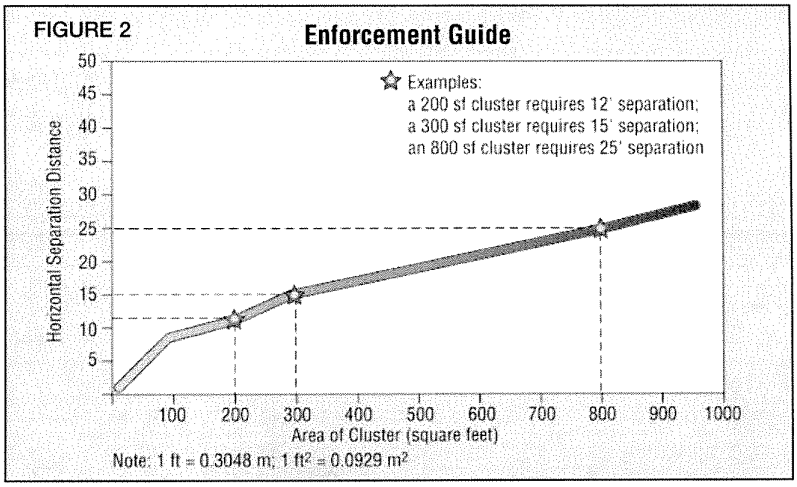
FIGURE 2



UNIT 2: INTRODUCTION TO FIRE DYNAMICS

TERMINAL OBJECTIVE

The students will be able to explain the progression of the fire, from start to extinguishment, given a fire scenario.

ENABLING OBJECTIVE

The students will define the terms heat flux/transfer, heat of combustion, heat release rate (HRR), T^2 fire, fire plumes, and ceiling jets.

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FIRE DYNAMICS

While mankind is believed to have discovered the use of fire 500,000 years ago, it only has been in recent years that research has been conducted into the scientific complexities of the fire environment. This research has given us a limited understanding of the chemical and physical properties that affect fire growth and spread, smoke and toxic gas production, and methods of heat transfer. Research also has continued in the areas of active and passive fire protection systems, such as fire sprinklers and fire-resistant barriers, respectively. Together, this knowledge is known as fire dynamics.

It is this body of knowledge that now enables those involved in the fire protection community to develop and use performance-based fire protection designs. Rather than relying on the accumulated observations and experiences that are codified in prescriptive building codes, architects and engineers use science-based research to measure successful outcomes.

Fire behavior research is a challenging and exciting field. "Basic" research occurs at a number of State and private universities, research laboratories, and Federal facilities. Scientists and engineers try to explain the phenomena of ignition, and the sequence of events that occurs during combustion and fire growth. Different fuels, ignition sources, and scenarios are evaluated to study fire behavior. "Applied" research involves applying and translating the scientific data into day-to-day uses: for example, better fire sprinkler designs, fire retardant fabrics and packaging, and materials handling and storage techniques.

A fundamental understanding of fire dynamics is necessary for the proper selection of design fires[1], the development of fire protection approaches and the evaluation of designs. For example, a car fire at a fuel dispenser would be a common design fire for a motor vehicle service station. If a designer or Authority Having Jurisdiction (AHJ) does not understand the fundamentals of fire behavior in the built environment, how can he or she successfully interpret design data?

AHJ's also should view fire dynamics studies and reports with an open--but suspicious--mind. Both basic and applied research occurs in tightly controlled conditions, whether in a small laboratory or a huge full-scale test facility. Scientists and technicians are trying to replicate fire behavior so they can develop relatively predictable outcomes. For example, if two or more standard wood cribs--used to evaluate the performance of portable fire extinguishers--differ in their potential heat of combustion, a technician cannot compare the performance of one type of fire extinguisher to another. The test must be consistent.

Outside the laboratory, though, this consistency is almost impossible to achieve. Differences in fuels, building construction materials, building construction techniques, ventilation, human behavior, building design, and fire department response time and performance are just a few of the unpredictable variables that may enter a structure fire combustion equation. The AHJ must remember that the data he or she receives likely will not reflect "real world" conditions accurately.

[1] In performance-based designs, "design fire scenarios" are those events that reasonably could be expected to occur in a building or facility.

For the purpose of this course, fire dynamics are discussed in these general areas:

- fire triangle/tetrahedron;
- combustion processes:
  - pyrolysis,
  - diffusion flame, and
  - premixed flame;
- ignition processes:
  - autoignition,
  - piloted ignition, and
  - spontaneous heating to ignition;
- fuels:
  - states, and
  - potential heat of combustion;
- fire development:
  - fire realms,
  - fire stages, and
  - fire growth;
- growth rates:
  - rate of heat release;
- structural and contents influences;
- ventilation:
  - natural, and
  - mechanical; and
- toxicity.

Fire behavior in structures is complicated. Fuels, oxygen, ventilation, compartmentalization, fire protection systems, interior and exterior design, weather conditions, and human activities affect the outcome of a fire. Those in the fire protection field know that even when given the same set of identical circumstances, it is unlikely two fires will behave the same or have the same result.

The chemical reaction with physical effects that is called "fire" is a complex and dynamic event even in controlled laboratory conditions. Thus, designers and AHJ's must apply their knowledge of fire dynamics with reasoned and experienced judgment to achieve the highest level of fire protection success under destructive and life-threatening conditions.

It is important for the designer, as well as the AHJ, to understand the factors that influence fire growth and behavior so they can propose--and review--the broad range of design fire that may be considered, as well as understand the impacts of architecture and structural components on fire behavior.

Measuring Fire Development: Conversion Factors

In the United States we still prefer the system of measurement that relies on the familiar feet, inches, pounds, watts, degrees Fahrenheit, and British thermal units. However, most of the test data or model predictions that may be generated as part of a performance-based design will be in the metric-based International System (SI) units including meters, kilograms, Pascals, degrees Celsius, and Joules. The AHJ must have an understanding of the units that may be used.

With the exception of the kilogram (kg), the conversions listed in the following table are to base units such as Joule (J) and Watt (W). When considering a building fire, these units are so small that the values must be reported as kilo-Joules (kJ) or kilowatts (kW). The "kilo" prefix means to multiply the base unit by 1,000. Another prefix that may be used is Mega (M). This prefix means to multiply the base unit by one million (1,000,000).

Figure 2-1 provides examples of unit conversions.

Property	To Convert From	To	Multiply By
Length	Foot (ft)	Meter (m)	0.3048
	Meter (m)	Foot (ft)	3.281
Mass	Pound (lb)	Kilogram (kg)	0.4536
	Kilogram (kg)	Pound (lb)	2.205
Time	Second (s)	Second (s)	1.0
Area	Square foot (ft^2)	Square meter (m^2)	0.0929
	Square meter (m^2)	Square foot (ft^2)	10.76
Volume	Cubic foot (ft^3)	Cubic meter (m^3)	0.0283
	Cubic meter (m^3)	Cubic foot (ft^3)	
Energy, work, quantity of heat	British thermal unit (Btu)	Joule (J)	1054.8
	Joule (J)	British Thermal Unit (Btu)	0.000948
Power, heat release rate	British thermal unit per minute (Btu/min)	Watt (W) = J/s	17.573
	Watt (W) = J/s	British Thermal Unit per minute (Btu/min)	0.05688
	Watt (W)	British Thermal Unit per minute (Btu/sec)	0.000947
	Btu/lb	Joule/Kilogram	2326
Heat flux	British thermal unit per square foot second ($Btu/ft^2/sec$)	Watts per square meter (W/m^2), or, Joules/m^2/second ($J/m^2/sec$)	189.15
	Watts per square meter (W/m^2), or, Joules/m^2/second ($J/m^2/sec$)	British Thermal unit per square foot second ($Btu/ft^2/sec$)	0.000088

Reference: NIST Special Publication 811, Guide for the Use of the International System of Units (SI)*, National Institute of Standards and Technology, Gaithersburg, MD, April 1995. **Note:** There are a variety of free online unit conversion services. Use your Web browser and type in "conversion," or the specific units you want (i.e., heat flux conversions) to find them. The National Fire Protection Association (NFPA) *Fire Protection Handbook* includes a table of conversion factors in its appendices.

Figure 2-1
SI Conversions

Temperature

Temperature can be provided in Fahrenheit (°F), Celsius (°C) or Kelvin (K) scale. In the Fahrenheit (°F) scale one unit or degree is equal to 1/180 of the difference between the temperature of melting ice and boiling water at standard temperature and pressure. For the Celsius (°C) scale, each unit or degree equals 1/100 of the difference between the temperature of melting ice and boiling water at standard temperature and pressure. Kelvin (K) or absolute temperature is the scale that is based on the average kinetic energy per molecule of a perfect gas. It uses the same size unit as the Celsius scale; however the degree symbol (°) is not used. Zero (0) on this scale is the temperature at which a perfect gas has lost all of its energy and all molecular activity ceases.

At zero elevation (sea level), standard temperature and pressure is 70.0°F (21.1 °C) and 14.7 pounds per square inch (psi) (101.3 kPa), which is the normal atmospheric pressure at sea level.

Figure 2-2 shows examples of temperature conversions.

Property	To Convert From	To	Formula
Temperature	Fahrenheit (°F)	Celsius (°C)	.56 x (°F-32)
Temperature	Celsius (°C)	Fahrenheit (°F)	(1.8 x °C) + 32
Temperature	Celsius (°C)	Kelvin (K)	°C + 273.15
Temperature	Fahrenheit (°F)	Kelvin (K)	°F + 459.69

Figure 2-2
Temperature Conversions

WHAT IS FIRE?

The Fire Triangle

Fire is a chemical reaction that produces physical effects: heat, light, and material decomposition. In the simplest of terms, the components of "fire" can be illustrated by the fire triangle. The sides of the triangle represent heat, fuel, and oxygen. As the graphic in Figure 2-3 shows, in addition to the heat, fuel, and oxygen, there is also the uninhibited chemical chain reaction. Some authors describe these conditions as a four-sided object: the fire tetrahedron. Regardless, while these depictions are sufficient for many situations, a more detailed understanding of the chemistry and physics of fire is necessary for the proper application of performance-based designs and codes.

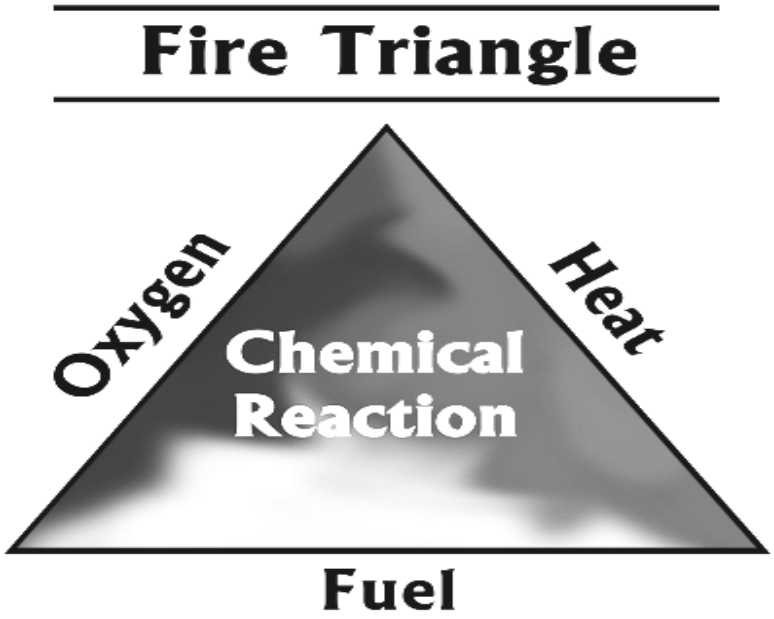


Figure 2-3
The Fire Triangle

COMBUSTION PROCESSES

In the precombustion phase of fire, fuels may be heated to their ignition temperature from a variety of sources. Ignition temperature is the minimum temperature a substance must attain in order to ignite under specific test (laboratory) conditions. Heat is the energy that is needed to maintain a change in temperature. Temperature is the measurement that expresses the degree of molecular activity of a material compared to a reference point such as the freezing point of pure water.

Pyrolysis

During the precombustion phase, vapors and solid particulate matter are being released from the fuel. These materials commonly are called pyrolysis products or pyrolyzate. Pyrolysis is the transformation of a material into one or more other substances by heat alone. Glowing combustion or smoldering may or may not be related to the oxygen level. Such glowing can occur during both the initial and final stages of a fire event. While a limited oxygen level may result in smoldering, such conditions also can be created by the amount of fuel vapor production or temperature.

Flaming combustion occurs when there is sufficient energy (heat), fuel vapors in the flammable range, and adequate oxygen. The chemical reaction must be unimpeded if the fire is to continue. These phases may exist individually or simultaneously in any given fire event.

Diffusion Flame Process

During flaming combustion, the flames are either diffusion or premixed. In most structural fire situations the pure fuel vapors are released and diffused or mixed with the surrounding air (oxygen). This mixing process is known as diffusion. If the fuel vapors and air mixture fall with the flammable range and an ignition source is present, ignition will occur. Flames, which are the result of this mixing of fuel vapors and air, are known as diffusion flames.

Premixed Flame Process

Premixed combustion occurs when the fuel vapors/gases are mixed in advance with an appropriate quantity of air or oxygen to form a mixture prior to ignition. Premixed combustion occurs during an explosion, but most commonly occurs with gas-fired appliances or industrial processes. Premixed combustion typically is more efficient and produces less smoke than diffusion flames.

THE IGNITION PROCESS

The traditional approach to fire and life safety is based on the assumption that unwanted ignition will occur, but that the building and fire protection features will minimize the impact of such ignition. Fire-resistive construction, compartmentalization, fire detection, and fire sprinkler systems "react" to the fire and--if all work properly--confine, report, and control the fire to some manageable level. If the fire is not suppressed by the fire protection system or timely occupant action, the local fire authorities may be called to intervene. Fire protection codes and protective inspections are intended to prevent fires from occurring, but if they do, the prescriptive design is called upon to perform.

In the context of performance-based design, the stakeholders must evaluate and explore the possibility and prevention of ignition by assessing the likelihood and frequency of fires in the property. The stakeholders must employ engineering techniques and reasoned judgment to predict the size and scope of a fire, and develop mitigating strategies to control it. The strategy is selected based on scientific principles and research into fire behavior, not just a list of prescriptive requirements printed in the codebooks.

Ignition

Ignition is that sequence of events that brings environmental fuels, oxygen, and a heat source together in adequate proportion to start a fire. Much of the content of fire prevention codes is based on ignition prevention: keeping flammable or combustible fuels away from heat sources.

When evaluating a building or facility, stakeholders must examine closely the potential types of ignition that might occur based on the operations, processes and storage that will exist. They are

- **Autoignition** that occurs when the fuel is heated sufficiently for the vapors to ignite without the presence of any outside arc, spark, ember, or open flame. Compressive and percussive forces often are adequate to ignite fuels.

- **Piloted ignition** that occurs when an arc, spark, ember, or open flame ignites fuel vapors. The amount of energy (heat) required for piloted ignition is less than that necessary for autoignition. This is because the "pilot" is igniting vapors, rather than heating the solid fuel.

- **Spontaneous heating to ignition**--often called "spontaneous combustion"--is a form of autoignition. Certain fuels are or can become "self-heating." This process is commonly known as spontaneous heating. This is a process whereby a material increases in temperature without drawing or absorbing heat from its surroundings. The process results from oxidation, often aided by bacterial action when agricultural products are involved. Under the right conditions, the self-heating can generate sufficient temperatures for ignition to occur. When ignition occurs as a result of spontaneous heating, it is known as "spontaneous ignition." Figure 2-4 lists some of the materials that are subject to spontaneous heating and ignition.

Alfalfa meal	Used burlap bags
Castor oil	Charcoal
Coal	Cocoanut oil
Cod-liver oil	Corn meal feeds
Cottonseed	Fish meal
Foam rubber	Linseed oil
Metal powders	Peanuts/Oil
Powdered eggs	Powdered milk
Powdered latex gloves	

Figure 2-4
Partial List of Materials Subject to Spontaneous Heating and Ignition

Ignition Temperatures

Different fuels have different ignition temperatures: the temperature to which they must be heated to sustain combustion. Unfortunately, laboratory-established ignition temperatures might not be replicable outside of scientifically controlled conditions in the "real" world. Due to the wide range of variables that can exist outside the lab, ignition temperatures should be regarded as approximations.

Variables affecting ignition temperature include the rate and duration of fuel heating, the shape and volume of the test container, the kind and temperature of the ignition source, airflow, and the variables of contaminants in the fuels. Fuels found in the environment seldom are as pure as those tested in a laboratory.

According to NFPA 325, *Guide to Fire Hazard Properties of Flammable Liquids, Gases, and Volatile Solids*, another dilemma occurs with the definition of when during the test a material actually ignites. Early research relied on visual flame observations, but now testing procedures detect flames with infrared and ultraviolet devices, thus permitting detection of flames before they give off light that can be seen by humans.

Some texts differentiate between "ignition temperature" and "autoignition temperature" to describe piloted ignition and nonpiloted ignition temperatures, respectively. Generally, autoignition depends on fuel composition and pressure. Figure 2-5 shows the variation in autoignition temperature for propane, a liquefied petroleum gas.

Percent Propane In Air	Autoignition Temperature	
	°F	°C
1.5	1,018	548
3.75	936	502
7.65	889	476

Source: NFPA *Fire Protection Handbook*, 18th Edition p. 1-58.

Figure 2-5
Autoignition Temperature Affected by Fuel Concentration (Propane)

Figure 2-6 provides a sample of some common products and their autoignition temperature.

Material	Autoignition Temperature	
	°F	°C
Acetone	869	465
Ammonia	928	498
Butane	550	288
Ethane	882	472
Ethanol	685	363
Gasoline (varies based on octane rating)	536-880	280-475
Methane	999	537
Methanol	725	385
Octane	403	206
Propane	842	450
Toluene	896	480

Source: NFPA *Fire Protection Handbook*, 18th Edition p. 3-34.

Figure 2-6
Autoignition Temperature of Common Fuels

Figure 2-7 provides some samples of fuels and their range of ignition temperatures.

Material	Ignition Temperature	
	°F	°C
Ammonia (refrigerant)	1,210	660
Asphalt	905	485
Cotton	750	400
Cottonseed oil	650	343
Ethanol	798	425
Gasoline (100 octane)	824	440
Kerosene (Fuel Oil No. 1)	410	210
Natural gas	900-1,170	482-632
Paper newsprint (cuts)	450	232
Polyester fiberglass composite wall panel	830	447
Polyethylene construction material (rigid)	824	444
Polypropylene siding, rigid	651	363
Polypropylene concrete forming unit	698	370
Polyvinyl chloride soffit material (rigid)	752	403
Recycled plastic/wood waste lumber substitute	698	370
Refrigerant, home air conditioner (hydro-fluorine)	386	198
Refrigerant, home air conditioner (hydro-carbon)	1,585	887
Urethane foam	852-1,074	456-759
Wood (fir, oak, pine, etc.)	378-507	192-265

Source: NFPA 325, *Guide to Fire Hazard Properties of Flammable Liquids, Gases, and Volatile Solids*; various product Web sites.

Figure 2-7
Ignition Temperatures of Sample Fuels

FUELS

Fuels may be materials used for the construction of the structural frame of the building, its interior finishes and its contents. Fire behavior is affected by both the available fuel and air or oxygen. Fuels may exist in the solid, liquid, or gaseous state, but only the vapors actually burn. For flammable liquids and gases, adequate concentrations of vapor may exist in their natural state that would enable piloted or autoignition to occur. For solids, pyrolysis releases vapors from the solid surface where they can mix with adequate quantities of air or oxidizers to sustain combustion.

Fuel or Fire Loading

Traditionally, fuel or fire loading has been expressed in pounds per square foot or kilograms per square meter, such as a value of 8,000 Btu's per pound (18,608 J per g). This method does not reflect the rate at which the fuel will burn, but is limited to the amount of potential fuel available.

Quantity of Heat Released

The quantity of heat released by a fuel is controlled by its heat of combustion--the amount of energy produced by the burning of the fuel. The heat of combustion is influenced both by the physical form of the fuel and its chemical composition, also known as "fuel chemistry." This simply represents how much energy the fuel would release if completely consumed. It does not reflect the release over any specific time period. In fire dynamics research, the heat output is measured by the Joule.

The "heat of combustion" should not be confused with the "heat release rate" (HRR) which is discussed later. "Heat of combustion" is the total caloric value that can be extracted from a fuel under perfect conditions. HRR pertains to the speed at which combustibles will burn.

The AHJ should remember that the heat of combustion values that are listed come from controlled experiments with the cone calorimeter. The calorimeter measures the oxygen consumed during a fire to establish the heat of combustion. The test procedures also presume 100-percent fuel consumption. While total fuel consumption may be feasible for flammable gases or liquids, it is uncommon for solid fuels. Also, remember the fuel samples are controlled for moisture, density, weight, and purity.

Fuels that normally exist in a gaseous state and those that produce sufficient vapors at normal ambient temperatures (flammable liquids, e.g., gasoline) present a higher hazard, since no preheating is necessary for combustion to occur in the presence of a competent ignition source. The development of a fire depends on the fuel and its state, the location and geometry of the fuel, and the ventilation.

Many of the materials used in the building construction and contents are synthetics or are hydrocarbon based, e.g., plastics. These materials have a much greater energy potential than traditional building materials such as wood. As the chart in Figure 2-8 shows, hydrocarbon-based fuels have approximately twice the energy potential of ordinary combustibles.

Material	Heat of Combustion (Btu/lb)	Heat of Combustion (kJ/kg)
Asphalt	17,150	39,890
Corrugated fiber carton	5,970	13,886
Cotton batting	7,000	16,282
Gasoline	19,250	44,775
Cottonseed oil	17,100	39,774
Paper newsprint (cuts)	7,883	19,336
Paraffin oil	17,640	41,030
Polystyrene	18,000	41,868
Polyvinyl chloride (rigid) (PVC)	7,500-9,500	17,445-22,097
Wood (sawdust shavings)	7,500-9,500	17,445-22,097
Wood--oak	8,493	19,754
Wood--pine	9,676	22,506
Wrapping paper	7,106	16,770

Note that the SI value is converted to kilojoules. One kilojoule equals 1,000 Joules.

Figure 2-8
Energy Potential (Heat of Combustion):
Common Combustibles

The heat of combustion values are inputted into some fire effects models to display outcomes. It is essential that the AHJ be aware of the data that is included as a system input to assure the results are within the limits he or she expects. If, for example, a fire effects modeler inadvertently inputs a heat of combustion value for cotton batting instead of polystyrene as a variable in the computer routine, the outcomes would be widely divergent.

Flammable or Explosive Limits

For any ignition to take place, the fuel must be heated sufficiently to produce enough vapors so that, when mixed with air, they fall within the flammable or explosive range/limit. Flammable limits are the upper and lower concentration limits of a vapor or gas in air that can be ignited. Several factors, working together, affect whether or not sufficient vapors will be produced. These factors include the temperature and energy of the heat source and the thermal properties, density, and heat absorbing capacity of the material (fuel).

Flammable ranges are important considerations in those occupancies where flammable or combustible liquids or gases are used, processed, dispensed, or stored. One recognized mitigation strategy to prevent fires in these environments is to provide natural or mechanical ventilation adequate to prevent vapor-to-air concentrations within their flammable range.

Figure 2-9 provides a sample of common products and their laboratory established flammable limits.

Material	Lower Flammable Limit (%)	Upper Flammable Limit (%)
Acetone	2.5	12.8
Acetylene	2.5	100
Benzene	1.2	7.8
Carbon monoxide	12.5	74
Ethylene	2.7	36
Gasoline	1.4	7.6
Isobutane	1.8	8.4
Propylene Glycol	2.6	12.5
Toluene	1.1	7.1

Source: NFPA 325, *Guide to Fire Hazard Properties of Flammable Liquids, Gases, and Volatile Solids*

Figure 2-9
Common Product Flammable Limits

Note: As with any hazardous materials analysis, the AHJ should consult at least three sources of information, including product Material Safety Data Sheets, independent consultants and chemists, product manufacturers, the local hazardous materials response team, or other reliable sources, before evaluating mitigation plans.

Fire Development

Traditional Fire Stages

Traditionally, fires have been categorized in three basic stages: incipient, free burning, and smoldering. The incipient stage is when there is no active or open flaming. In this stage, glowing or smoldering combustion may be present for a considerable period of time. In the free-burning stage, open flaming is present, with increased fuel consumption and heat production. The last stage, smoldering, occurs when the oxygen level decreases below 14 to 15 percent. If an additional oxygen supply is introduced, the fire may return to the free-burning stage. These descriptions, while helpful in certain circumstances, are not definitive enough for use in performance-based design.

Fire Realms

Some fire protection texts have established different realms of the fire process. These realms are shown in the table in Figure 2-10 and graphically in Figure 2-11.

Realm	Approximate Range of Fire Sizes	Major Factors That Influence Growth
1. Preburning/ Precombustion	Overheat to ignition.	• Amount and duration of heat flux • Surface area receiving heat from material ignitability • Pyrolyzation rate
2. Initial burning	Ignition to radiation point 10" (254 mm) high flame.	• Fuel continuity • Material ignitability • Thickness • Surface roughness • Thermal inertia of fuel • Pyrolyzation rate
3. Vigorous burning	Radiation point to enclosure point 10" (254 mm) to 5' (1.5 m) flame.	• Interior finish • Fuel continuity • Feedback • Material ignitability • Thermal inertia of the fuel • Proximity of flames to surfaces
4. Interactive burning	Enclosure point to ceiling point 5' (1.5 m) to flame touching ceiling	• Interior finish • Fuel arrangement • Feedback • Height of fuels • Proximity of flames to walls • Ceiling height • Room insulation • Size and location of openings • HVAC operation

Figure 2-10
Realms of the Fire Process

Realm	Approximate Range of Fire Sizes	Major Factors That Influences Growth
5. Remote burning	Ceiling point to full room involvement Flame touching ceiling to flashover.	• Fuel arrangement (amount and location) • Ceiling height • Length/Width ratio • Room insulation • Size and location of openings • HVAC
6. Full room involvement	Ceiling point to full room involvement Flame touching ceiling to flashover.	• Fuel arrangement (amount and location) • Ceiling height • Length/Width ratio • Room insulation • Size and location of openings • HVAC • Fire protection and control features

Figure 2-10 (cont'd)
Realms of the Fire Process

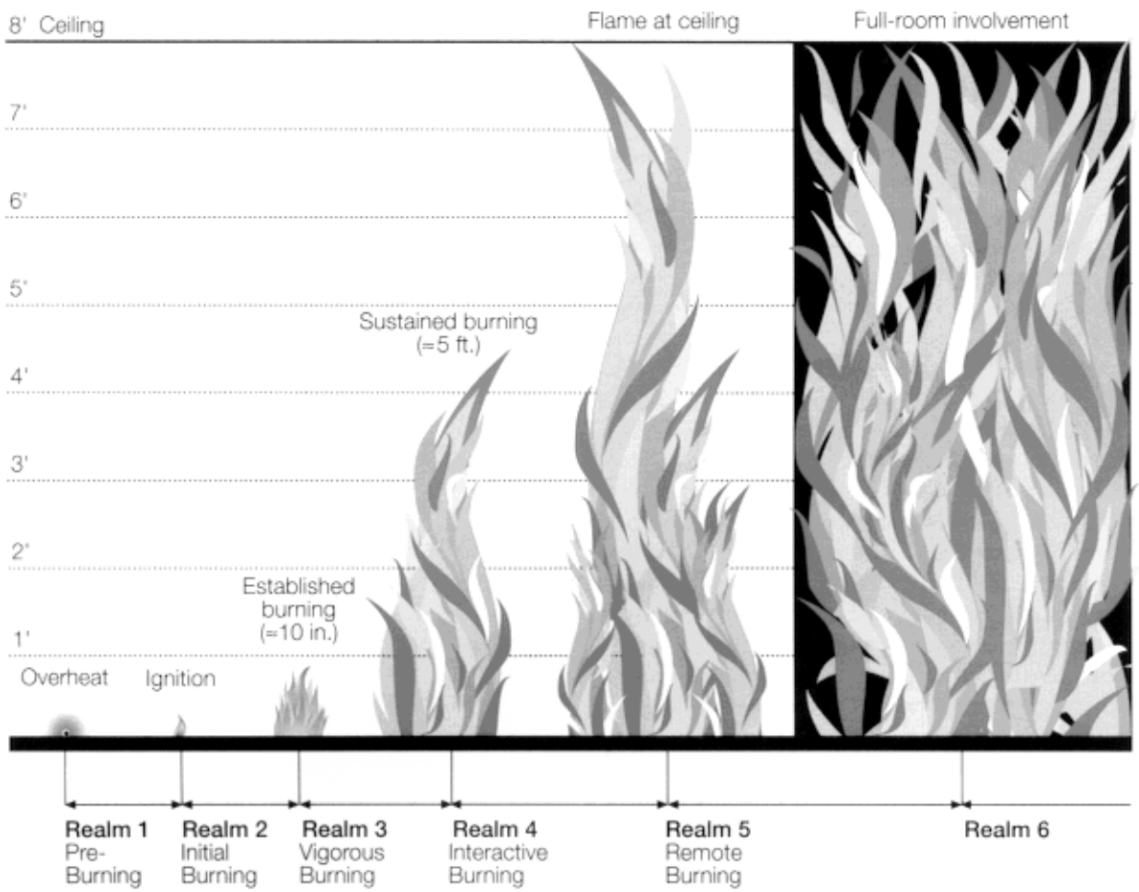


Figure 2-11

Graphic Depiction of the Fire Realms

The behavior of the initial fire within a compartment often will determine the extent of fire spread within and beyond the compartment of origin. While preventing ignition from ever occurring is a laudable goal, in most instances it must be assumed that ignition will occur. When a fire has reached a point where the size of the flame is sufficient to allow for continued flaming combustion without any additional, independent heat source, it is considered to be "established burning." The flame height during this phase often is considered to be at 10 inches (250 mm) from the fuel surface.

Fire Plumes

Directly above the fire, a column of hot gases and combustion products rises upward. This column is known as a "plume." As the hot gases rise, cooler air is drawn in or entrained into the plume; this is known as "entrainment." This cooler air is drawn from around the base of the fire and the boundaries between the plume and the surrounding air. The temperature of the plume decreases with the height above the fire, due to cooling effects of the entrained air.

As long as the environment around the fire plume is relatively stable and not influenced significantly by ventilation, the fire plume will rise in the shape of a cone. (When this pattern remains on a vertical surface after a fire, investigators often describe it as a V-pattern.) If doors or windows are opened, or a smoke management system operates, the path of the fire plume may vary dramatically. If the fuel array within the space is irregular, the fire plume may follow it.

If the plume temperature equals the surrounding air temperature, fire gases and smoke stop rising because they lose their buoyancy. Buoyancy is upward force due to the molecular activity of the heated gases near the fire plume. When this equalization occurs, the smoke begins to spread out horizontally, or stratify. In a tall compartment, such as an atrium or covered stadium, or with low energy fires, this loss of buoyancy may result in delayed activation of automatic fire detection devices, automatic fire sprinklers, rooftop smoke vents, or smoke management systems. Prescriptive building codes for a long time have required horizontal separations to prevent vertical air currents from carrying heat and toxic gases throughout the upper stories of a building. Normally, except for atrium designs, the model prescriptive building codes prohibit more than two adjacent floors from sharing a common atmosphere.

In day-to-day conditions, we often observe indoor air movement patterns that are influenced by the exterior weather conditions. The "stack effect" is the natural, vertical air movement in buildings caused by temperature differences and densities between indoor and outdoor air. Like fire plumes, when the buoyancy of the natural air currents diminishes, the stack effect may cause normal air pollutants in the ambient environment to spread horizontally.

Ceiling Jets

When the flames reach a ceiling or other horizontal barrier, the smoke and combustion products will spread laterally from the plume centerline. If the ceiling is smooth and flat, the flow generally is equal in all directions. The movement of the smoke and combustion products across the ceiling is known as the "ceiling jet." Plumes and ceiling jets are the mechanisms by which the hot gases and combustion products reach automatic fire detection devices and sprinklers.

Obstructed construction (such as beam pockets, waffle-slab construction, or deep joists), sloped or arched ceilings, irregular shapes, and finish materials affect the speed and direction of ceiling jets. Fire effects models for studying fire jets include only smooth ceiling configurations in their parameters, so the AHJ should be careful when evaluating test results to assure the proposed design matches the input data.

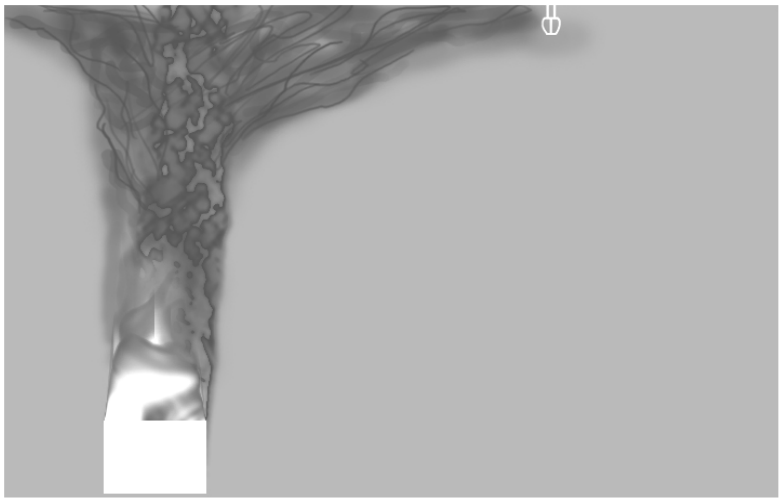


Figure 2-12
A Fire Plume and a Ceiling Jet

Flashover

As the fire in a compartment progresses, hot gases and combustion products rise, flames reach the ceiling, spread out (the ceiling jet), and begin to fill the upper portions of the room forming what is commonly known as the "upper layer." The upper layer is sometimes also referred to as the smoke layer or hot gas layer. As the fire continues, the upper layer thickens and will flow out into adjoining compartments through any openings. As the fire intensifies (increased heat release rate), the upper layer will descend closer to the floor. This results in what is known as "radiation feedback:" the condition of electromagnetic waves reflected from one heated surface to another. In this case, the opaque surface of the upper layer is an excellent reflector to radiate the heat back toward the floor. The temperature in the upper layer also will increase, resulting in greater radiant heat levels on other objects in the compartment.

If sufficient radiant heat is projected on the other objects in the room, flashover will occur. Flashover is the transition phase in the development of a fire: the combustible surfaces exposed to thermal radiation reach ignition temperature nearly simultaneously and fire spreads rapidly throughout the space. Under flashover conditions, the fire is dominated by the burning of all items in the compartment. It is the final realm of a growing fire.

Flashover generally occurs when the upper layer temperature reaches approximately 1,10°0F (593°C) and the radiant flux (heat flow) from the upper layer reaches approximately 20 kW/m^2 (0.00176 $Btu/ft^2/sec$). It has been shown that if the flame can be prevented from reaching the ceiling, the possibility of flashover occurring is reduced. Once flashover occurs, excess fuel vapors that cannot be consumed or combusted with the air available in the compartment will be produced and the fire will become ventilation controlled.

This may result in flame extension through vent openings into adjacent compartments and/or windows, if they fail or are open. Flashover will not occur in every fire scenario. If the fuel is limited or ventilation is insufficient, the ceiling layer may not develop sufficiently to make the transition to flashover.

Flameover or Rollover

It is possible for flameover to occur prior to flashover. Flameover is the condition where the underburned smoke and gases accumulated in the ceiling layer ignite. It is possible for flameover to occur without flashover. This condition also is known as "rollover."

Fully Developed Fire

A fully developed fire is a steady or postflashover fire at peak heat release rate. Its peak burning will last for a short or extended time, depending on available fuel and oxygen. Some fully developed fires occur with total involvement of the fire enclosure, often spreading to other enclosures if adequate fuel and oxygen exist and there is no compartmentalization or active fire protection to slow or suppress the fire.

Fuel Geometry or Location

The geometry or location of the fuels also can affect overall fire behavior. Large volume compartments or compartments with high ceilings allow dilution of fire gases and provide a "reservoir" for smoke. A fuel package that is located in a corner will result in faster fire growth than one located against a flat wall or out in the compartment. The number and configuration of compartment walls also can affect overall fire behavior. These factors will influence heat transfer and thus affect overall fire behavior. In performance-based design, this "reservoir" concept may be an effective method to consider for managing smoke migration throughout a structure.

Fuel geometry (the placement of fuel in the structure) also is important. Fuels that already are in a liquid or gaseous state are more hazardous than solid fuels because they are more easily ignited and may respond to environmental conditions such as wind or gravity; but even the configuration of solid fuels is important.

Consider a cut Christmas tree as an example. The typical tree weighs about 12 pounds (5.472 kg), but due to its large surface area and density, it is much easier to ignite than a solid block of wood that may have an equivalent heat of combustion. Once ignited, the tree burns at a much greater rate than the solid block.

Due to radiation feedback, a fire that originates in a small or confined space typically will grow faster than one that originates in the center of a large room. Certain construction materials, such as concrete or masonry floors, walls, and ceilings, are noncombustible and will act as heat "sinks," absorbing heat energy. Combustible materials that usually will ignite include paneling,

wallboard, ceiling tiles, wood framing, manufactured wood, and oriented strand board (OSB). The presence of heat sinks and combustible surfaces affects the rate at which a building contents fire becomes a structure fire, and the likelihood it will spread beyond the room of origin.

Fuel placement of such items as furniture, storage, or finishes within a building influences the development of a fire. How fuel burns depends on ventilation, surface area, and radiation feedback among the combustible materials and the room, walls, and ceiling surfaces. Some of the most dramatic examples of the impact of fuel placement come from applied research performed by FM Global Research (formerly Factory Mutual Research). Their warehouse fire protection study videos clearly show how materials stored on closely arrayed racks or pallets burn more ferociously than similar products separated by wide aisles and stored less than 12 feet (4.2 m) above the floor.

The size of the fuel also influences the fire development, as does the density--the thermal thickness or thinness--of the fuel. For example, a thick board will not burn as quickly as thin paneling; and a flat wall will burn less readily than a corner section (all things being equal, especially finishes).

All of these factors can influence the ignition potential, ventilation, available fuel, surface area, and heat transfer mechanisms during a fire event.

Ventilation

Atmospheric Oxygen

The third leg of the fire triangle is "oxygen." When combined with adequate fuel and a viable ignition source, the introduction of oxygen enables combustion to occur.

In the typical fire, the oxygen source is atmospheric air. The air we breathe consists of about 18 percent oxygen, 72 percent nitrogen, and trace amounts of other gases. The oxygen in air combines readily with fuels to sustain combustion. As long as the oxygen concentration remains above 14 to 15 percent, free-burning combustion can occur. As the amount of oxygen decreases, the "quality" of combustion decreases with greater production of toxic gases (especially carbon monoxide), soot particles, and smoke.

As the environment in an enclosure deteriorates due to consumption of the available oxygen, dangerous "backdraft" conditions can develop. A backdraft may occur when oxygen is introduced into a heated, confined space that is oxygen-deficient. The in-rush of oxygen enables the heated combustibles to ignite nearly simultaneously with almost explosive results. In fact, some fire suppression personnel use the term "smoke explosion" to describe a backdraft. During fire operations, firefighters work hard to open windows, doors, and other barriers to relieve smoke buildup before it reaches backdraft conditions.

Generally, in the early stages of fire development, the behavior of the fire is "fuel controlled," that is, there is a sufficient, if not excess, amount of air but a limited fuel supply. In a compartment with little or no ventilation, the fire will continue to grow and may reach a point

where the amount of fuel vapors being produced exceeds the amount that can be consumed with the available air or oxygen. A fire that is controlled or limited by the amount of available air or oxygen is "ventilation controlled."

Oxidizing Agents

In some circumstances, the oxygen portion of the fire triangle may be provided by an "oxidizer," a material that yields oxygen or other oxidizing gas, or that reacts to promote or initiate combustion of combustible materials. These materials support combustion in the absence of atmospheric oxygen. A list of oxidizers may include organic (with molecular carbon) or inorganic chemicals.

These materials have excess oxygen which may be liberated, especially at higher temperatures. This capacity to provide oxygen makes these chemicals a fire and explosion hazard when they come in contact with all forms of combustibles (wood, paper, textiles, plastics, etc.). In addition, mixtures of oxidizers and combustibles can be ignited by a heat energy originating from a weak ignition source such as friction, physical impact, or static electricity. Some of these compounds are capable of reacting with combustibles at room temperature with resulting in a fire and/or explosion. Figure 2-13 provides the classifications and a description of the potential hazards.

Class Rating	Hazard Description
Class 1	An oxidizing material whose primary hazard is that it may increase the burning rate of combustible material with which it comes in contact.
Class 2	An oxidizing material that will moderately increase the burning rate, or which may cause spontaneous ignition of combustible material with which it comes in contact.
Class 3	An oxidizing material that will cause a severe increase in the burning rate of combustible material with which it comes in contact, or which will undergo vigorous self-sustained decomposition when catalyzed or exposed to heat.
Class 4	An oxidizing material that can undergo an **explosive reaction** when catalyzed or exposed to heat, shock, or friction.

Figure 2-13
Oxidizer Hazard Classes

Other materials without oxygen in their chemical formula may be classified as oxidizers. To be defined as an oxidizer, the chemical substance simply must be capable of accepting electrons. Chemicals in the class of compounds known as the halogens (materials that can act as halogenating agents) fall into this category. Examples include fluorine and chlorine in the gaseous state, and bromine in the liquid state. Figure 2-14 provides a sample of some oxidizing chemicals by hazard class.

Hazard Class	Sample Oxidizers
Class 1	Aluminum nitrate, potassium dichromate, ammonium persulfate, potassium nitrate, barium chlorate, potassium persulfate, barium nitrate, silver nitrate, barium peroxide, sodium carbonate peroxide, calcium chlorate, sodium dichloro-s-triazinetrione, calcium nitrate, sodium dichromate, calcium peroxide, sodium nitrate, cupric nitrate, sodium nitrite, hydrogen peroxide (8-27.5%), sodium perborate, lead nitrate, sodium perborate tetrahydrate, lithium hypochlorite, sodium perchlorate monohydrate, lithium peroxide, sodium persulfate, magnesium nitrate, strontium chlorate, magnesium perchlorate, strontium nitrate, magnesium peroxide, strontium peroxide, nickel nitrate, zinc chlorate, nitric acid (<70% conc.), zinc peroxide, perchloric acid (<60% concen.)
Class 2	Calcium hypochlorite (<50% wgt), potassium permanganate, chromium trioxide (chromic acid), sodium chlorite (<40% wgt.), halane, sodium peroxide, hydrogen peroxide (27.5-52% conc.), sodium permanganate, nitric acid (>70% conc.), trichloro-s-triazinetrione
Class 3	Ammonium dichromate, potassium chlorate, hydrogen peroxide (52-91% conc.), potassium dichloroisocyanurate calcium hypochlorite (>50% wgt.), sodium chlorate, perchloric acid (60-72.5% conc.) sodium chlorite (>40% wgt.), potassium bromate, sodium dichloro-s-triazinetrione
Class 4	Ammonium perchlorate, ammonium permanganate, guanidine nitrate, hydrogen peroxide (>91% conc.), perchloric acid (>72.5%), potassium superoxide

Source: NFPA 325, *Guide to Fire Hazard Properties of Flammable Liquids, Gases and Volatile Solids*

Figure 2-14
Sample Oxidizers

Heat Transfer

In the environment, warm objects release their heat energy to cooler objects until a thermal balance is achieved. This balance is called "homeostasis." As heat is applied to a fuel in the early phases of combustion, some of the heat is absorbed or conducted into the interior of the material by molecular action. Conductivity is the ability of material to conduct heat, and is represented in formulas by the term "k." Materials with a higher density have a tendency to be more efficient heat conductors and thus have a higher k. The density of the material is

represented by the term "ρ" (pronounced "rho"). A material's capacity to store energy is expressed by the term "c." The amount of energy necessary to increase the temperature of a specific material is expressed by the term "$k\rho c$" (k rho c) also known as thermal inertia. This term represents the material's conduction, density, and heat capacity.

The effect of a material's k can be demonstrated by the following examples:

- Grasp an empty expanded plastic foam coffee cup. Notice that your hand feels warmer. This is because your body heat, which previously had been lost to the atmosphere, now is retained by the insulation effect of the cup and sensed by the nerves in your skin. The foam material has a low k factor. Likewise, it has a low ρ because during the manufacturing process the styrene material is air-injected to create its expanded characteristics.

- To compare, place your hand on a dense wooden surface like a tabletop. Notice that your hand feels cooler than before. This is because some of the heat from your hand is being absorbed into the metal, which has a high k factor and a high ρ.

When a fuel has a high $k\rho c$, it requires more molecular energy to raise its temperature. The surface of such a material will heat slower and therefore delay ignition. Conversely, the surface of a material with a low $k\rho c$ will heat more rapidly, and ignition will occur more quickly. Many building materials used in fire-resistive construction (i.e., gypsum, concrete masonry units, monolithic concrete, spray-on fireproofing) are effective because of their high $k\rho c$ values.

Ignition temperature is represented by the term "$T_{ig.}$" For ignition to occur, a "competent" ignition source must be present. A competent ignition source is one that has both sufficient temperature and energy to raise a fuel to its ignition temperature during the contact period. While the temperatures of many potential ignition sources exceed the ignition temperature of common fuels, the ignition source must last long enough, and be in contact with the fuel long enough, to raise the fuel to its ignition temperature.

As an example, an 110/220-volt electrical arc results in temperatures in the 6,000°-10,000°F (3,343°-5582°C) range; however in most instances the event is extremely short lived and the contact period is limited. Unless the arc occurs in the presence of flammable vapors or other material with a low $k\rho c$, ignition will most likely not occur.

Heat Transfer Mechanisms

A major factor affecting fire behavior is the transfer of heat. This affects ignition, growth, spread, decay, and extinction. The three mechanisms of heat transfer are conduction, convection, and radiation.

Conduction

Conduction is the form of heat transfer that takes place within or between solids when one portion of an object is heated. For example, if you place your hand on your desk it will feel cold

because you are transferring heat from your hand to the desk. Energy is transferred from the heated area to the unheated area. If the thermal conductivity (k) of the material is high, the rate of heat transfer will be high.

Convection

Convection is the transfer of heat energy by the movement of heated liquids or gases from the source of heat to a cooler part of the environment. For example, if you place your hand above a lighted candle, you will receive heat by convection. Convection plays a major role in the spread of smoke and fire gases to the upper portions of the room of origin and throughout a building.

Radiation

Radiation is the transfer of heat energy from a hot surface to a cooler surface by electromagnetic waves without an intervening medium. For example, if you put a lighted candle into a holder and hold your hands on either side of it, your hands will be heated by radiation. Radiant energy is transferred only by line of sight and will be reduced or blocked by intervening opaque materials.

Measuring Heat Transfer

Heat Flux

Heat flux is simply the measurement of the amount of heat that is transferred to a surface or target fuel. Heat flux is expressed as the heat flow rate per unit area and is measured in $Btu/ft^2/sec$ or kW/m^2. Heat flux measurement is important when evaluating the likelihood that a fire will migrate through a structure. It also is used in the Radiant Panel Test (see below) to evaluate the combustibility of floor covering products.

Figure 2-15 provides samples of representative heat fluxes.

Heat flux radiated from	Btu/ft^2/sec	kW/m^2
Human body on hot summer day (98°F; 37°C)	0	0
Interior through insulated wall (R19) on cold winter day (14°F; -10°C)	0.008	0.009
Human body on cold winter day	0.22	0.025
Sun, on a clear day in the tropics	0.12	1.4
100-watt incandescent bulb at 3.9 inches (10 cm)	0.56	6.4
Source that burns human skin in 10 seconds	0.88	10
Source that burns human skin in 1 second	4.41	50
Propane torch at flame tip	8.81	100
Oxy-acetylene torch at flame tip	88	1,000
Surface of the sun (radiation only)	5,727	65,000

Source: Vatell Corporation

Figure 2-15
Heat Flux Values for Common Conditions

Figure 2-16 provides samples of the minimum heat flux required to ignite these products.

Material	Btu/ft^2/sec	kW/m^2
Phenolic foams, rigid	0.616	7
Red oak	0.968	11
Polyethylene, rigid	1.672	19
Polyethylene, foam	1.672-1.936	19-22
Polypropylene	1.76	20
Polystyrene, foams or rigid	1.584-2.376	18-27
Polyvinyl chloride (PVC)	1.848	21

Source: NFPA Fire Protection Handbook, 18th Edition.

Figure 2-16
Minimum Heat Flux for Ignition

Heat Release Rate or Rate of Heat Release

The rate at which a fuel burns and releases its energy is known as the heat release rate (HRR). Some fire protection texts refer to this as the rate of heat release (RHR). The rate of heat release is determined by multiplying the mass loss rate (mass/time) by the heat of combustion (energy/mass) and the combustion efficiency (the portion of the mass actually converted to energy).

The HRR is influenced by the fuel's physical form and its chemical composition, also known as "fuel chemistry." HRR is quantified using the kilowatt. Remember, "heat release rate" is not the same as "heat of combustion" since it describes release over any specific time period.

In formulas, the RHR is expressed as "$\dot{Q}$". This is expressed in units of energy per unit time watts (Joules/second), kilowatts (kiloJoules/second), or megawatts.

A fire that is increasing in energy output is classified as a "growing fire." Normally, this type of fire will be fuel controlled. When the HRR becomes relatively constant over time, with neither a rapid increase nor decrease, the fire is considered to be in a "steady state."

Figure 2-17 graphically depicts a steady state fire.

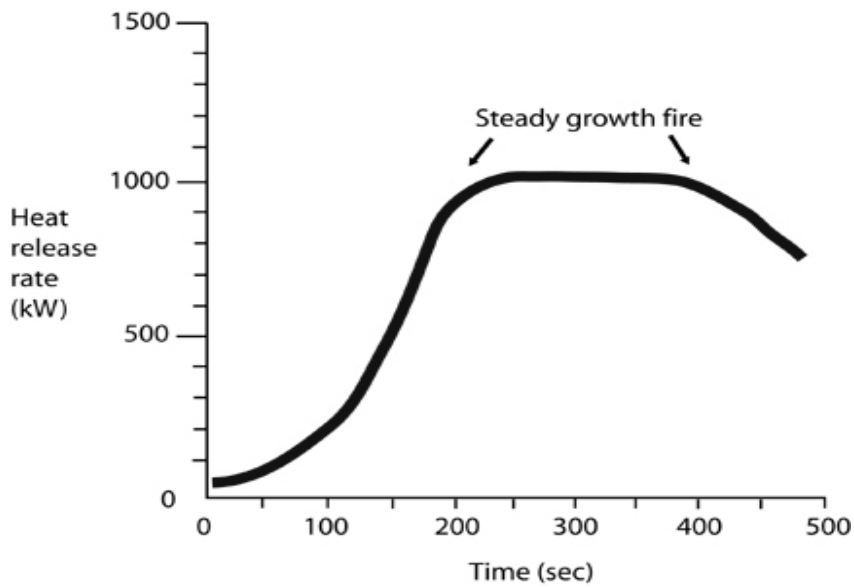
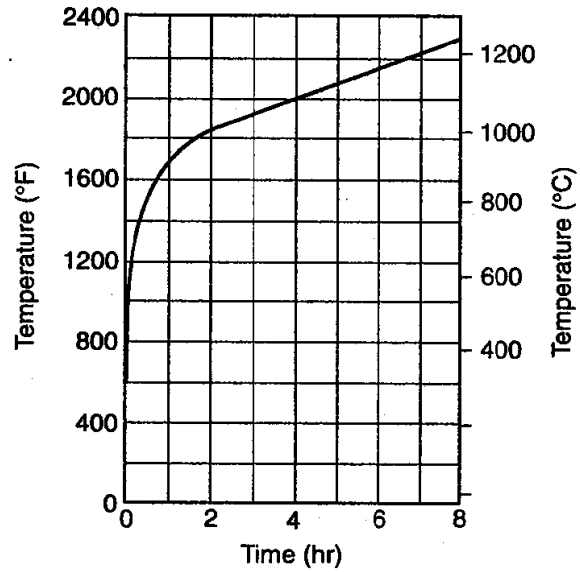


Figure 2-17
Graph of a Steady State Fire

Steady state fires are the basis for the Standard Time/Temperature Curve (STTC) used for evaluating the fire-resistance performance of common building materials. The STTC was adopted by the American Society of Testing and Materials (ASTM) in 1918, and is the basis for several NFPA fire test standards.



Note: The following are the points that determine the curve.

1000°F (538°C).....at 5 minutes
1300°F (704°C).....at 10 minutes
1550°F (843°C).....at 30 minutes
1700°F (927°C).....at 1 hour
1850°F (1010°C).....at 2 hours
2000°F (1093°C).....at 4 hours
2300°F (1260°C).....at 8 hours or over

Source: NFPA 251, *Standard Methods of Tests of Fire Endurance of Building Construction and Materials*, 1999 Edition.

Figure 2-18
Standard Time/Temperature Curve

T^2 Fires

Fires also can be defined by the time it takes to reach a given HRR. While we base current fire protection decisions on a test procedure almost a century old, current research shows that most fires grow exponentially, that is, the RHR increases to the square of the burning time. These fires are commonly referred to as "T squared fires." The HRR of the growth phase can be expressed as:

$\bar{Q} = \alpha t^2$
α = fire growth constant usually expressed in kJ/sec $^{(n-1)}$
t = time after ignition beginning with open flaming, normally expressed in seconds

By comparing the T^2 fires to the STTC, it is evident more research needs to be accomplished to assess the performance of fire-resistive construction when exposed to the fuel arrays more commonly seen today.

Heat Release Rate for Different Types of Fuel

Research has also established fire growth constants (α) for four standardized T^2 fires as follows:

Category	Fire Growth Constant kJ/sec $^{(n-1)}$	Time to Reach 1 MW Heat Release Rate
Ultrafast	α = 0.1876 kJ/sec$^{(n-1)}$	75 sec. or 1.25 min
Fast	α = 0.0469 kJ/sec$^{(n-1)}$	150 sec. or 2.5 min
Medium	α = 0.01172 kJ/sec$^{(n-1)}$	300 sec. or 5 min
Slow	α = 0.00293 kJ/sec$^{(n-1)}$	600 sec. or 10 min

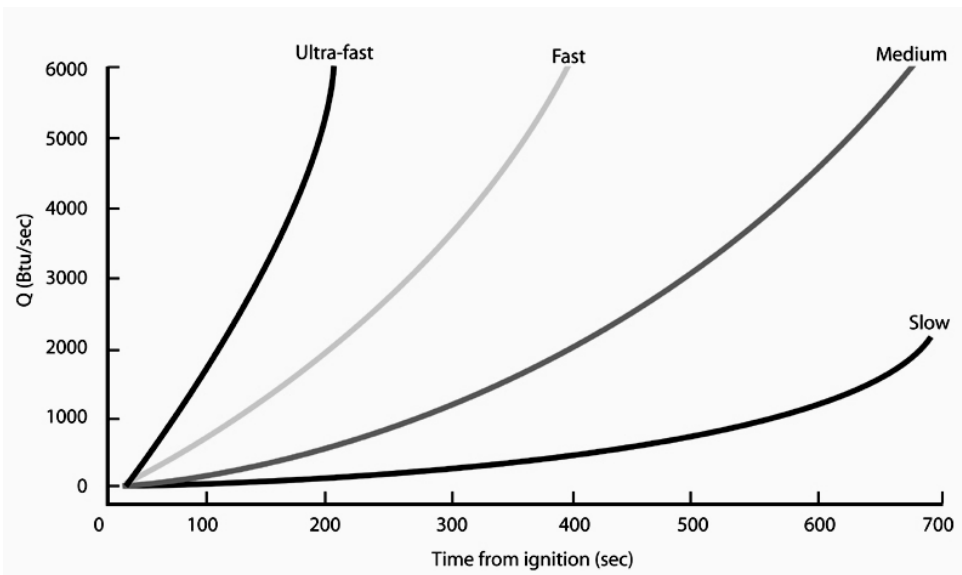


Figure 2-19
Fire Growth Rates for T^2 Fires (Btu/sec)

Examples of these fires shown in Figure 2-20, are as follows:

Category	Fuel Array
Ultrafast	Thin plywood wardrobe cabinet, upholstered furniture.
Fast	5 ft. high stack of empty wood pallets; 15 ft. high stack of cartons of various contents.
Medium	3 ft. high pallet stack of full mailbags; cotton/polyester innerspring mattress.
Slow	Solid wood cabinetry; wood table; bedroom dresser.

Figure 2-20
T^2 Fire Fuel Arrays

Other examples can be found in NFPA 92B, Guide for Smoke Management Systems in Malls, Atria, and Large Areas, Appendix B.

These "standardized" fires should be used with caution in performance-based design, when other specific fire data are not available. In certain circumstances or conditions, the use of these data would be inappropriate. These standardized fires would not be appropriate for use in situations where flammable liquid pool fires are anticipated, or for occupancies such as warehouses or "big box stores."

Figure 2-21 shows the HRR for a sofa.

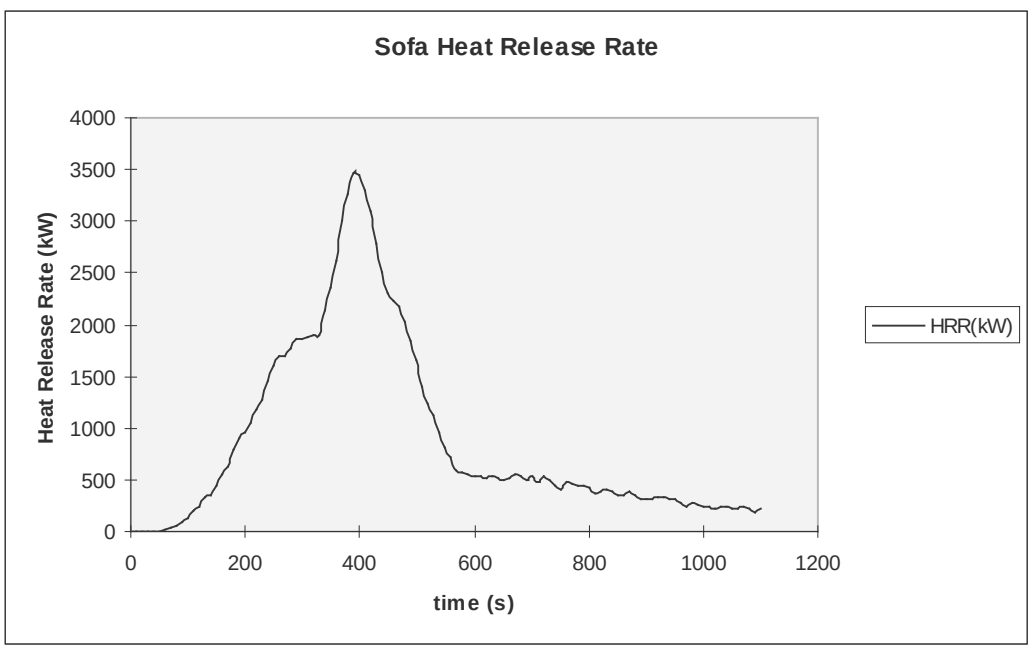


Figure 2-21
Heat Release Rate for a Sofa

A lot of research remains to be done in this field. The complex interrelationships of fuel, ventilation, and geometry mean that every fire will be different.

While it is important to study a materials' rate of heat release, another term occurs in fire studies: **peak** heat release rate. This is the point in the fire where the burning material is releasing its maximum heat output. For example, a fire in a pile of waste paper releases a relatively small amount of heat until optimum fuel: oxygen ratios are reached causing the fire to burn its hottest.

Figure 2-22 provides a list of common materials and their **peak** heat release rates under laboratory conditions.

Item	Weight (lbs)	Peak HRR (Btu/sec)	Peak HRR (kW)
Burning cigarette		0.004739	0.005
Burning match		0.75828	0.08
Small trash can fire	1.5 to 3	47.355 to 284.13	50 to 300
Trash bags, 11 gallon with mixed plastic and paper trash	2.5 to 7.5	132.7 to 331.7	140 to 350
Cotton mattress	26 to 29	37.9 to 919.4	40 to 970
Televisions sets	69 to 72	113.7 to 274.8	120 to 290
Plastic trash bags with paper trash	2.6 to 1	113.7 to 331.7	120 to 350
PVC waiting room chair, metal frame	34	255.9	270
Cotton easy chair	39 to 70	274.8 to 350.7	290 to 370
Gasoline/Kerosene in 2 ft^2 pool		379.1	400
Christmas trees, dry	14 to 16	473.9 to 616.1	500 to 650
Polyurethane mattress	7 to 31	767.7 to 2492.8	810 to 2630
Polyurethane easy chair	27 to 61	1279.6 to 1886.2	1350 to 1990
Burning upholstered chair		75.68 to 2369.6	80 to 2500
Polyurethane sofa		2957.3	3120
Burning Christmas tree	12 to 14	1516.5 to 4928.8	1600 to 5200
Base design fire*		4995.7	5275

Source: NFPA 921, *Guide for Fire and Explosion Investigationss*

* Minimum Heat Release Rate design fire for smoke management system design required by the *International Building Code*.

Figure 2-22
Sample Peak Heat Release Rates

CONVERSIONS

1 Btu per second	=	1.055 kW
1 kW	=	0.94786 Btu per second
1 kW	=	1,000 W
1 MW	=	1,000,000 W
1 GW	=	1,000,000,000 W

Interior Finish Flammability

Even if a building is constructed of noncombustible materials, human occupants still introduce combustible finishes to soften the environment. Many tragic fires have occurred from easily ignited or fast-burning interior finishes on walls or ceilings.

Walls and Ceilings

To identify and categorize materials as to their relative fire risk, building codes classify interior wall and ceiling materials by flame-spread ratings in accordance with Steiner Tunnel Test requirements (ASTM E84 and NFPA 255 Standards). Materials are classified to indicate their ability to support combustion and flame. Finish materials are compared to the fire-spread characteristics of red oak to express their relative risk.

Almost all building codes cite ASTM E84 as the basis for their applied standards. This test, widely known as the Steiner Tunnel Test, simulates a fire exposure of about 2,400°F (1,316°C) in the area of the flame. In the test, a 36-square-foot (3.34 m^2) test sample is placed in the top of the Steiner Tunnel, and heated by gas flames for 10 minutes at a rate of about 5,000 Btu/min. (88kW). This creates a temperature near the test sample of about 1,600°F (871°C).

The time is measured for the flame to travel down the tunnel for the length of the material, or until the flame ceases. That time is then imposed on a scale developed by rating cement asbestos board time performance at "0," and the time performance of select grade red oak at "100." These ratings indicate the rate at which fire will spread across the surface of a material. For example, a wall decorated with paper will have a faster flame spread rating than a bare wall.

Figure 2-23 represents the classifications from the Steiner Tunnel Tests. The numbers in the Flame Spread Rating column are derived from mathematical formulas, and are **not** interpreted as feet/sec., inches/min., etc.,

Class	Flame Spread Rating	Max. Smoke Development
1 or A	0-25	450
2 or B	26-75	450
3 or C	76-200	450

Figure 2-23
Flame Spread Classifications

Likewise, the Maximum Smoke Development values are mathematically derived from a light absorption per minute relationship. NFPA 255, *Surface Burning Characteristics of Building Materials*, Appendix D, provides a detailed explanation of the Steiner Tunnel Test procedures.

Floor Finishes

Floor surfaces, because of their orientation and radiation feedback from heated upper layers of a fire, respond differently from walls or ceiling finishes. Consequently, they must be tested under different conditions.

Floor covering samples are tested in accordance with ASTM E648 and NFPA 253 standards that measure "critical radiant flux": the amount of energy from an overhead test apparatus that will ignite the floor finish. The test is intended to simulate the conditions from a room flashover.

The building and fire codes establish floor finish "classes" based on the materials' ignition resistance. Class "1" indicates a higher amount of heat is required ($0.45 W/cm^2$). Class "2" indicates a lower amount of heat is required ($0.22 W/cm^2$). From a fire safety perspective, Class 1 is preferable to Class 2.

Fire officials must remember that before approving a product for installation, the test data must represent the conditions in which the material will be used. For example, carpeting that will be installed on a wall must be tested in accordance with the flame-spread requirements established in the Steiner Tunnel Test rather than the critical radiant flux procedures.

Structures and Contents

In the context of performance-based design, this review and emphasis on fire dynamics is important for the AHJ. When evaluating a performance-based design, rather than comparing the proposal to a prescriptive list of fire safety options based primarily on empirical evidence, the AHJ must consider scientifically derived data and its application to the built environment.

The geometry of structures and contents has a significant effect on the outcome of a fire. Even the prescriptive codes recognize this by establishing property line setbacks, minimizing vertical openings, separating or isolating hazardous processes or occupancies, and providing active fire protection to confine and control a fire.

Building Design Influences

We construct buildings to protect people and possessions from the elements, including rain, snow, sleet, floods, earthquakes, cold, heat, dust, and even outdoors fires. When we erect structures, we create spaces that define boundaries. The walls, floors and roofs of buildings provide an "envelope" in which myriad human activities occur. Unfortunately, one of these activities can be unwanted fires.

Students of fire protection history know how major fires and catastrophes influence changes in building and fire codes (see Unit 1: Introduction). We anticipate these changes result in better

structures that are able to resist these environmental influences. But what about the buildings' interiors? What designs, orientations, architectural statements or materials influence fire behavior? Not every building shares the same geometric features of slab floor, plumb walls, flat ceilings, or limited openings. The wide variety of spatial designs affect fire plumes, ceiling jets, heat transfer, and smoke migration. These design considerations also include the location of the structure on the site and its proximity to other buildings or fire hazards, e.g., structures, fuel tanks, and the proximity of the fire to walls and corners, all of which also affect fire behavior.

In the prescriptive building codes, passive fire-rated separations (i.e., firewalls and floor/ceiling assemblies) and fire sprinklers systems are required to provide a means to slow a fire for occupant escape, or keep a fire small enough that the fire suppression forces should be capable of controlling it. In performance-based designs, these separations may not be employed when considering the other features that may be provided. Therefore, the AHJ must look at the overall performance of the building design when evaluating performance solutions.

Some of the building design influences that the AHJ must consider in performance-based designs include

- **Compartment volume**. Small compartments generally will reach flashover conditions faster than large ones because of the reradiative effects of the smoke layer and the proximity to adjacent combustibles.

- **Ceiling height**. All things being equal, it seems obvious that the higher the ceiling is above the fire, the longer it takes for the fire plume to reach it. But what about conditions where the ceiling height is variable in the same compartment? When evaluating fire effects model performance, how might the AHJ assure that the model considers these deviations?

- **Ceiling configuration**. Fire effects models are based on flat, smooth ceiling construction. How does the designer represent the challenges created by heavy timber or concrete waffle-deck construction where deep pockets affect air currents, creating eddy effects in fire plumes and ceiling jets?

- **Ceiling slope**. The design and geometrics of sloped ceilings are limited only by an architect's creativity and an engineer's ability to provide structural support. One must consider the differences in fire plumes and ceiling jets among arched, sloped, clerestory, or dome ceiling designs.

- **Atriums**. A popular design feature used to provide interior spaciousness, atriums penetrate more than two adjacent floors of a building, thus creating a chimney effect for hot smoke and toxic gases. Air flow through and from adjacent tenant spaces may affect air distribution currents. Many atriums are outfitted with sprinklers and smoke management systems that will affect fire behavior.

- In some circumstances, the height of the atrium is significant enough to observe stack effect in the atrium: the condition where heated fire gases lose their upward buoyancy and begin to settle out or travel horizontally.

- **Vertical and horizontal openings**. Prescriptive building and fire codes focus heavily on confining fires both vertically (floor/ceiling assemblies, stair enclosures, shaft construction) and horizontally (fire separations, fire-walls) within the limits established by the codes. Performance-based designs may rely on these passive barriers less and less as they substitute alternate means of protection.

- Furthermore, the prescriptive codes pay close attention to those spots where penetrations occur through fire-resistive barriers. Pipes, tubes, cables, and related features that are "punched through" fire-resistive walls and ceilings are a weak spot in the barrier, and must be protected to an equivalent level of fire resistance.

- **Surface finishes**. The interior finish of the space must be evaluated carefully. Material flame spread ratings must be considered, especially if the proposed design incorporates a new material, or an old material applied in a new way. The performance-based codes do not prescribe maximum flame spread ratings like the prescriptive codes do, so the AHJ must remember the important interaction between and among the wall, floor and ceiling finishes.

- **Construction materials**. Performance-based codes do not address specific construction materials. If a designer can justify a four-story wood frame structure on top of an eight story noncombustible building, and make it meet the stakeholders' performance criteria, there is no prohibition of this mixed type of material.

- **Active fire protection**. Sprinklers, water spray, smoke management, and special agent systems all play an important part in fire control. The AHJ must assure these items are considered when reviewing the potential fire behavior in a structure.

- **Ventilation**. Natural or mechanical ventilation, or both, dramatically affect fire behavior in buildings. Fire effects models are limited in their ability to assess the impact of openings (called "vents") on fire dynamics in a building. An architect or designer may want to design a facility that relies heavily on natural ventilation, but how can that be modeled or evaluated over a 24-hour-a-day, 365-day-a-year period for the life of the building? How might "normal" air currents change when the heating, ventilation, and air conditioning system (HVAC) operates? Or, what will occur when the HVAC system--which may be an integral part of the smoke management system--fails to operate?

Influences of Contents

Building contents may change daily. One day, a structure may have a nominal amount of combustibles in it, and the next, it may be full of highly flammable materials. While this is true as well for buildings constructed under prescriptive codes, it is particularly acute for performance-based designs when fire effects models must consider heat of combustion and heat release rates to measure successful performance of the design.

Some of the contents influences that the AHJ must consider in performance-based designs include

- **Fuels**. For years, the fire service has referenced "Class A" combustibles: those products that leave an ash when they burn. The fire behavior of most Class A combustibles is compared to that of ordinary wood products having a heat of combustion of about 8,000 to 10,000 Btu/lb (18,606 to 23,260 kJ/kg), and usually easily extinguished with adequate quantities of water.

  Now, however, fuels come in a variety of materials: rigid and foamed plastics, flammable and combustible liquids, mixed plastics and ordinary combustibles, animal and vegetable products, metals and wood, plastics and wood, and polymers. Add to this the vast selection of packaging and shipping materials, and the fire protection challenge is enormously complicated. When evaluating performance-based design proposals, the AHJ must be prepared to ask--and document--specific, detailed questions about the type and environment of the fuels.

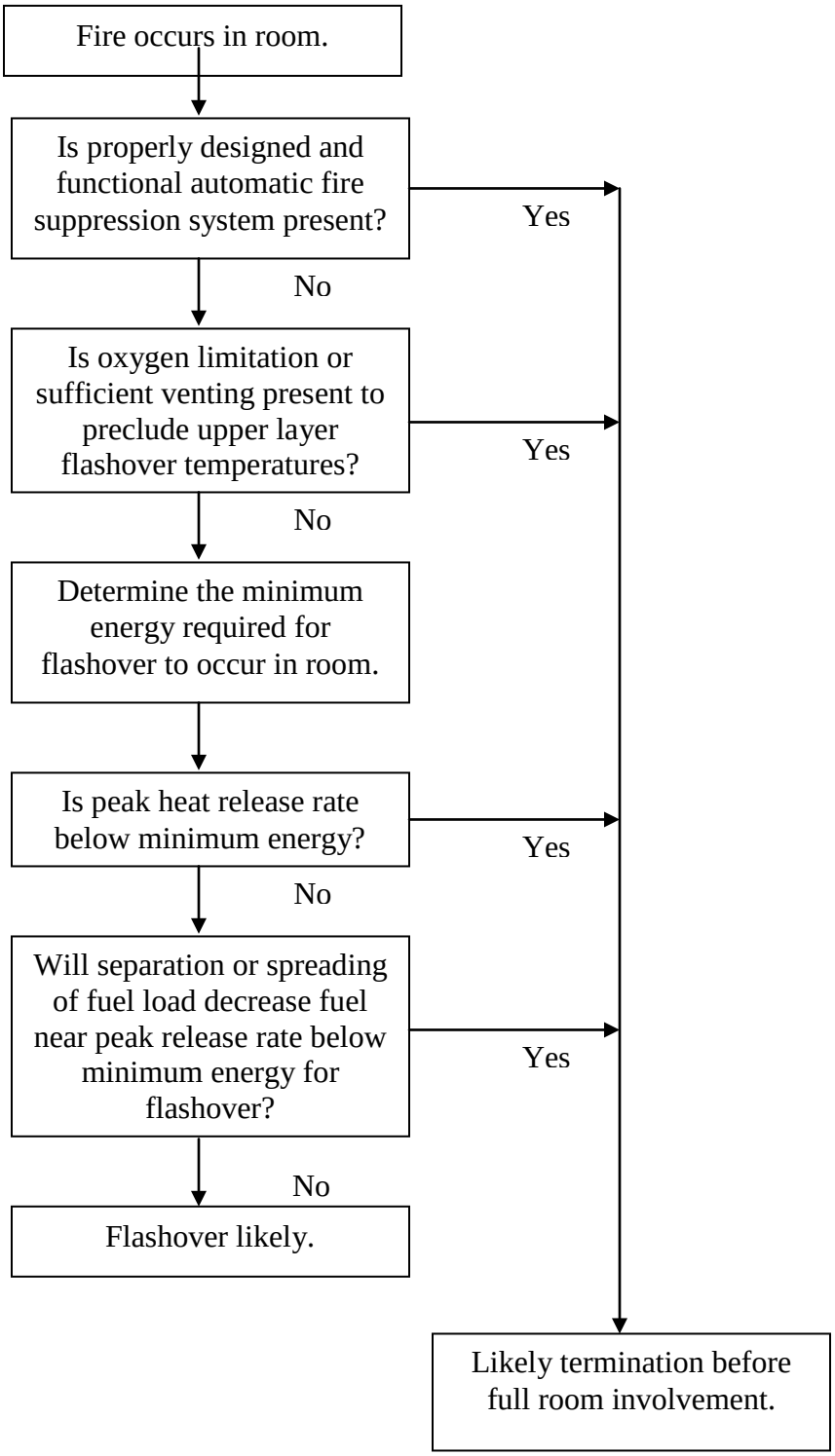
  As an example, under the prescriptive requirements of NFPA 13, *Standard for the Installation of Sprinkler Systems*, in storage occupancies, contents are categorized into "commodity classes." The commodity class that is assigned (I to IV, with IV being the most hazardous of the list) establishes fire sprinkler system requirements for discharge density and area of application. Generally, it is most cost effective to install fire protection for the commodity class that most likely will occur in the facility. Thus, if a storage facility operator stores only books in cardboard boxes, the fire protection system likely would be designed to protect a Class III commodity. If the commodity were changed to Class IV, the fire sprinkler system may not be adequate to protect the new risk.

- **Storage arrays**. The location and method of contents and storage in a building also affects the successful outcome of a fire. Ordinarily, wide aisles with lots of space between displayed goods, furniture, or other contents are the best means of preventing fire from spreading from one storage area to another.

  When combustibles are stored on racks, shelves, pallets, or in other configurations, the fire protection challenge increases. Factory Mutual (FM) Global Research has performed years of study on the issues of these so-called "high challenge" fires. The AHJ must know exactly how materials will be stored or handled in a building to evaluate the adequacy of the performance design.

NFPA 555

NFPA 555, *Guide on Methods for Evaluating Potential for Room Flashover* provides designers and the AHJ a seven-step flowchart to assess the likelihood that flashover will occur within the room of fire origin. While much of the guide is based on sophisticated scientific principles and measurements, the flowchart focuses decisionmaking into those factors that may affect an incipient fire's outcome.



Source: NFPA 555, *Guide on Methods for Evaluating Potential for Room Flashover*, 2000 Edition.

Figure 2-24
Flowchart for Evaluating Potential Room Flashover

Toxicity

Fire officials and health care practitioners have known for a long time that despite the public's perception about fires, smoke and toxic gases really are the predominant killers.

During combustion, fuels may release toxic constituents, or chemical reactions that occur during the fire may create toxic materials. These materials may include gases or particulates, including carbon monoxide, carbon dioxide, hydrogen cyanide, formaldehyde, hydrogen fluoride, soot, nitric oxide, and nitrogen dioxide. Figure 2-25 below provides a list of some toxic materials that result from combustion of various products.

Material	Toxic Gas or Vapor
All combustible materials containing carbon	Carbon dioxide, carbon monoxide
Celluloid	Nitrogen oxides
Leather, plastics containing nitrogen, cellulose materials, cellulosic plastics, and rayon	Hydrogen cyanide
Rubber, thiokols	Acrolein
Fire retardant plastics, fluorinated plastics	Sulphur dioxide
Melamine, nylon, urea formaldehyde resins	Halogen acids (hydrochloric, hydrobromic, hydrofluoric acids, phosgene)
Phenol formaldehyde resin	Ammonia
Phenol formaldehydes, wood, nylon, polyester resins	Aldehydes
Polystyrene	Benzene
Foamed plastics	Azo-bis-succino-nitrile
Some fire-retardant plastics	Antimony compounds
Polyurethane foams	Isocyanates

Figure 2-25
Toxic Fire Gases

Even incomplete combustion causes problems: carbon monoxide is one of the leading causes of fire deaths because of its affinity for the oxygen-carrying red blood cells in humans. Carbon monoxide quickly attaches to the red blood cells, "blocking out" their oxygen-carrying capacity and creating a potentially lethal condition where oxygen is unable to get to the brain and sustain life. Even if a person is not killed outright, the effects of carbon monoxide poisoning include disorientation and impairment.

Smoke, another constituent of incomplete combustion, reduces visibility and increases occupant anxiety. Increasing smoke conditions may prevent occupants from seeing exits or exit signs. Choking smoke may keep people from leaving to clearer areas.

The subject of toxicity and smoke is a specialized and highly technical topic that will not be covered here. The important matter for the AHJ to remember is that any performance-based proposal must address the issues of smoke management, human behavior, and egress.

SUMMARY

An understanding of the dynamics of fire behavior will enable the AHJ and the designer to use building design strategies to control fire development and spread. The AHJ should ensure that any fire-effects models used reflect the types of space in the structure and the construction materials to be used.

Design strategies that promote fire safety include

- limiting or removing sources of ignition;
- separation of fuel and ignition sources; and
- using materials with good fire performance.

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Activity 2.1

Jeopardy™ Game

Purpose

To review fire dynamics terms.

Directions

1. This activity uses a version of the Jeopardy™ game to review some fire dynamics terms.
2. You will be assigned to one of four teams.
3. Appoint a team captain who will give the team's response.
4. Each team captain will be given a bell.
5. The Instructor will show a series of statements on the screen.
6. As each statement appears, the first team to identify the question to which the statement is the correct answer is to ring its bell and provide the question.
7. Your team will have 15 seconds to respond to each statement.
8. Your team will receive 5 points for each correct response, and lose 5 points for each incorrect response.
9. If the first team to respond provides an incorrect question, a second team can answer.
10. When time is up, the correct question will be shown.

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Activity 2.2

Making Conversions Work

Purpose

To become familiar with the International System of Units (SI) as it pertains to fire behavior.

Directions

1. Take 10 minutes to work individually and complete the exercise on the following Worksheet.

2. Answer each question, and prepare to review your answers in class.

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Activity 2.2 (cont'd)

Worksheet

Questions

1. To convert 7 cubic feet of water to cubic meters, one must multiply the cubic feet by _____.

2. The ceiling jet of a fire is measured at 980°C. How hot is that in degrees Fahrenheit? _____

3. A fire scientist wants to establish the total latent heat of combustion for a wooden crib weighing 144 pounds. In order to enter data into her fire model, she must convert this amount to kilograms. How many kilograms are in half of this crib? _____

4. Gasoline has about 18,000 Btu's of energy potential per pound of product. A gallon of gasoline weighs about 6.8 pounds. What is the total potential energy (in SI units) of 7.46 gallons of gasoline? _____

5. In 4 minutes, 6 pounds of shredded newspaper will be consumed completely by fire. What is the rate of heat release in SI units for the newspaper? _____

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Activity 2.3

Effects of Fuel Geometry

Purpose

To demonstrate the effects of fuel geometry on a fire in a performance-based deign.

Directions

1. A building tenant has office workstations in a performance-based design building, with partitions on two sides. He/She has asked the owner to allow him/her to install partitions to enclose the workstations on three sides. The desired configuration is shown in Drawing A; the current configuration is shown in Drawing B on the following page.

2. The owner has asked permission from the AHJ to make the changes the tenant requested.

3. You represent the AHJ. Would you:

   a. Approve the change requested by the tenant?

   b. Disapprove the change request?

4. Check your answer. If you check "No," give your reason. You can also suggest some mitigation that would make the change acceptable to you. You will have 10 minutes to do this.

5. Be prepared to share your decision with the class.

❑ Yes. Why?
❑ No. Why? _____
Suggested mitigation:
_____

_____

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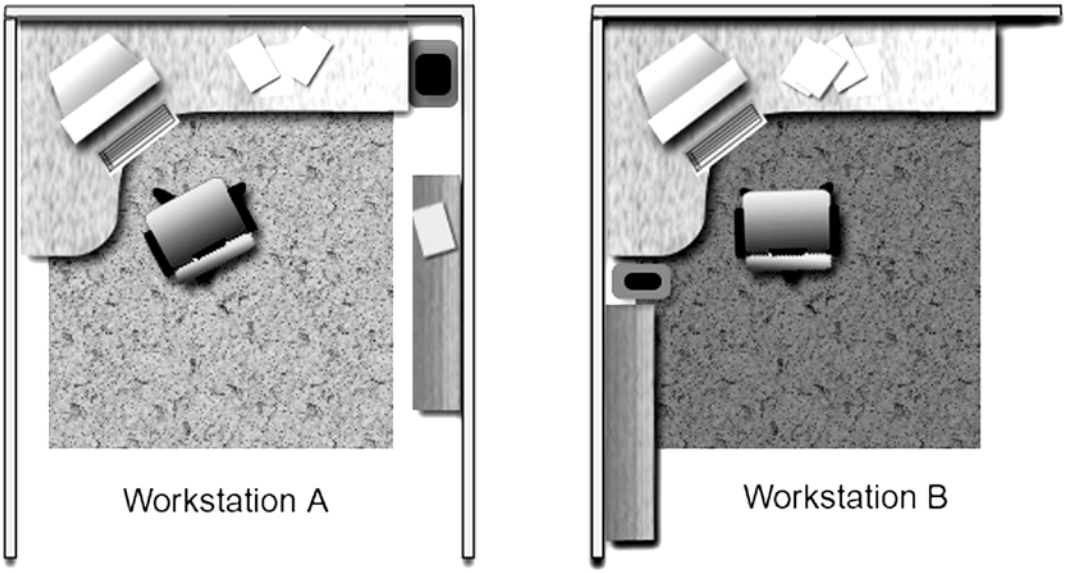
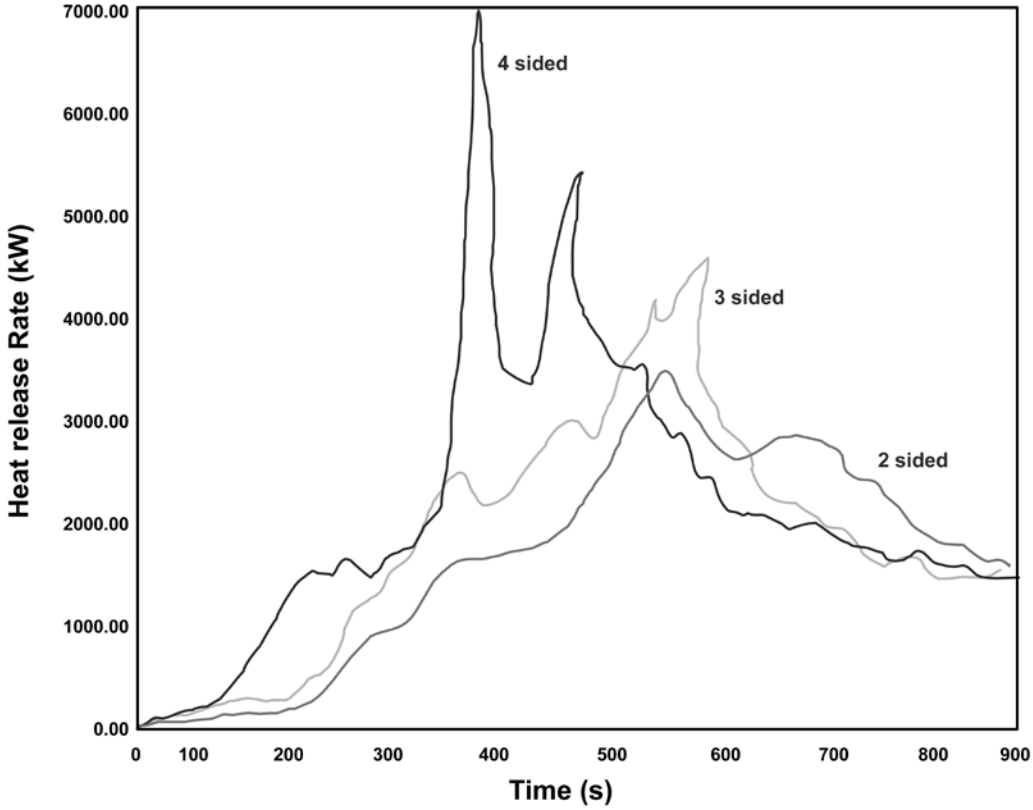
Activity 2.3 (cont'd)





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Activity 2.4

Understanding Fire Dynamics

Purpose

To identify influences of building design and content arrangement on fire dynamics.

Directions

1. Your instructor will display a series of slides. They show different methods of construction, design, or contents arrangement that may affect fire dynamics.

2. Look at each slide, and answer the corresponding questions on the following Worksheet orally with other students.

3. Be prepared to discuss your responses with the class.

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Activity 2.4 (cont'd)

Worksheet

Questions

1. Identify two methods of heat transfer from a first floor fire that could have an effect on the second floor and roof. (Slide 2-99)

2. Identify at least one design feature in this room that may affect fire and smoke spread, and one likely method of heat transfer between and among the seats. (Slide 2-100)

3. What is identifiable in this photograph that might affect fire behavior in this occupancy? (Slide 2-101)

4. Explain how the design and construction of this floor/ceiling assembly may affect the behavior of fire plumes and ceiling jets. (Slide 2-102)

5. List at least two items in this photograph that may affect the heat release rate of a fire in this building. (Slide 2-103)

6. Identify two factors that may influence fire spread in this storage array, and how the geometry of the array might result in different fire outcomes from the same fuel load stacked not more than 6 feet above the floor. (Slide 2-104)

7. Identify at least two construction features of this multiple-family dwelling that may influence vertical and horizontal fire spread. (Slide 2-105)

8. Identify at least three conditions that may affect the rate of heat release of a fire occurring in this property. (Slide 2-106)

9. Explain how the various physical states of combustibles in this occupancy affect HRR and quantity of heat released. (Slide 2-107)

10. Identify at least three features at this facility that affect HRR, heat transfer and quantity of heat released. (Slide 2-108)

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APPENDIX

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Job Aid 2.1

Conversion Table*

Most of the test data or model prediction results that may be generated as part of a performance-based fire safety design will be in International System (SI) units. Therefore it is important for the AHJ to have an understanding of the units that may be used.

With the exception of the kilogram (kg), the conversions given in the table below are to base units such as a Joule (J) or a Watt (W). In the scope of a fire within a building, these units are small, so the values would be reported as kilo-Joules (kJ) or kilo-Watts (kW). The kilo prefix means multiply the base unit by 1000. Another prefix that may be used is **Mega**. This prefix means multiply the base unit by 100,000.

Property	To Convert From	To	Multiply By
Length	Foot (ft)	Meter (m)	0.3048
Mass	Pound (lb)	Kilogram (kg)	0.4536
Area	Square foot (ft^2)	Square meter (m^2)	0.0929
Volume	Cubic foot (ft^3)	Cubic meter (m^3)	0.0283
Energy, work, quantity of heat	British thermal unit (Btu)	Joule (J)	1055.0
	Btu/lb	Joule/kilogram	2326
Power, heat release rate	British thermal unit per minute (Btu/min)	Watt (W) = J/s	17.573
Heat flux	British thermal unit per square foot minute (Btu/(ft^2 min))	Watts per square meter (W/m^2)	189.15
Temperature	Celsius (°C)	Fahrenheit (°F)	(1.8 x °C) +32
			Add
	Celsius (°C)	Kelvin (K)	(°C) + 273.15

**NIST Special Publication 811, Guide for the Use of the International System of Units (SI).* Gaithersburg: National Institute of Standards and Technology, April 1995.

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Job Aid 2.2
Sample Peak Heat Release Rates

Source: NFPA 921 *Guide for Fire and Explosion Investigations*

Item	Weight (lbs)	Peak HRR (Btu)	Peak HRR (kW)
Burning cigarette		0.004739	0.005
Burning match		0.075828	0.08
Small trash can fire	1.5 to 3	47.3 to 284.3	50 to 300
Trash bags, 11 gallon with mixed plastic and paper trash	2.5 to 7.5	132.7 to 331.7	140 to 350
Cotton mattress	26 to 29	37.9 to 919.4	40 to 970
Televisions sets	69 to 72	113.7 to 274.8	120 to 290
Plastic trash bags with paper trash	2.6 to 31	113.7 to 331.7	120-350
PVC waiting room chair, metal frame	34	255.9	270
Cotton easy chair	39 to 70	274.8 to 350.7	290 to 370
Gasoline/kerosene in 2 ft^2 pool		379.1	400
Christmas trees, dry	14 to 16	473.9 to 616.1	500 to 650
Polyurethane mattress	7 to 31	767.7 to 2492.8	810 to 2630
Polyurethane easy chair	27 to 61	1279.6 to 1886.2	1350 to 1990
Burning upholstered chair		2369.6	2500
Polyurethane sofa		2957.3	3120
Burning Christmas tree		1516.5 to 4928.8	1600-5200
Base Design Fire*		5000	5275

* Minimum Heat Release Rate design fire for smoke management system design required by Section 909.9 of the *International Building Code*.

CONVERSIONS

1 Btu per second	=	1.055 kW
1 kW	=	0.94786 Btu per second
1 kW	=	1,000 W
1 MW	=	1,000,000 W
1 GW	=	1,000,000,000 W

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UNIT 3: INTRODUCTION TO FIRE EFFECTS AND EGRESS MODELS

TERMINAL OBJECTIVE

Given a performance-based design, the students will be able to describe the capabilities and limitations of the models on which the design was based, including the characteristics of the building occupants and the assumptions of the risk analysis used.

ENABLING OBJECTIVES

The students will:

1. *Given a fire simulation provided by the National Institute of Standards and Technology (NIST), and working in groups, identify the variables the simulation incorporates in terms of materials and structure and occupants.*

2. *Given an egress model, explain how the model takes into account the occupants of a building.*

3. *Given a performance-based design, complete a risk analysis matrix.*

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FIRE EFFECTS MODELS

The term "model" can be defined in many ways, ranging from a "miniature representation of an object" to "a system of postulates, data, and inferences presented as a mathematical description of an entity or state of affairs." Fire effects models are basic to performance-based designs. In the field of fire protection, a fire effects model is defined as a structured approach to predicting one or more effects of a fire. The Authority Having Jurisdiction (AHJ) should not expect fire effects models to mimic specific fire events. They should expect designers to present a range of conditions for review and consideration.

Fire Effects Modeling Programs

While fire effects modeling programs have been available for a number of years, their widespread practical use has been somewhat limited in conjunction with the prescriptive codes. Performance-based codes and performance-based designs, however, will rely heavily on the application and use of the various fire effects modeling programs.

Fire effects modeling can be done using only hand calculations or can use complex computer-based programs. Regardless of their complexity, these models incorporate engineering, engineering judgment, and scientific principles in the analysis of fire and fire effects. Models can be used to simulate, or some would say, predict the characteristics and conditions of a specific fire under specified conditions. Regardless of the model used, it must be appropriate for the specific fire scenario(s). One must always remember the fire effects model is providing results in very specific terms that must be evaluated against "real world" conditions.

Fire effects models simulate fire scenarios and incorporate conditions that define the development of a fire and the spread of combustible products. They are based on safety goals agreed on by all the stakeholders. They are not intended to analyze fire behavior in spaces that are outside of the prescribed limits of the models' intended dimensions.

Fire characteristics simulated in fire effects models include

- gas/surface temperature;
- flow rates of gas;
- heat flux;
- smoke obscuration;
- toxic gas movement;
- building elements;
- activation time for sprinklers/detectors; and
- various fire parameters.

Fire Scenarios

A fire scenario is a specific set of conditions that define the development of fire, the spread of combustion products throughout a building or portion of a building, the reactions of people to

fire, and the effects of combustion products. Design fire scenarios are those that are used for the evaluation of a proposed design. All stakeholders in a performance-based design must agree on the fire and design fire scenarios.

The various fire effects models can be used to simulate or predict conditions such as gas and surface temperatures, gas flow through openings, heat flux, smoke obscuration, and toxic gas production. Models also can be used to predict the effects of heat on structural elements and activation times for automatic sprinklers and smoke and heat detectors.

Types of Fire Effects Models

There are two types of fire effects models: Zone models and field models.

Zone Models

Zone models simplify the fire environment within the compartment(s). This type of model divides the compartment into zones. Most models have two zones: the upper layer, or hot gas or smoke zone; and the lower layer, or cooler zone.

The model assumes each zone has a uniform temperature and gas concentrations mix. During model execution, the bottom of the hot layer descends over time into the compartment(s), as a direct function of the predicted heat release rate and ventilation factors. The temperature of upper and lower layers and various surfaces, such as the ceiling and floor, also can be predicted.

Zone models may be developed for implementation with either hand calculators or computer-based software programs, with computer programs being the more common approach. Because of some of the assumptions built into the models regarding heat transfer and other conditions, there can be legitimate questions as to the relevance of each model to reflect actual fire conditions.

Figures 3-1, 3-2, and 3-3 show graphic representations of three zone models, DETACT-QS, LAVENT, and FPETool. DETACT-QS predicts detector/sprinkler activation. It assumes smooth, flat, and unconfined ceilings. FPETool outputs include layer temperatures and height and thermal activation. As in all fire effects models, heat release rate (HRR) is an input. Figure 3-4 provides a description of the different inputs to these three models.

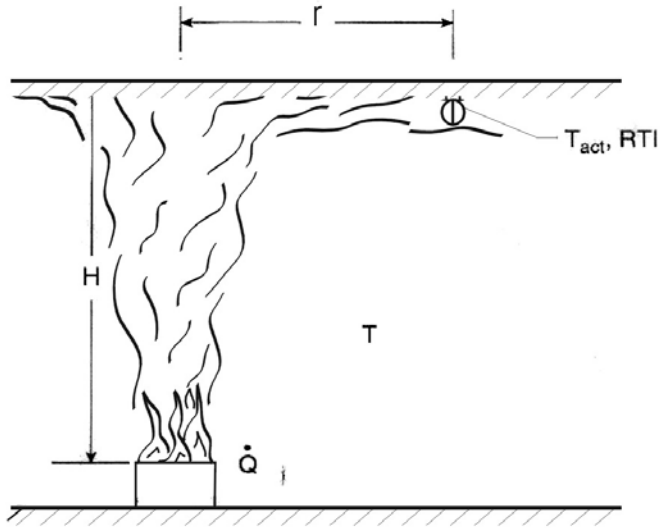

Figure 3-1
DETACT-QS Detectors and Sprinklers

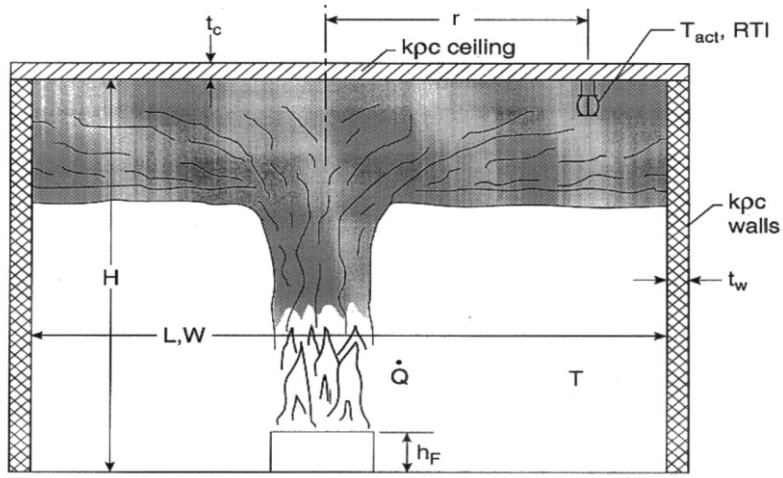

Figure 3-2
LAVENT
Fusible Link Sprinklers

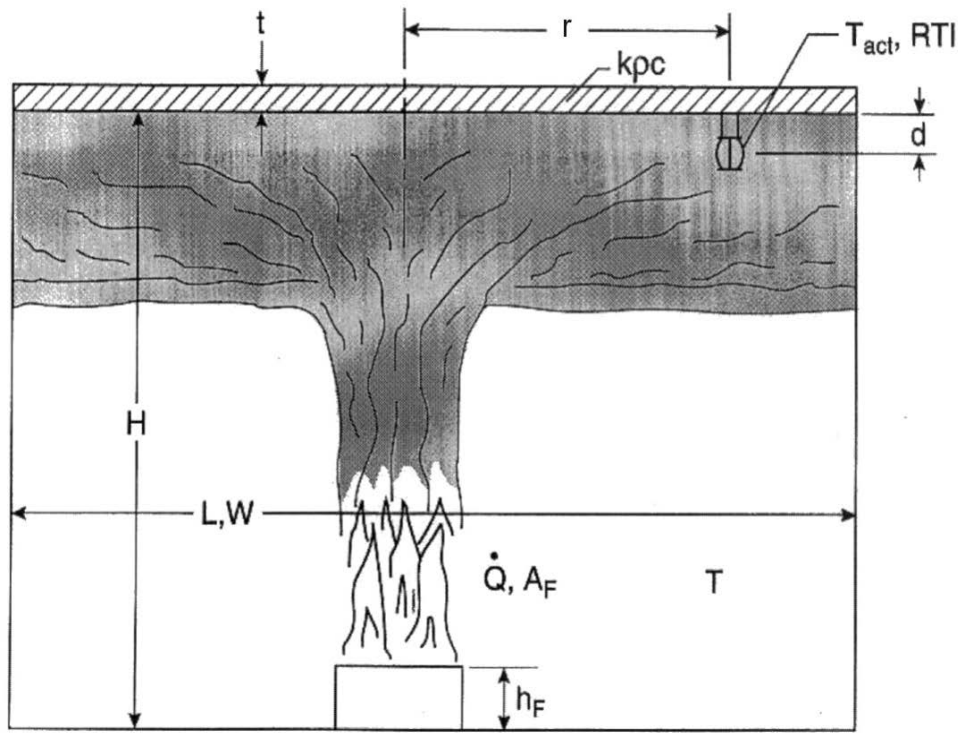

Figure 3-3
FPETool Fire Simulation
Fire Protection System in a Single Compartment

Inputs to Three Zone Models				
Symbol	**Meaning**	**DETACT-QS**	**LAVENT**	**FPETool**
H	Floor to ceiling height	x	x	x
L	Length of room		x	x
W	Width of room		x	x
$\bar{Q}$	Heat release rate (HRR)	x	x	x
h_f	Fire or fuel height-the lowest elevation that the fire can entrain air		x	x
T	Ambient room temperature		x	x
t_c	Thickness of ceiling material		x	x
$k\rho c$	Thermal conductivity of ceiling material		x	x
t_w	Thickness of wall materials			x
$k\rho c$ walls	Thermal conductivity of wall material			x
r	Radial distance to the detector/ sprinkler	x	x	x
T_{act}	Activation temperature of the detector	x	x	x
RTI	Response Time Index of the detector	x	x	x
A_F	Area of the fuel	x	x	
d	Distance of the detection device below the ceiling			x

Figure 3-4
Inputs to Three Zone Models

Zone Model Limitations

Zone models assume horizontal, smooth ceilings. Relative compartment dimensions are restricted, and door and window locations cannot be specified. They also do not model interior finish flame spread, or ignitability from smoldering; and fire suppression is not fully modeled.

Field Models

Field models are much more complex than zone models and require the use of more powerful computers. These models use computational fluid dynamics (CFD) and divide the fire compartment(s) into thousands of small rectangular cells. The models then will predict the density, velocity, temperature, pressure, and concentration of the fire gases in each cell. They compute gas movement based on layers of mass, momentum, and energy. While these models

can provide a more detailed analysis, they also make some simplifying assumptions and have limitations.

Fire Dynamic Simulator Models

The NIST Fire Dynamics Simulator (FDS) consists of two programs, *FDS* and *Smokeview*.

FDS predicts smoke and/or air flow movement caused by fire, wind, ventilation systems, etc. It uses material properties of fuel to simulate fire growth. (See Figure 3-5.)

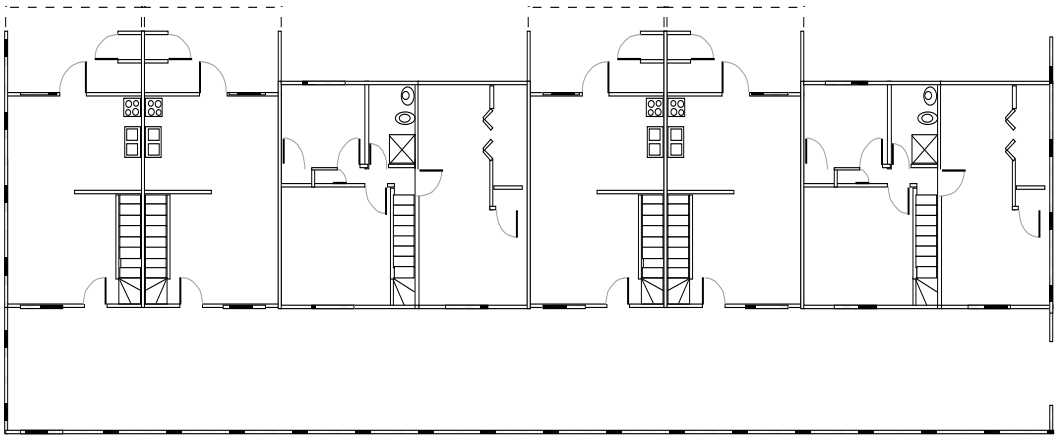

Figure 3-5
Fire Dynamics Simulator (FDS)
Multiroom, Multifloor Simulation

Smokeview visualizes or converts the data from the predictions generated by the *FDS* to a color graphic visual representation as shown in Figure3-6.

Smokeview visualizes *FDS*-computed data by animating time-dependent particle flow, two dimensional slice contours, and surface boundary contours. Data at a particular time also may be visualized using two-dimensional or three-dimensional contour plots or vector plots.

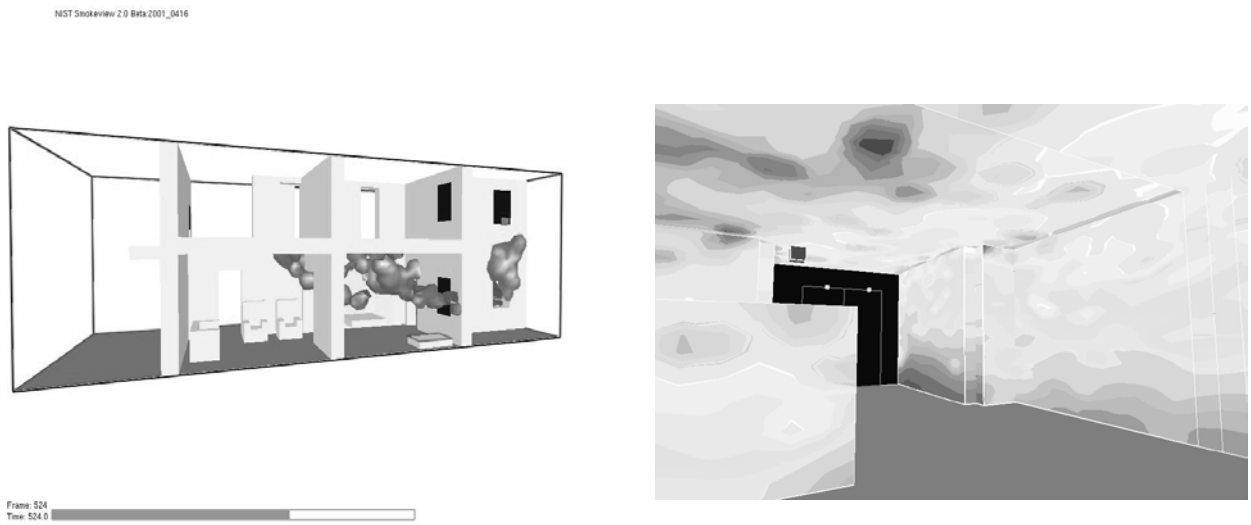

Figure 3-6
Smokeview Simulation

Fire Effects Model Limitations

Every modeling program or approach has limitations. As noted previously in zone models, the room geometry is based upon smooth, flat ceilings, with doors and windows at fixed locations. The combustible nature and flame spread of interior finish materials is not included in fire growth calculations.

CFD fire effects models cannot calculate the ignitability of objects from small flames or the spread of fire over surfaces. The effects of fire suppression systems also are not fully modeled and no NIST model is available for non-water-based fire suppression systems.

It is important for both the AHJ and the designer to understand the limitations that exist with fire effects modeling. These limitations are reflected in the "disclaimer" that NIST publishes with all fire effects modeling software. In general, this disclaimer states that the program is intended to be used only by those competent in the field of fire safety and, in some instances, the fields of fluid dynamics, thermodynamics, combustion and heat transfer. The model is intended only to supplement the informed judgment of the qualified user.

Computer modeling may or may not have predictive capability when applied to a specific set of factual circumstances. Lack of accurate predictions by the model could lead to erroneous conclusions with regard to fire safety. All fire effects modeling results should be evaluated by an informed user.

Models are not intended to analyze fire behavior spaces that are outside the prescribed limits or intended dimensions of the models.

Fire Effects Modeling Using Calculators

Some modeling can be done without the use of computers. These hand calculations can be used in a simple fire environment to predict initial growth rate, steady burning rate, peak heat release rate, flame height, flame temperature, and fire plume velocity. Many examples of hand calculations can be found in *The SFPE Handbook of Fire Protection Engineering*.

Computer Programs for Fire Effects Modeling

Numerous computer-based fire effects modeling programs are available from NIST. Many of them can be downloaded directly from the NIST Web site (www.nist.gov). These fire programs were developed or sponsored by the NIST Building and Fire Research Laboratory. These programs run in a disk-operating system (DOS) environment. Descriptions of the NIST programs available are listed in Job Aid 3.3.

Fire Tests

Another way of "modeling" the effects of fire is the use of actual fire tests. These tests provide a way of observing and directly measuring the fire effects under specific circumstances and protection arrangements. Such testing may be full scale, intermediate scale or small scale. Important concerns are that the test conditions reflect the eventual "end use" of the structure and that the test can be replicated.

Models: Points to Consider

In evaluating a performance-based design that uses fire effects models, an AHJ should ask these questions:

- How does the model work?
- On what design is it based?
- What assumptions does the model make?
- Are the model assumptions consistent with your fire scenario?
- Is the model sensitive to small changes, in particular input scenarios?
- Are the hypotheses tested consistent with the scenarios and acceptance criteria established by the stakeholders?
- Are the timelines used consistent with timelines for critical fire events established by the stakeholders?

- What happens if the bounding conditions change or if the model assumptions change?

Additional Resources

For further information on fire effects modeling, read "Introduction to Fire effects modeling" in Section 11, Chapter 4 of the *NFPA Fire Protection Handbook*, or visit the NIST Web site at www.nist.gov. There, you can find more than 600,000 articles on fire effects modeling, burn test and experiment data, videos, downloadable models, and recreations of fire incidents.

HUMAN FACTORS IN FIRE EFFECTS MODELS

An essential, if not the most critical, component of any modeling evaluation is fire-related human behavior, or the human factor. All modeling and performance-based design must take into account physiological and behavioral responses to fire. In every fire scenario there is the human factor in the ignition of the unwanted fire, whether it be through intent or carelessness. How the occupants of a building react under fire conditions also has a direct impact on the outcome. Inappropriate actions can make the situation worse or have an impact on the effectiveness of fire safety systems.

Egress models variables can include the number of occupants, their distribution in the building, the complexity of the egress route, occupant movement through openings, their susceptibility to products of combustion, and the Americans With Disabilities Act (ADA) *Accessibility Guidelines* requirements.

Problems in Modeling Human Behavior

The study of fire-related human behavior has in the past been affected by several problems. Obviously, experimental subjects cannot be placed in actual fire scenarios, and after-the-fact information from witnesses may contain errors. Research has concentrated on the behaviors exhibited by persons in fires, from their first awareness of a possible problem through completion of the evacuation process. Data have been accumulated through indepth case studies and statistical, summary studies of large numbers of incidents.

Egress models cannot include

- occupant characteristics;
- familiarity with the building;
- mobility/effect of crowding;
- movement through smoke;
- audibility of alarm in ambient noise;
- training and instructions;
- response to cues;
- decisionmaking;

- distribution of exits; and
- results if an exit is compromised.

Exception: Travel speeds can be adjusted

The O&M Manual should include directions on training in safe egress. A very good overview of the matter is contained in the article "Human Behavior and Fire: An Introduction," which is found at the end of this Unit.

Modeling Programs

Modeling programs are available as part of FPETool, Hazard I, and other models to calculate egress times and the tenability limits of various fire gases and oxygen depletion. The stand-alone egress models, such as Pathfinder and EVACNET, provide minimum time to egress from a building. While these predictions can be made, what remains most unpredictable is the human factor. In these various modeling programs variables such as the number of occupants, their distribution within the building, the complexity and capacity of the egress system, and the susceptibility of the occupants to the products of combustion are considered.

Limitations of Egress Models

While these are important factors, equally important but not considered or included in the models are characteristics of the occupants (age, physical condition, sleeping, awake, etc.), the familiarity of the occupants with the building, the audibility of the alarm signal, and the actual reaction of the occupants to the alarm signal or fire conditions such as oxygen deprivation, heat, gases, power failure, or smoke obscuration. The models cannot predict the decision process--that is, how the individual will recognize and validate the fire threat, evaluate the actual danger, and then act on the evaluation.

This is an area where the AHJ needs to ask a lot of "what if" questions: How can or will the design compensate for the lack of proper response by the occupants? What if the alarm is not heard? What if the occupants don't respond promptly? The active and passive fire protection features of a building must be designed to protect the occupants from themselves. Designs that rely heavily upon the human factor for an acceptable outcome are clearly questionable. Designs must consider realistically the effectiveness and reliability of evacuation training and accountability systems. The O&M Manual provided in the performance-based design should specify the level of evacuation training required, who should be trained and when, and how all occupants will be accounted for.

RISK ANALYSIS

As fire protection personnel, we have a great deal of experience identifying hazards. An open container of Class I-B flammable liquid in a place of assembly is an obvious fire hazard.

Exposed, charged electrical wires with loose connections are another hazard. Locked or blocked exits are common hazards we confront on a regular basis. Fire inspectors are trained to identify hazards and order their correction.

But what about "risk"? We often use the terms fire "hazard" and fire "risk" interchangeably. However, in the performance-based design environment, this substitution is incorrect. The definitions of these two words are distinctly different when assessing life safety and fire protection challenges, and they must be used in the correct context when working with stakeholders, especially fire protection engineers or insurance underwriters who are intimately familiar with the terms.

No one should confuse "hazard" or "risk" with "safety" "Safe" is a subjective condition that everyone views differently. Society establishes what it considers to be "safe" through a process of legal documents: both laws and the court interpretations of them. Is a building that meets the prescriptive code requirements "safe?" Are you "safe" when you occupy a building that is entirely fire resistant and protected by the latest in sprinklers and fire alarm technologies? "Hazard" and "risk" are recognized terms in the design, construction, engineering, architectural and scientific worlds, "safe" is not.

The American Society for Testing and Materials (ASTM) E176-01a "Standard Terminology of Fire Standards" defines fire "hazard" as "the potential for harm associated with fire." A fire may pose one or more types of hazards to people or property such as burns, loss of function, toxicity, or explosive damage. A hazard assessment might be considered a "what if" evaluation of different fire scenarios.

The stakeholders might be asked to evaluate some or all of these sample fire hazards:

- How will an unanticipated pyrophoric gas release affect production in the semiconductor fabrication facility?

- If 20 percent of the exit discharge capacity is removed, what effect will this have on egress times?

- How might a production room fire spread to an unsprinklered portion of the plant through a fire-rated separation wall with protected openings?

ASTM defines "risk" as "an estimation of expected fire loss that combines the potential for harm (hazard) in various fire scenarios with the probabilities of occurrence of those scenarios." It measures the likelihood of an event. Risk also needs to be defined clearly with measurable factors: dollars, injuries, lost time, interrupted business, etc. Risk is a product of the hazard and the frequency at which the specific hazard might occur.

By comparison to the hazard analysis, the stakeholders might be asked to evaluate these risks:

- Given the chances of four unanticipated pyrophoric gas releases per year, how will production be affected in the semiconductor fabrication facility?

- If 20 percent of the exit discharge capacity is removed, what effect will this have on egress times if the facility occupant load is reduced by 60 percent during regular holiday shutdown periods?

- In our other plants, we experience five production room fires every 3 years, and they never have spread to an unsprinklered portion of the plant through a fire-rated separation wall with protected openings. Are we willing to risk that this behavior will continue to occur with the same results?

As you can see from these definitions, hazards are just part of a risk assessment. You cannot complete a risk assessment without considering the probability or frequency of the hazard occurring.

The stakeholders must evaluate properly and thoroughly the risk or probability of a fire occurring in the performance designed facility. The basic questions they should ask are:

- What fires are anticipated?

- What level of loss/damage/injury/death is acceptable?

- How often might this happen?

As they ask themselves these questions, and develop the variety of scenarios to which to apply them, the stakeholders must remember that obtaining consensus on acceptable levels of risk is essential to the successful outcome of the project.

Risk analysis techniques evolved from the chemical process industries (petrochemicals, toxic gas production, pesticide manufacturing, etc.) where the risk of a system or process failure could have catastrophic effects. Many remember the tragedy in Bhopal, India, where thousands in a poor residential neighborhood were killed by a methyl isocyanate release. Risk analysis is used today for evaluating potential terrorist threats and determining appropriate levels of target hardening.

Hazard Analysis

A hazard analysis will identify potential ignition sources, available fuels, and fire development potential. This analysis considers the predicted or expected magnitude of a fire loss associated with one or more fire scenarios. It is based on fire dynamics correlations and fire effects modeling tools. This analysis will be used in the evaluation of fire scenarios and trial designs. Other hazards such as wind, earthquake, flood, terrorist attack, lightning strike, adjacent building collapse, or gas leak and explosion also may be considered in the overall analysis.

Hazard	Ignition Scenario	Expected Loss Confined to
Open top dip tank with conveyor operations containing 1,500 gallons of Class I-B flammable liquid heated to 128°F (53.3°C)	Autoignition Electric arc Welding/Cutting Belt friction Compression Sabotage Smoking/Open flame	Room of origin Object of origin Room of origin Building of origin Object of origin Building of origin Room of origin
Cut-off welding gas room containing oxygen, acetylene, and liquefied petroleum gas (LPG) cylinders.	Autoignition Electric arc Welding/Cutting Belt friction Compression Sabotage Smoking/Open flame	N/A Room of origin N/A N/A Room of origin Building of origin Room of origin
Office records and supplies storage room adjacent to exit corridor in a sprinklered building.	Autoignition Electric arc Welding/Cutting Belt friction Compression Sabotage Smoking/Open flame	N/A Object of origin N/A N/A N/A Building of origin Room of origin

Figure 3-7
Fire Hazard Analysis

Risk Analysis

Risk analysis incorporates the likelihood of a specific event and the severity of the outcome. This process combines both the severity and the probability of all relevant fire loss scenarios. Remember that it is the intent of a performance-based code to establish the acceptable or tolerable level of risk. The overall analysis must consider not only the frequency of a fire's occurrence, but the effectiveness and reliability of the entire fire protection system. Risk analysis provides a quantitative measure of the risk. It also can establish the basis for evaluating acceptable losses and selecting design fire scenarios.

Stakeholders use two different evaluative methods in risk and hazard analysis: deterministic and probabilistic.

Deterministic Analysis

Deterministic analysis relies on the laws of physics and chemistry, or on correlations developed through experience or testing, to predict the outcome of a particular fire scenario. In the deterministic approach, one or more possible design fire scenarios can be developed that

represent the worst possible credible fires in a specific building. In this approach, the frequency of possible occurrences need not be evaluated.

Example: Given a grease fire in a bakery within a 44,000 square-foot supermarket with reinforced concrete masonry unit (CMU) walls erected on a slab floor, and having a 16-foot high roof, which of the following design scenarios likely will result in a total roof collapse?

- Scenario 1: A sprinklered building with wooden columns supporting wooden trusses and a roof having a plywood deck covered by asphalt.

- Scenario 2: A nonsprinklered building with wooden columns supporting wooden trusses having a plywood deck covered by asphalt.

- Scenario 3: A sprinklered building with steel columns supporting steel trusses with a steel roof deck and built-up roof surface.

- Scenario 4: A nonsprinklered building with steel columns, steel trusses, and a steel roof deck covered by a built-up roof surface.

- Scenario 5: A sprinklered building with wooden columns supporting steel trusses covered by a plywood roof deck and a standing seam metal roof.

- Scenario 6: A nonsprinklered building with wooden columns, steel trusses, plywood roof deck, and a standing seam metal roof.

- Scenario 7: A sprinklered building with wood columns, steel trusses, steel roof deck, and asphalt roof surface.

- Scenario 8: A nonsprinklered building with wood columns, steel trusses, steel roof deck, and asphalt roof surface.

- Scenario 9: A sprinklered building with steel columns supporting wooden trusses with a plywood deck covered by a built-up roof surface.

- Scenario 10: A nonsprinklered building with steel columns, wooden trusses, steel roof deck, and a built-up roof surface.

- Scenario 11: A sprinklered building with wood columns, wood trusses, plywood roof deck, and metal standing seam roof.

- Scenario 12: A nonsprinklered building with wood columns, wood trusses, plywood roof deck, and metal standing seam roof.

- Scenario 13: A sprinklered building with steel columns supporting steel trusses with a lightweight concrete roof deck and surface.

- Scenario 14: A nonsprinklered building with steel columns supporting steel trusses with a lightweight concrete roof deck and surface.

- Scenario 15: A sprinklered building with steel columns supporting steel trusses with a plywood deck and an asphalt roof.

The following table represents graphically these scenarios with the changing design consideration.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8	Scenario 9	Scenario 10	Scenario 11	Scenario 12	Scenario 13	Scenario 14	Scenario 15
Sprinklers	●		●		●		●		●		●		●		●
Columns															
Wood	●	●			●	●	●	●			●	●			
Steel			●	●					●	●			●	●	●
Trusses															
Wood	●	●							●	●	●	●			
Steel			●	●	●	●	●	●					●	●	●
Roof deck															
Plywood	●	●			●	●			●		●	●			●
Steel			●	●			●	●		●					
Lt. concrete													●	●	
Roof Surface															
Asphalt	●	●					●	●							●
Built-up			●	●					●	●					
Metal					●	●					●	●			

Note: A dot (●) in the square indicates that is a feature of that design scenario.

Figure 3-8
Deterministic Matrix for Roof Collapse Risk Analysis

Given this information, and the variety of design scenarios, the stakeholders can draw conclusions based on their knowledge and research as to which combination of elements (sprinklers/columns/trusses/roof decks and roof surfaces) likely will fail in the event of a bakery fire.

Deterministic analysis often uses fire effects modeling. The analysis must consider each design scenario independently and include the expected performance of any fire protection system(s). For a design to be successful, all performance criteria must be met, with consideration given to the known variations and unknown effects. For example, if a range hood fire suppression system is out of service, how will that affect the performance of a fire sprinkler system when the thermal plume eventually reaches the ceiling?

Probabilistic Analysis

Probabilistic analysis evaluates the statistical likelihood that a fire will occur and what losses and consequences will result. This approach may use both statistics and historical information. Fire statistics will identify the most likely areas of ignition, the items ignited, and the likelihood of fire spread beyond the compartment of origin.

History from fires involving similar buildings or equipment, building contents, or other items can be considered. The frequency of occurrences of a particular type of fire is evaluated.

Given the same supermarket scenario described above, a probabilistic analysis might include the following data:

Factor	Value
Number of supermarkets in US†	166,003
Number of supermarkets with bakeries	148,239
Number of fires per year in store and office properties‡	12,339
Cooking fires per year in store and office properties‡	876
Ratio of cooking fires to supermarkets with bakeries	1:170
Total dollar loss in store and office properties‡	$428.3 million
Dollar loss from cooking fires in store and office properties‡	$5,567,900
Average loss per cooking fire in store and office properties	$6,356

† Source: U.S. Census Bureau, 2000 Census.
‡ Source: "Fire in the United States," United States Fire Administration.

Figure 3-9
Factors to Consider in Supermarket Bakery Fire Protection Probabilistic Analysis

The outcome of this analysis reveals that any one supermarket has about a 0.59 percent chance of suffering a cooking fire with a resulting loss of about $6,500. (These are **direct** losses, and do not consider lost business opportunities, tax revenues, lost customers, etc.) Given that information, the stakeholder can establish the severity of the risk in relation to the overall protection scheme for the property.

The availability and reliability of all types of fire protection systems also must be considered. Systems may not always be operational or perform as designed or intended. Using the same example, the analyst may calculate that the supermarket's fire sprinkler system is shut down for service 2 hours per year, or that a one-time fire-related failure of the range hood suppression

system might result in the operation of more sprinklers than the water supply is designed to deliver.

Uncertainty

Any risk analysis method must anticipate a certain level of "uncertainty." Uncertainty describes those factors or circumstances that--if altered--affect the desired outcome.

In the supermarket example, sources of uncertainty in this analysis might include the failure of the range hood fire suppression system, a staff member inadvertently tossing a 5-gallon pail of water on the burning grease, a catastrophic collapse of the commercial hood and duct system that knocks the fryer over and spills flaming grease, or even an explosion from a ruptured fuel gas line or flour dust in the atmosphere.

Other sources of uncertainty that may be considered:

- **Building material variations.** Imagine a design that anticipates rooms having painted gypsum wallboard interior finishes, and the tenant decides to apply 1/8-inch imitation wood paneling with a flammable adhesive. What does this do to potential flame spread and rate of heat release characteristics?

- **Installation unknowns.** Minor changes often occur during construction that initially seem to have little or no effect on a building, but may significantly affect a performance design. For example, what outcome might be expected from a positive pressure smoke management system if the installed fans did not provide the designed air volume or velocity?

- **System and component variability.** A fire sprinkler system is engineered and designed for installation in a gridded layout. The installer decides he or she can save money by changing the sprinkler branch lines from Schedule 10 to Schedule 40. How might this affect sprinkler performance?

- **Unanticipated uses of systems.** In one scenario, a fire alarm technician might install a smoke detection system throughout a building to detect fires and notify occupants to evacuate within the prescribed time developed within the fire evacuation models. What might happen if another contractor inadvertently connected to that system to operate a clean agent fire suppression system in a computer room?

- **Unpredictable human action.** Fire and smoke separation walls are an important element in fire protection and life safety. We expect their integrity will be maintained throughout the building's existence. As tenants move in and out, and their needs are met, occupants may alter these barriers without realizing the impact. A destructive event as simple as punching a hole for routing computer or telephone cables may compromise performance-based design features.

Consequence Ranking and Frequency Ranking

Risk is the product of potential consequences and the expected frequency of occurrence. Consequences for humans may include death, serious injury, or time lost from work, and for businesses may include the extent of structural damage, monetary loss, business interruption, or environmental impact. The occurrence frequency may be an estimate of how often the project loss might occur. The frequencies listed in the following table are illustrative, and may not reflect real events.

Event	Frequency	Outcome
Employees inadvertently locked out by altered electronic security codes.	3 times per day	Loss of production.
Fire in paint spray booth.	6 times per year	Potential serious injury. Loss of production. Reconstruction costs.
Shipping room conveyor belt jumps track.	3 times per year	Loss of production. Repair costs.
Vandals break into storage yard and burn idle pallets.	1 time per 2 years	Loss of production. Potential fire damage.
Worker falls from catwalk around bulk tanks.	1 time per 5 years	Potential fatality. Potential serious injury. Potential litigation.
Smoke management system in warehouse fails to operate.	1 time per 20 years	Potential serious injury. Potential fire and smoke damage. Loss of stock. Reconstruction costs.

Figure 3-10
Frequency Ranking for Typical Hazards

Risk Binning

Risk binning is an alternative to the more classic risk analysis, and is considered to be much simpler. Instead of identifying and evaluating every possible hazard, it quantifies (measures) the consequences of the most severe events and matches them with an approximate event frequency. The concept is based on the idea that if one prepares for the worst-case scenario, lesser damaging events will result in favorable outcomes. As an example, if a warehouse owner provides fire sprinkler protection for storing Group A plastics in encapsulated Group A bin boxes on low-density polyethylene pallets in 36-foot high multiple row racks, the sprinkler system should have no problem protecting wooden pallet loads of beer stacked 8 feet high on the floor.

For each type of event, the maximum consequence must be established. Consequences may include death or serious injury; or massive structural damage, absolute loss of production, severe environmental damage, or total business interruption. The consequences should represent the largest realistic event of each type.

Frequency→ **Consequence ↓**	**Beyond Extremely Unlikely**	**Extremely Unlikely**	**Unlikely**	**Anticipated**
High	Aircraft commandeered by terrorists crashes into highrise building.			Fire caused by welding and cutting in a petroleum processing plant.
Moderate		Natural gas pipeline rupture in remote area.	Fire sprinklers fail to control fire in cabinet shop.	
Low			Wildland fire spreads to log storage yard.	Toilet paper fire in high school lavatory.
Negligible	Pea-sized meteorite hits abandoned car in desert.	Tornado in southeast States hits forested area.		

Figure 3-11
Examples of Risk Binning for Sample Hazards

Each consequence is ranked (i.e., negligible, low, moderate, and high). The frequency or number of times a specific event may occur also is established. This frequency ranking is measured on a scale ranging from "anticipated" to "beyond extremely unlikely."

The *SFPE Engineering Guide to Performance-Based Fire Protection* contains additional information on the risk binning analysis method, including the example of the risk-binning matrix shown below. (The numbers in the table are for identification only, and do not represent a ranking.)

Frequency → Consequence ↓	Beyond Extremely Unlikely	Extremely Unlikely	Unlikely	Anticipated
High	10	7	4	1
Moderate		8	5	2
Low		9	6	3
Negligible	11	12		

Key

High Risk Moderate Risk Low Risk Negligible Risk

Figure 3-12
SFPE Example of a Risk Binning Matrix

A similar matrix, shown below, is included in the ICC Performance Code for Buildings and Facilities. This matrix also correlates the frequency of event and the maximum level of consequence. It also provides guidance on the Performance Group to which occupancies may be assigned. For example, an occupancy that rarely expects incidents causing moderate damage would be assigned to Performance Group III.

		INCREASING LEVEL OF BUILDING PERFORMANCE MAXIMUM LEVEL OF DAMAGE TO BE TOLERATED			
		SEVERE	HIGH	MODERATE	MILD
MAGNITUDE OF EVENT Increase Magnitude of Event	VERY LARGE (Very Rare)	II	III	IV	(Exceed Performance Level IV)
	LARGE (Rare)		II	III	IV
	MEDIUM (Less Frequent)	NP		II	III
	SMALL (Frequent)	NP	NP		II

Figure 3-13
ICC Example of a Risk Binning Matrix

SUMMARY

Under a performance-based code, the acceptable or tolerable levels of hazard or risk must be defined. It also is critical to the effective and proper use of performance-based codes and performance-based designs that all stakeholders agree on acceptable risk levels.

Unlike the prescriptive codes, which are based on fixed values, the performance-based codes use terms such as "adequate" and "reasonable" to allow design flexibility. It is incumbent upon all of the stakeholders to base their determinations of what constitutes "adequate" and "reasonable" on sound professional judgment.

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Activity 3.1

Verifying Fire Model Selections

Purpose

To determine if models proposed for a specific design proposal are suitable.

Directions

1. Take 30 minutes to work as a group and brainstorm the following exercise.
2. Review the proposed scenario with your group members and determine if the models selected are suitable for the submitted design. Mark your answers on the sheet provided.
3. Select a spokesperson and share your responses with the class for discussion. Be prepared to justify your answers.

Scenario

Your community sits at the intersection of four major transportation arteries in an important business corridor. Two interstate highways, a major rail line, and a deep-water port are within the boundaries of your jurisdiction.

Matexa EA, a Spanish import/export firm, wants to build a 6-million-square-foot industrial and warehouse facility. The facility will process flammable and combustible liquids, and the one-story warehouse will store them until they are ready for shipment via one of the methods described above. Storage will occur in a variety of plastic and metal containers, ranging from 1 liter to 232 liters (about 1 quart to 60 gallons U.S.). The warehouse storage will be mechanized, carousel storage 9.14 m (30 feet) high. At full operation, the total estimated capacity of the warehouse will be 75,166,000 liters (20 million gallons) of product. The warehouse is sprinklered with foam-water suppression equipment, and storage arrays are isolated from one another by draft curtains. Smoke removal consists of temperature sensitive, spring-loaded roof vents.

Due to their extensive experience with performance-based design in Europe and Australia, they propose a performance-based solution to their design challenges in this project. Their design team submits a matrix of models to assess the fire safety of the following conditions. Processing and transfer facilities are designed in compliance with the latest American Petroleum Institute (API) prescriptive standards.

You are to determine if the proposed models listed on the next page are suitable for the application.

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Activity 3.1 (cont'd)

Model	Application	Suitable	Unsuitable
FIRDEMND	To assess the performance of the automatic foam-water fire sprinkler systems above the carousel storage arrays.		
LAVENT	To assess the performance of up to five of the thermal links in the heat-operated ceiling vents		
GRAPH	To visually represent the performance of LAVENT output.		
MASBANK	To assess the thermophysical properties of the tilt-up construction walls used to form the outer edges of the warehouse.		
ASMET	To measure the degradation effect by heated ceiling jets on the draft curtains.		
HAZARD I	To assess the rate of heat release from a fire in a single carousel storage area for the purpose of predicting sprinkler response times.		
DETACT-T2	To assess the performance of the actuation time of the quick response sprinklers installed in the room of origin.		
ELVAC	To assess the performance of smoke evacuation methods at the anticipated elevated temperatures in the warehouse.		

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Activity 3.2

Egress Model Assumptions

Purpose

To review an egress model.

Directions

1. You will work in table groups.

2. List an objective, performance objective, and performance criteria related to occupant egress described in the O'Hara and Bierwerth article in the Appendix to Unit 1.

   _____

   _____

   _____

3. List two assumptions the designers made in using FPETool to model occupant egress.

   Designer assumption #1: _____

   Designer assumption #2: _____

4. Write two different assumptions you could make about the building occupants and describe how the different assumptions might change the anticipated outcomes.

   Different assumption #1: _____

   Effect: _____

   Different assumption #2: _____

   Effect: _____

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Activity 3.3

Uncertainties

Purpose

To identify uncertainties that may be involved in risk analysis. Uncertainties include the factors, events, or conditions that may alter a design

Directions

1. Take 15 minutes to work as a group and brainstorm the following exercise.
2. Review the examples with your team members and list sources of uncertainty for each.
3. List your answers on the easel pad.
4. Select a spokesperson and share your responses with the class for discussion. Be prepared to justify your answers.

Scenario 1

A local 4-million square foot, three-story covered shopping mall is proposed to be used for rock concerts aimed at preteens and teenagers up to 18 years old.

Scenario 2

A three-story wood-frame, unsprinklered apartment building with all exterior exits will be converted to housing for the elderly and disabled.

Scenario 3

In a baled alfalfa storage warehouse (sprinklered, but nothing stored over 12 feet high), a portion of the building will be separated by permanent partitions to store 250-gallon LPG tanks during the winter. The tanks may have residual liquefied petroleum gas in them.

Scenario 4

The historic vaudeville theater will be converted to a mutliplex cinema, but will retain a small 150-seat area for live performances.

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Activity 3.4

Using A Risk-Ranking Matrix

Purpose

To determine the level of fire safety risk in the three fire scenarios.

Directions

1. You will work in your table groups.
2. On the following page is a blank risk-ranking matrix.
3. You will have 15 minutes to develop the risk ranking for each of the scenarios below.
4. To assess the degree of risk of fire for each fire scenario, locate the block on the matrix where the frequency of fire and the consequences of the fire intersect, and write your scenario number in that block. You may use the Consequences and Frequency tables in the *SFPE Design Guide.*
5. Select a spokesperson to go to the podium, display the group's risk matrix on the projector, give the rationale for the group's risk rankings, and respond to class comments.

Here is the problem:

The designers of a shopping mall need to decide, based on a risk analysis, whether sprinklers should be installed in the mall areas described in each scenario. You are to give a risk ranking to the scenario that was assigned to your group. The information in each scenario was developed through prior analysis.

Scenario 1

In this main concourse of this shopping mall, it is estimated that 100 trash can fires will occur each year.

Outcomes:
These fires are always detected early.
The fuel in the trash cans is limited.
No fire ever spreads beyond the can where it started.

Scenario 2

In the main concourse of the shopping mall, vendors will burn scented candles to demonstrate their products. In a typical year, it is estimated that a candle will start one small fire in one vendor's stall.

Outcomes:
There is some smoke.
Evacuation is effective.
The fire does not spread beyond the vendor's stall.
There is business interruption for 3 hours in the immediate area.

Scenario 3

In the area of individual stores off the main concourse in this shopping mall, it is estimated that one of the stores will burn out every 15 years.

Outcomes:
The mall is closed for a week.
There are smoke-related injuries.

Risk-Ranking Matrix

Frequency→ Consequence ↓	Beyond Extremely Unlikely	Extremely Unlikely	Unlikely	Anticipated
High				
Moderate				
Low				
Negligible				

How to use this matrix:

For a given fire scenario, assess the degree of risk of fire by locating the block where the frequency of fire and the consequences of the fire intersect.

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APPENDIX A

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Job Aid 3.1

Eight Standard NFPA Design Fire Scenarios

Design Fire Scenario	Fire Type	Concern Addressed in the Scenario
Scenario 1	An occupancy-specific design fire scenario representative of a typical fire for the occupancy.	Shall explicitly account for 1. Occupant activities. 2. Number and location of occupants. 3. Room size. 4. Furnishings and contents. 5. Fuel properties and ignition sources. 6. Ventilation conditions. The first item ignited and its location shall be defined explicitly.
Scenario 2	An ultrafast developing fire, in the primary means of egress, with interior doors open at the start of the fire.	Shall address the concern regarding a reduction in the number of available means of egress.
Scenario 3	A fire that starts in a normally unoccupied room that potentially can endanger a large number of occupants in a large room or other area.	Shall address the concern regarding a fire starting in a normally unoccupied room and migrating into the space that can, potentially, hold the greatest number of occupants in the building.
Scenario 4	A fire that originates in a concealed wall or ceiling space adjacent to a large occupied room.	Shall address the concern regarding a fire originating in a concealed space that does not have either a detection system or suppression system and then spreading into the room within the building that can, potentially, hold the greatest number of occupants.
Scenario 5	A slowly developing fire, shielded from fire protection systems, in close proximity to a high occupancy area.	Shall address the concern regarding a relatively small ignition source causing a significant fire.

Job Aid 3.1 (cont'd)

Design Fire Scenario	Fire Type	Concern Addressed in the Scenario
Scenario 6	The most severe fire resulting from the largest possible fuel load characteristic of the normal operation of the building.	Shall address the concern regarding a rapidly developing fire with occupants present.
Scenario 7	An outside exposure fire.	Shall address the concern regarding a fire starting at a location remote from the area of concern and either spreading into the area, blocking escape from the area, or developing untenable conditions within the area.
Scenario 8	Fire originating in ordinary combustibles in a room or area with each passive or active fire protection system independently rendered ineffective.	This set of design fire scenarios shall address the concern regarding each fire protection system or fire protection feature, considered individually, being unreliable or becoming unavailable. *Exception: This scenario shall not be required to be applied to fire protection systems for which both the level of reliability and the design performance in the absence of the system are acceptable to the AHJ.*

Job Aid 3.2

Checklist for Evaluating Fire Scenarios and Design Fires

Are performance criteria:

- Measurable?
- Agreed upon by all stakeholders?
- Described in clear terms?

What criteria were used in developing the fire scenario related to:

- ignition temperatures;
- smoke concentrations;
- property damage;
- environmental damage;
- heat, fuel, and ventilation (natural/mechanical);
- fuel type;
- fuel array;
- interior finishes; and
- failure of primary fire protection features?

What data sources were used to develop the fire scenario?

- trial designs;
- expert opinion and qualifications; and
- experience with similar designs.

How does the design anticipate

- managing fire by controlling combustion, fuel, and the fire environment;
- suppressing fire by detection or automatic and manual suppression;
- controlling fire by construction that will vent or contain the fire; and
- protecting life by egress management or defend-in-place strategy?

What assumptions does the design make about:

- sprinkler systems;
- alarms (automatic/manual);
- fire department response (time, staffing, equipment/apparatus);
- occupant egress capability; and
- smoke control?

What timelines were used in the trial design for these key fire events?

- ignition;
- detection;
- suppression;
- notification (automatic/manual/oral/verbal);
- evacuation (begins and ends);
- emergency response begins;
- untenable conditions in room of origin;
- vent failure;

Job Aid 3.2 (cont'd)

- flashover;
- spread beyond room of origin;
- emergency responders arrive;
- manual suppression;
- failure of structural elements; and
- extinguishments.

How was the design evaluated?

- Using computer models? Which ones? Were they appropriate to the design?
- Were they small-scale fire effects models?
- Were they intermediate-scale fire effects models?
- Were they full-scale fire effects models?

Does the evaluation method used demonstrate that the design meets the performance criteria:

- for safety of people; and
- for safety of property?

Job Aid 3.3

Fire Effects Modeling Programs Available from National Institute of Science and Technology (NIST) www.NIST.gov (301) 975-6850 100 Bureau Drive, Stop 8600 Gaithersburg, MD 20899-3460

ALOFT-FTTM (A Large Outdoor Fire Plume Trajectory Model--Flat Terrain)

A computer based model to predict the downwind distribution of smoke particulate and combustion products from large outdoor fires. It solves the fundamental fluid dynamic equations for the smoke plume and its surroundings with flat terrain. The program contains a graphical user interface for input and output and a user modifiable database of fuel and smoke emission parameters. The output can be displayed as downwind, crosswind and vertical smoke concentration contours.

ASCOS (Analysis of Smoke Control Systems)

A computer program for steady air flow analysis of smoke control systems. This program can analyze any smoke control system that produces pressure differences with the intent of limiting smoke movement in building fire situations. The program is also capable of modeling the stack effect created in taller buildings during extreme temperature conditions. The program input consists of the outside and building temperatures, a description of the building flow network and the flows produced by the ventilation or smoke control system. The output consists of the steady state pressures and flows throughout the building.
Limitations: Assumes steady state airflow. Cannot account for changes in the building or air handling system during a fire.

ASET-B (Available Safe Egress Time--Basic)

A program for calculating the temperature and position of the hot smoke layer in a single room with closed doors and windows. ASET-B is a compact easy-to-run program, which solves the same equations as ASET. The required program inputs are a heat loss fraction, the height of the fire, the room ceiling height, the room floor area, the maximum time for the simulation, and the rate of heat release of the fire. The program outputs are the temperature and thickness of the hot smoke layer as a function of time.
Limitations: Based upon a single compartment with no openings. Does not provide species concentrations or time to detection.

Job Aid 3.3 (cont'd)

ASMET (Atria Smoke Management Engineering Tools)

Consists of a set of equations and a zone fire effects model for analysis of smoke management systems for large spaces such as atria, shopping malls, arcades, sports arenas, and exhibition halls.

BREAK1 (Berkeley Algorithm for Breaking Window Glass in a Compartment Fire)

A program which calculates the temperature history of a glass window exposed to user described fire conditions. The calculations are stopped when the glass breaks. The inputs required are the glass thermal conductivity, thermal diffusivity, absorption length, breaking stress, Young's modulus, thermal coefficient of linear expansion, thickness, emissivity, shading thickness, half-width of window, the ambient temperature, numerical parameters and the time histories of flame radiation from the fire, hot layer temperature and emissivity, and heat transfer coefficients. The outputs are temperature history of the glass normal to the glass surface, and the window breakage time.

CCFM (Consolidated Compartment Fire Model Version VENTS)

A two-layer zone-type compartment fire effects model computer code. It simulates conditions due to user-specified fires in a multi-room, multi-level facility. The required inputs are a description of room geometry and vent characteristics (up to 9 rooms, 20 vents), initial state of the inside and outside environment, and fire energy release rates as a function of time (up to 20 fires). If simulation of concentrations of products of combustion is desired, then product release rates must also be specified (up to three products). Vents can be simple openings between adjacent spaces (natural vents) or fan/duct forced ventilation systems between arbitrary pairs of spaces (forced vents). For forced vents, flow rates and direction can be user-specified or included in the simulation by accounting for user-specified fan and duct characteristics. Wind and stack effects can be taken into account. The program outputs for each room are pressure at the floor, layer interface height, upper/lower layer temperature and (optionally) product concentrations.

CCFMPLT

A graphics program which runs in conjunction with CCFM. The results from CCFM are sent to a user specified data file at each prescribed time step. CCFMPLT plots this data on an IBM-PC compatible microcomputer and can optionally provide hardcopy output.

Job Aid 3.3 (cont'd)

CFAST

A zone model that predicts the effect of a specified fire on temperatures, various gas concentrations and smoke layer heights in a multi-compartment structure.
Limitations: Assumes flat horizontal ceilings.

DETACT-QS (DETector ACTuation--Quasi Steady)

A program for calculating the actuation time of thermal devices below unconfined ceilings. It can be used to predict the actuation time of fixed temperature heat detectors and sprinkler heads subject to a user specified fire. DETACT-QS assumes that the thermal device is located in a relatively large area, that is, only the fire ceiling flow heats the device and there is no heating from the accumulated hot gases in the room. The required program inputs are the height of the ceiling above the fuel, the distance of the thermal device from the axis of the fire, the actuation temperature of the thermal device, the response time index (RTI) for the device, and the rate of heat release of the fire. The program outputs are the ceiling gas temperature and the device temperature both as a function of time and the time required for device actuation.

DETACT-T2 (DETector ACTuation--Time Squared)

A program for calculating the actuation time of thermal devices below unconfined ceilings. It can be used to predict the actuation time of fixed temperature and rate of rise heat detectors, and sprinkler heads subject to a user specified fire which grows as the square of time. CT-T2 assumes that the thermal device is located in a relatively large area, that is, only the fire ceiling flow heats the device and there is no heating from the accumulated hot gases in the room. The required program inputs are the ambient temperature, the response time index (RTI) for the device, the activation and rate of rise temperatures of the device, height of the ceiling above the fuel, the device spacing and the fire growth rate. The program outputs are the time to device activation and the heat release rate at activation.

Job Aid 3.3 (cont'd)

ELVAC (Elevator Evacuation)

An interactive computer program that estimates the time required to evacuate people from a building with the use of elevators and stairs. It is cautioned that elevators generally are not intended as a means of fire evacuation, and they should not be used during fires. However, it is possible to design elevator systems for fire emergencies, and ELVAC can be used to evaluate the potential performance of such systems. ELVAC calculates the evacuation time for one group of elevators. If a building has more than one group of elevators, ELVAC can be run on each group separately. Input consists of floor to floor heights, number of people on floors, number of elevators in the group, elevator speed, elevator acceleration, elevator capacity, elevator door type and width, and various inefficiency factors. The output is a table of elevator travel time, round trip time, people moved, and number of round trips for each floor plus the total evacuation time.

FASTLite

A user-friendly software package which builds on the core routines of FPETool and the computer model CFAST to provide calculations of fire phenomena for use by the building designer, code official, fire protection engineer, and fire-safety related practitioner.
Limitations: Models up to 3 compartments with flat horizontal ceilings with multiple openings. Assumes a user specified fire in one of the compartments.

FIRDEMND

Simulates the suppression of post flashover charring and non-charring solid-fuel fires in compartments using water sprays from portable hose-nozzle equipment used by the fire departments. The output of the Fire Demand Model (FDM) shows the extinguishing effects of water spray at various flow rates and droplet sizes. The calculations are based on a heat and mass balance accounting for gas and surface cooling, steam-induced smothering, water-spray induced air entrainment, direct extinguishment of the fire by water, and the energy transport via inflow and outflow of heat and products of combustion.
This model can be complicated, but it is very powerful.

Job Aid 3.3 (cont'd)

FIRST (FIRe Simulation Technique)

The direct descendant of the HARVARD V program developed by Howard Emmons and Henri Mitler. The fire may be entered either as a user-specified time-dependent mass loss rate or in terms of fundamental properties of the fuel. In the latter case, the program will predict the fire growth rate by considering the changing oxygen concentration and smoke layer conditions in the room of fire origin. It can also predict the heating and possible ignition of up to three targets. The original fire and targets may also be user specified fires. The required program inputs are the geometrical data describing the rooms and openings, and the thermophysical properties of the ceiling, walls, burning fuel, and targets. The generation rate of soot must be specified, and the generation rates of other species may be specified as a yield of the pyrolysis rate. Among the program outputs are the temperature and thickness of, and species concentrations in, the hot upper layer and also in the cooler, lower layer in each compartment. Also given are wall surface temperatures, heat transfer rates and mass flow rates.

MASBANK

Used to create and maintain a data base of materials and their fire properties for use by the FIRST program. MASBANK can accommodate 20 properties for up to 50 materials. The program has the capability to add, delete, change, alphabetize and view the material properties in the data bank. Material properties from MASBANK may be transferred directly into the FIRST program. MASBANK is written in FORTRAN.

FPETool

A set of engineering equations useful in estimating potential fire hazard and the response of the space and fire protection systems to the developing hazard. Version 3.2 incorporates an estimate of smoke conditions developing within a room receiving steady-state smoke leakage from an adjacent space. Estimates of human viability resulting from exposure to developing conditions within the room are calculated based upon the smoke temperature and toxicity.
Limitations: Based on a single compartment. Each FPETool routine also has its own limitations.

Job Aid 3.3 (cont'd)

LAVENT

A program developed to simulate the environment and the response of sprinkler links in compartment fires with draft curtains and fusible link operated ceiling vents. The model, used to calculate the heating of the fusible links, includes the effects of the ceiling jet and the upper layer of hot gases beneath the ceiling. The required program inputs are the geometrical data describing the compartment, the thermophysical properties of the ceiling, the fire elevation, the time dependent energy release rate of the fire, the fire diameter or energy release rate per area of the fire, the ceiling vent area, the fusible link response-time-index (RTI) and fuse temperature, the fusible link positions along the ceiling, the link assignment to each ceiling vent, and the ambient temperature. A maximum of five ceiling vents and ten fusible links are permitted in the compartment.

The program outputs are the temperature, mass and height of the hot upper layer, the temperature of each link, the ceiling jet temperature and velocity at each link, the radial temperature distribution along the interior surface of the ceiling, the radial distribution of the heat flux to the interior and exterior surfaces of the ceiling, the fuse time of each link, and the vent area that has been opened.
Limitations: Models up to 5 vents and 10 fusible links in a single compartment.

GRAPH

A graphics program which runs in conjunction with LAVENT. The results for LAVENT are sent to the data file, GRAPH.OUT, after each prescribed time step. GRAPH then allows the user to choose two sets of variables to be plotted on the screen and has the additional capability of hardcopy output.

NIST Fire Dynamics Simulator and Smokeview

The NIST Fire Dynamics Simulator predicts smoke and/or air flow movement caused by fire, wind, ventilation systems etc. **Smokeview** visualizes the predictions generated by NIST FDS.

HAZARD I

Another available fire effects modeling program is HAZARD I, originally developed by the Building and Fire Research Laboratory at NIST. It is currently available for purchase from NFPA.

The model provides a method for quantifying the hazards to occupants of buildings from fires, and the relative contribution of specific products to those hazards. The model combines fire prediction calculations and simulation of the decisions, actions and progress of occupants during a specified fire.
Limitations: Designed for residential structures. Other applications require a more detailed knowledge of the model.

Job Aid 3.4

Types of Fire Effects Models Used in Fire Safe Building Designs

Physical		
Model Type	**Pros**	**Cons**
Full-Scale Fire Experiments Example: UL or FM high rack storage burn.	• Potential to closely represent actual fire of interest.	• Expensive. • Limited number, if any, replicate tests. • Limited experimental control. • Limits of test facility may not represent the fire. • Building, test uncertainties due to materials, weather, source of ignition.
Reduced-Scale Experiments Examples: 2/5 scale fire compartment, saltwater modeling, cold smoke model at NFA.	• Less expensive than full scale. • Replicate testing. • Typically more parameters can be varied. • Better experimental control.	• Physical fire properties do not scale the same. • Saltwater models or "cold smoke" models do not include heat transfer effects.
Mathematical		
Model Type	**Pros**	**Cons**
Hand Calculations Examples: Flame height, minimum HRR for flashover.	• Quick estimations. • No special equipment needed.	• Considers only a limit apart of total problem. • Many assumptions behind the simplified algorithm. • Labor intensive to study many different situations. • Usually address steady-state scenarios.

Job Aid 3.4 (cont'd)

Mathematical		
Model Type	**Pros**	**Cons**
Computer Models Examples: DETACT, ASET-B, FDS)	• Consider many factors together, fire properties as well as building geometry consider-ations, in order to predict the impact of inter-action between the two. • Can address growing fire scenarios.	• A good understanding of the physics and assumptions behind the computer program is needed. • Set-up and run time on complicated models can be very time intensive.

About Fire Effects Models

Types of computer-based fire effects models include "Zone Models" and "Field Models."

About Zone Models

In the simplest form, a zone model divides a single room into a "hot gas layer" and a "cool gas layer." The laws of conservation of mass and conservation of energy are taken on the "hot gas layer." In other words, a mass and energy balance needs to be accounted for on the hot gas layer. So the energy input to the hot gas layer from the fire must equal the energy in the hot gas layer, plus energy losses caused by heating the ceiling and walls of the room, and any losses of energy flowing out of open doors or windows.

The same is true of the mass added to the hot gas layer by the burning fuel. A two-layer zone model is well suited to modeling a rectangular compartment with a smooth, flat horizontal ceiling. Effectively, the two-zone model has one computational cell for each room modeled.

Zone models do not account for changes in pressure caused by a fire. Zone models do not predict the growth and development of a fire. The fire growth must be input into the model. The fire is considered as a "point source," a source of thermal energy that has no relation to the size or shape of the flames that would compose the "real" fire in a room.

Zone models use a "quasi-steady" assumption, which means that a change in the fire input at the source results in an instantaneous change to conditions in the hot gas layer. No transportation time is considered. Only one "characteristic temperature" will be predicted for the hot gas layer, though in reality, the temperature near the ceiling will be significantly hotter than the temperature near the lower edge of the hot gas layer.

Job Aid 3.4 (cont'd)

About Field Models

A field model or computational fluid dynamics model (CFD) has the capability of modeling compartments or a building of various shapes and sizes, since the model can partition a room or building into thousands or hundreds of thousands of computational cells. In addition to using the laws of conservation of mass and energy, CFD models also use the laws of conservation of momentum and species to provide a more realistic and detailed description of the movement of fire gases and what they contain.

A gas temperature and velocity will be predicted for each computational cell at very small time intervals, yielding significant quantities of predicted values. These models are usually used with another program that can turn the numbers into a graphical output for analysis. The visualization programs typically use isotherms and vectors to describe model output in the same manner as temperature and wind data is displayed on weather maps during the evening news.

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Job Aid 3.5

A Sample of Computer Fire Effects Models and Their Properties

The chart below presents a cross representation of computer-based fire effects models, ranging from the simplest model (DETACT-QS) to the most complex (FDS/Smokeview). A list of the values that the model can predict, as well as a partial list of limitations, is given for each model to give the AHJ a sense of the capabilities of the models and the types of limitations each model has. Further information about each of the models can be found in the technical documentation for each of these models. The AHJ should ask for these documents when a design relying on a fire effects model is presented.

Name of Model	Type	Predicts	Limitations
DETACT-QS	Empirical/Zone	• Ceiling jet temperature. • Heat detector activation time.	• Smooth, flat, horizontal, unconfined ceiling. • Assumes maximum ceiling jet temperature. • Input of fire HRR required.
ASET-B	Zone	• Smoke layer temperature. • Smoke layer height above floor.	• Smoke layer described by only one temperature and thickness. • Smooth, flat horizontal ceiling. • Single room with closed windows and doors with assumed leakage. • Fire assumed to be in center of room. • Input of fire HRR required.

Job Aid 3.5 (cont'd)

Name of Model	Type	Predicts	Limitations
FPETool Fire Simulator	Zone	• Ceiling jet temperature. • Ceiling jet velocity. • Heat detector activation time. • Smoke layer temperature. • Smoke layer height above floor.	• Smoke layer described by only one temperature. • Smooth, flat horizontal ceiling. • Fire assumed to be in center of room. • Input of fire HRR required.
FAST	Zone	• Ceiling jet temperature. • Ceiling jet velocity. • Heat detector activation time. • Smoke layer temperature. • Smoke layer height above floor.	• Smoke layer described by only one temperature. • Smooth, flat horizontal ceiling. • Input of fire HRR required
FDS/Smokeview	Field or CFD	• Simulates fire growth. • Heat detector activation time. • Gas temperature throughout modeled room or building. • Gas velocity throughout modeled room or building. • Tracks gas concentrations. • Wall and ceiling temperatures. • Limited suppression effects. • Good visualization of output.	• Requires more detailed data. • Requires more expertise to use. • Labor intensive. • Requires more computer power. • Limited database of material properties for input. • Models are still under develop-ment and are changing.

Job Aid 3.6

Checklist to Evaluate Appropriateness of Fire Effects Models

What is the design fire scenario?

Does the fire effects model used include all the conditions that define the development of fire and its spread through all or parts of the building?

Does the fire effects model address each stakeholder safety goal?

How does the fire effects model simulate

- structural failure of building elements;
- activation times for sprinklers and detectors;
- occupant egress times; and
- production of toxic gases?

What are the data on which the occupant egress behavior is based?

- number of occupants;
- distribution in the building;
- stair widths;
- median width of doors;
- estimated time for occupants to evacuate; and
- susceptibility of occupants to smoke and other toxicities.

How are uncertainties addressed in the fire effects model?

- building material variations;
- installation;
- system and component variability;
- unanticipated uses of systems; and
- unpredictable human action.

Is the fire size realistic for the fire scenario?

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Job Aid 3.7

Checklist to Evaluate Design Assumptions Related to Risk

What fire risks does this design anticipate?

What does the design assume are the greatest possible risks, and what are their anticipated consequences related to:

- life safety;
- property loss;
- business continuance; and
- environmental damage?

What might introduce uncertainty related to the design assumptions about risk?

- building materials variation;
- installation unknowns;
- system and component variability;
- unanticipated uses of systems; and
- human actions

What is the evidence that:

- The design or system will function as designed?

- The design or system be available at all times?

- The owner will be able to afford the cost of installing the design and maintaining its integrity over the life cycle of the building?

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Job Aid 3.8

Risk-Ranking Matrix

Frequency→ Consequence ↓	Beyond Extremely Unlikely	Extremely Unlikely	Unlikely	Anticipated
High				
Moderate				
Low				
Negligible				

How to use this matrix:

For a given fire scenario, assess the degree of risk by locating the block where the frequency of fire and the consequences of the fire intersect.

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Job Aid 3.9

Uncertainty Considerations at Each Step of the Performance-Based Design Process*

Step 1	Define Project Scope	Uncertainties related to life-cycle use and safety of buildings.
Step 2	Identify Goals	Uncertainties related to providing equitable outcomes for all stakeholders and incorporation of societal values.
Step 3	Define Stakeholder and Design Objectives	Uncertainties related to risk perception and values. Variability in the ways stakeholders perceive and value risks.
Step 4	Develop Performance Criteria	Uncertainties related to probabilistic statements of performance involving: • Criteria: Which should be evaluated? • Threshold: Values of negative consequences for each criteria. • Probability: Levels of acceptable risk. • Time: Time to exceed acceptable risk level.
Step 5	Develop Design Fire Scenarios	Uncertainties related to: • Selecting calculation procedures (models, live tests). • Selecting crucial input parameters. • Determining the likelihood of occurrence of fire scenarios, based on statistical data, judgment and design goals. • Determining the number of scenarios.
Step 6	Develop Candidate Designs	Uncertainty in the development of candidate designs related to: • Fire protection systems. • Construction features. • Operations that meet the performance criteria.
Step 7	Evaluate Candidate Designs	Uncertainties related to: • Calculating a set of values for each outcome criteria. • Determining criteria (threshold, probability, time). • Determining the effect of each candidate design on each of the scenarios. • Evaluating the importance of uncertainty in each candidate design.
Step 8	Determine that the Design Meets the Performance Criteria	Uncertainty related to judging a design's acceptability related to all four elements of the probabilistic statement of performance (criteria, threshold, probability, time).
Step 9	Select Final Design	Uncertainty in selecting an appropriate final design from design options available.
Step 10	Prepare Design Documentation	Uncertainty related to the performance-based design: • Implementation. • Maintenance. • Continuity of design assumptions.

*Adapted from Notarianni, 2000, Chapter 3.

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APPENDIX B

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PSYCHOLOGICAL VARIABLES THAT MAY AFFECT FIRE ALARM Design

By Dr. John L. Bryan

Beginning with the 1996 edition, the *National Fire Alarm Code®* specified a distinctive "evacuation signal" that used a three-phase temporal pattern signal in all new fire alarm systems. The specification for the three-phase temporal pattern can be seen in Figure 1.

The three-phase temporal pattern (ANSI S3.41) *Audible Emergency Evacuation Signal* is intended to be used where immediate evacuation is intended. Where relocation of occupants or defense in place is intended, the *National Fire Alarm Code* contains requirements for an "emergency voice/alarm communications service," which provides for verbal communication to the occupants to facilitate the selective evacuation or protection procedures.

The *Life Safety Code*, NFPA 101[1] specifies when a fire alarm system is required and the features of the system that may vary from the requirements of the *National Fire Alarm Code*.[2] The *Life Safety Code* provides two exceptions to the activation of the "general evacuation alarm signal" throughout the building. One of these exceptions provides buildings with physical environments which make total evacuation of the occupants impractical, e.g., many high-rise buildings. The second of these exceptions provides for the occupancies in which the occupants are incapable of "self-protection" and evacuation without the assistance of staff personnel is not feasible, such as occurs in healthcare or detention and correction facilities.

The *Life Safety Code* permits automatically transmitted or "live voice" evacuation instructions. This provision for the utilization of recorded or "live voice" communications with the exceptions to the general evacuation notification were first introduced in the 1981 edition of the *Life Safety Code*.

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INITIAL DESIGN AND UTILIZATION OF VOICE ALARM SYSTEMS

One of the first evaluations of the design criteria for a voice alarm system was established and reported by McCormick as early as 1964. This design criteria consisted of the following critical elements for an effective vocal alarm system.[3]

1. Audible (heard above background noise)
2. Quick-acting (capable of evoking a quick reaction)
3. Alerting
4. Discriminable (easy to differentiate from other signals)
5. Informative
6. Compatible (consistent with others in use)
7. Nonmasking (not prone to interfere with other functions by drowning out other audio signals)
8. Nondistracting (not startling)
9. Nondamaging (not prone to cause irreversible damage to hearing)

One of the early listings of the characteristics of a voice alarm system was developed at the International Conference

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on Fire Safety in High-Rise Buildings in 1971.[4, 5] These characteristics were reported to have consisted of the following nine factors:[6]

1. A voice alarm system can give precise instruction under varying emergency conditions (fire, bomb threat, etc.).
2. Instructions can vary for different zones of the building.
3. Recorded alerting sounds can capture attention of the people and alert them to emergencies at hand by preconditioning.
4. Prerecorded messages can be used for preplanned conditions.
5. Prerecorded voice announcements can be used automatically to respond to manual or automatic fire alarms.
6. The voice system can be used to modify or update information.
7. Number and type of speakers are dependent on the situation of the area covered.
8. A voice alarm system may be combined with a music/paging system. If so, the music system can be turned off, and the emergency announcement system can operate at predesignated volume levels.
9. Manual voice directions can override or cancel automatic voice transmission.

One of the first "vocal alarm systems" was designed by Keating and Loftus in the Seattle Federal Building in 1974. The critical design variables of this system consisted of the following features:[7]

The alerting tone consisted of a 1000 Hz, pure sine wave tone (the then-authorized FCC warning signal). The human ear is reported to be most sensitive in the 500-3000 Hz range.[7]

The voice qualities of the communicator were varied with a female voice to initiate the announcement and a male voice to provide the emergency communication.

The actual wording of the messages provided the following three essential elements:

1. Tell the occupants exactly what has happened.
2. Tell the occupants what they are to do.
3. Tell the occupants why they should do it.

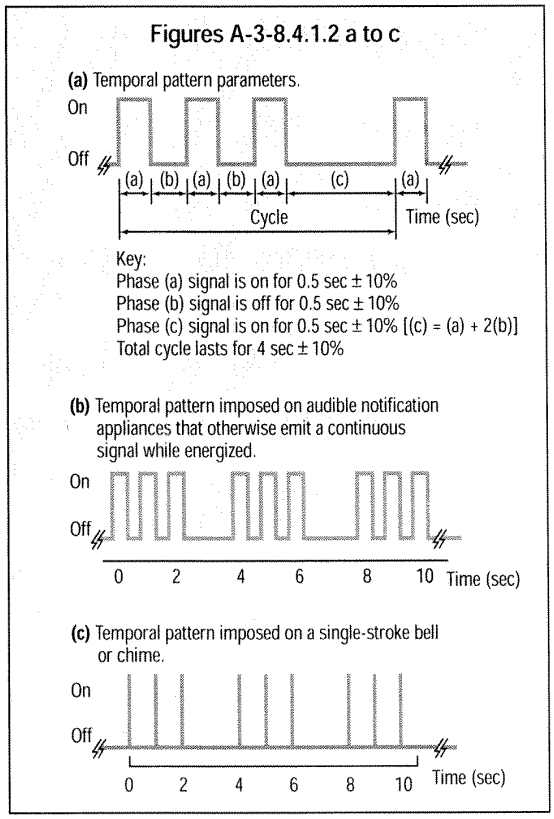

Figure 1. Figures A-3-8.4.1.2 a to c
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STUDIES AND OBSERVATIONS OF OCCUPANTS' RESPONSE TO ALARMS

There have been both experimental and observational studies involving practice evacuations and fire incidents. These studies have involved both systems using evacuation signals and voice notification systems over the past thirty years. The following summaries of study reports are illustrative of the published observational and experimental research studies relative to the responses of building occupants to the various types of alarm signals or voice messages:

1. Seattle Federal Building, Seattle, WA, 1974.[6]

Keating and Loftus conducted two practice evacuations involving 205 participants consisting of adults, both visitors and employees. The alarm system consisted of a voice notification to the floors involved with the relocation and the floors receiving the relocated personnel. The report indicated the occupants on the floors being relocated had vacated these floors within 1.5 minutes of the alerting tone initiating the voice announcements. This report indicated the following general observation of the relocating occupants in response to the voice announcements:[6]

"Personnel unhesitatingly went to the stairwells to evacuate, no one attempted to use the captured elevators, nor was there any pushing, running, or other panicky behavior observed."

2. World Trade Center, New York, NY, 1975.[8]

Lathrop has reported on a voice alarm system involved in a fire incident in the South Tower on April 17 at approximately 9:04 a.m. The fire involved a trash cart in a storage area on the fifth floor, adjacent to an open stairway door. This configuration with the thermal column from the cart fire enabled smoke to penetrate the ninth through the twenty-second floors. The occupants on these floors moved into the core corridors of the floors as previously conducted during the practice evacuations. At approximately 9:10 a.m., a voice announcement from the Tower Communications Center monitoring these areas advised the occupants to remain calm and to return to their respective office areas. In spite of this announcement, the occupants remained in the corridor areas and became more concerned about the visible and irritating smoke condition. The Tower Communications Center then announced an evacuation message at approximately 9:16 a.m. It should be noted that the validity of any announcement will be questioned by occupants if the announcement is in conflict with direct physical aware-

ness cues evident to the occupants. Thus, in this situation, the physical presence and discomfort from the smoke resulted in the occupants disregarding the information presented by the voice announcement.

3. Conference Room, London, UK, 1987.[9, 10]

Pigott has described an experimental study in a basement conference room in an office building with two randomly selected groups, consisting of ten adults, five males and five females. The adults were seated at two tables, six at one table and four at the other, with the seating selected by the participants. They were given questionnaires to fill out prior to being called for interviews on market research. The participants were given biscuits and coffee while filling out the questionnaires.

The first group was subjected to a continuous sounding alarm bell. After the bell had operated, the ten subjects discussed among themselves the meaning of the bell. The first subject to leave the room left after a period of three minutes, with the remaining nine persons leaving after eleven minutes. The second group of ten subjects had the identical refreshments and questionnaire. This group was subjected to a voice alarm announcement initiated after three seconds of the ringing bell stated in the following manner:[10]

"Attention. This is an intelligent fire warning system. There is a fire above you on the ground floor. Evacuate now."

The second group subjected to the above voice announcement all left the conference room within thirty seconds. It should be noted, as in many practice evacuations, the ten subjects in each group all left the basement level of the building by the way they entered, disregarding a corridor door marked as a "Fire Exit."

4. Lecture Theatre, Portsmouth, UK. 1989.[11]

Michiharu and Sime studied two practice evacuations with biology and pharmacy students in the age range of 18-19 years. Two different lecture theatres were utilized, one with the fire exit and the entrance/exit at the rear of the theatre, and one with the fire exit at the front of the theatre and the entrance/exit at the rear of the theatre. The fire alarm notification was by a continuous bell. The first evacuation practice involved the theatre with the entrance/exit and the fire exit at the rear of the theatre. This evacuation involved a total of 56 individuals with 31 persons (55 percent) leaving by the entrance/exit and 25 (45 percent) leaving by the fire exit. Upon hearing the bell alarm, the lecturer, after a period of 13 seconds, indicated the following:[11]

"We'd better all run for exits."

The second evacuation practice involved the theatre with the entrance/exit at the rear and the fire exit at the front of the theatre. This evacuation involved a total of 77 individuals, and they all evacuated through the fire exit due to the directions of the lecturer. The lecturer issued the exiting directions after a few moments of hesitation, upon hearing the alarm bell in the following manner:[11]

"I gather it sounds like a fire alarm, have to go that way."

The authors of this study indicate the importance of instructions from a valid and reliable source in influencing the behavior of the occupants as follows:[11]

"The fact that everyone in the R lecture theatre left by the fire exit, as a result of the lecturer's instruction, demonstrates how crucially important evacuation instructions from an authoritative and credible source can be."

5. Underground Station, Newcastle, UK, 1991.[12]

Proulx and Sime conducted five practice evacuations in the Monument underground transit station These evacuations involved approximately 304 participants, consisting of adults, children, and infants. The study utilized seven observers in the station, the 12 closed circuit television cameras in the station, and 133 questionnaires completed by adult participants. The practice evacuations were all conducted at approximately noon time on a weekday, and 5 seconds after Train 124 arrived in the station. Five different alerting scenarios were utilized in the practice evacuations, consisting of the alarm bell, staff directions, and public address system announcements.[12]

Evacuation 1: The alarm bell was rung; there was no staff in the station and no public address (PA) used.

Evacuation 2: Two staff members on Platform 3 knew a drill was scheduled, gave a PA announcement to *"evacuate the station,"* and directed evacuation.

Evacuation 3: Each 30 secs. (10 sec. message, 20 sec. interval) PA announcement *"Please evacuate the station immediately."* No staff in the station.

Evacuation 4: Two staff members assisted evacuation with PA directions to passengers on platform to take trains and those on concourse to leave by exits.

Evacuation 5: No staff in station. Directed PA was used: *"To all passengers. There is a suspected fire on the North/South escalator between the concourse and platforms 1 and 2. Passengers on all platforms should board the first available train. Passengers at concourse level should leave by the nearest exit. Do not use the lift."*

Table 1 contains a summary of the results of these evacuations.

Table 1. Summary of Times and Movements:[12]

Evacuation	Time to Start to Move		Time to Clear the Station	Appropriateness of Behavior
	Concourse	Bottom Escalator		
1 Bell only	8:15	9:00	Exercise ended 14:47	Delayed or no evacuation
2 Staff	2:15	3:00	8:00	Users directed to concourse
3 PA	1:15	7:40	10:30	Users stood at bottom of escalator
4 Staff + PA +	1:15	1:30	6:45	Users evacuated
5 PA ++	1:30	1:00	5:45 (10:15)	Users evacuated by trains and exits

Note: In Evacuation 5, the indicated time of (10:15) to clear the station was by a woman with two small children and a baby in a push cart.

6. Apartment Buildings, Ottawa, Montreal, North York, Vancouver, Canada, 1993.[13]

Proulx studied practice evacuations in four 6- and 7-story apartment buildings, one evacuation in each building. The total study population consisted of 254 participants with adults, seniors, impaired adults, and children. The alarm/notification systems consisted of bells. The results of these practice evacuations indicated the time to initiate the evacuation varied from 30 seconds to 24 minutes, with a mean time of 2.5 minutes. The most prevalent pre-evacuation activities were:[13]

"Find pet, gather valuables, get dressed, look in corridor, move to balcony, find children."

7. High-Rise Apartment Building, Ottawa, Canada, 1997.[14]

Proulx studied this fire which occurred in a unit on the sixth floor of a 25-story apartment building at approximately 4:30 p.m. This study involved the conduct of interviews with occupants of the sixth and seventh floors and the distribution of questionnaires to all the other units. A total of 137 questionnaires were utilized in the study consisting only of persons that were in the building at the time of the fire. The population in the building was predominately adults with 68 percent over 65 years, 29 percent between 21 and 65 years, and only 3 percent children or teenagers. A total of 43 adults consisting of 23 percent reported perceptual, physical, or mental impairments. The fire alarm system consisted of a sounding device through speakers in each unit, with the fire alarm signal being overridden by voice messages through the speakers. The building manager operates the voice communication system and made the following four announcements as indicated in the report:[14]

The first message was given before the arrival of the fire department; it stated: *"There is a fire on the sixth floor. The fire department is on its way."* After the fire department's initial assessment of the situation, the chief in command gave the order to evacuate. The resident manager issued the message: *"All occupants should evacuate using Stairwells B and C."* After encountering occupants coming down Stairwell A that was being used for fire-fighting, another message was issued: *"Occupants should not evacuate through Stairwell A."* Finally, many exhausted, anxious occupants exited from all stairwells into the lobby complaining of the crowd and smoke conditions they encountered. The chief in command decided to change strategy, and a last message was issued: *"Occupants who have not started to evacuate should remain in their units."*

A new alarm system had been installed five months before the fire, and this system was tested monthly with a voice announcement prior to the test. The ten occupants who indicated they had hearing impairments all indicated they were alerted by the fire alarm and eight indicated the voice announcements were clear. Considering all the occupants responses, 95 percent indicated the instructions over the voice announcements were clear.

In spite of the confusion created by the contradictory voice instructions "to evacuate" and then "not to evacuate," the report of this fire incident concludes in the following manner relative to the utilization of the voice announcements:[14]

"The occupants placed considerable trust in the information received over the voice communication system. This is evident from the 83 percent of the respondents who attempted evacuation as a result of evacuation instructions given over the voice communication system. It confirms that, in most instances, the public is prepared to follow voice communication instructions, especially if this means of providing information has been accurate in the past and if the message comes from a person in which they confide or from figures of authority such as the fire department."

SUMMARY

The characteristics of voice alarm systems have been established since the 1960s and early 1970s. The effectiveness of these systems has been demonstrated in both practice evacuations[6, 9, 10, 12, 15] and actual fire incidents.[8, 14] The critical function needed for a fire alarm system is to direct an adaptive behavioral response of the occupants by providing the essential definitive and directive information relative to the fire incident to the occupants. This information cannot be conveyed by a signaling type of system, due to the lack of the communication capability to provide the following information to the occupants:[7, 14]

What has happened.

What they are to do.

Why they should do it.

Ramachandran in his review of the studies on human behavior in fires in the United Kingdom formulated the following conclusions which emphasize the importance of providing complete and valid information to the building occupants upon the detection of possible fire cues:[16]

"Early behavior is characterized by uncertainty, misinterpretation, indecisiveness, and seeking additional information for confirmation – the 'gathering phase.' Such delay can be dangerous, as actions taken at the early stages of a fire have the most decisive effect on the eventual outcome."

The response to fire alarm bells and sounders tends to be less than optimum. There is usually skepticism as to whether the noise indicated a fire alarm and if so, is the alarm merely a system test or drill?

In the stress of a fire, people often act inappropriately and rarely panic or behave irrationally. Such behavior, to a large extent, is due to the fact that information initially available to people regarding the possible existence of a fire and its size and location is often ambiguous or inadequate.

Valid information is needed relative to a perceived fire incident by the occupants of a building, and both the *National Fire Alarm Code*[2] and the *Life Safety Code*[1] permit the utilization of voice alarm systems which provide the needed communication capabilities to transmit this information.

Ramachandran in the report on an informative fire warning system developed a psychological design criteria for a fire alarm system:[17]

1. The meaning of a fire alarm must be obvious and distinct from other types of alarms.
2. Fire alarms must be reliable and valid indicators of the presence of a fire.
3. People need to know the location of a fire so they can authenticate the alarm and plan their response.
4. There is a need to provide infor-

mation to building occupants on the most appropriate response to an alarm, including information on available escape routes.

The adaptation of the behavioral and psychological principles previously illustrated should enable fire protection engineers to more effectively utilize the communication and information capabilities of voice alarm systems in the design, specification, and installation of fire alarm systems.

Significant scientific research is also needed to compare the effectiveness of the human behavioral response of various populations to the ANSI S3.41 *Audible Emergency Evacuation* signal as compared with voice alarm systems and other existing audible signaling systems.

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APPENDIX C

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Estimates of the Operational Reliability of Fire Protection Systems

R. W. BUKOWSKI, E. K. BUDNICK and C. F. SCHEMEL

INTRODUCTION

Background

Fire protection strategies are designed and installed to perform specific functions. For example, a fire sprinkler system is expected to control or extinguish fires. To accomplish this, the system sprinklers must open, and the required amount of water to achieve control or extinguishment must be delivered to the fire location. A fire detection system is intended to provide sufficient early warning of a fire for occupant notification and escape, fire service notification, and in some cases activation of other fire protection features (e.g., special extinguishing systems, smoke management systems). Both system activation (detection) and notification (alarm) must occur to achieve early warning. Construction compartmentation is generally designed to limit the extent of fire spread as well as to maintain the building's structural integrity as well as tenability along escape routes for some specified period of time. In order to accomplish this, the construction features must be fire "rated" (based on standard tests) and the integrity of the features maintained.

The reliability of individual fire protection strategies such as detection, automatic suppression, and construction compartmentation is important input to detailed engineering analyses associated with performance based design. In the context of safety systems, there are several elements of reliability, including both *operational* and *performance* reliability. *Operational* reliability provides a measure of the probability that a fire protection system will operate as intended when needed. *Performance* reliability is a measure of the adequacy of the feature to successfully perform its intended function under specific fire exposure conditions. The former is a measure of component or system operability while the latter is a measure of the adequacy of the system design.

The scope of this study was limited to evaluation of *operational* reliability due primarily to the form of the reported data in the literature. In addition to this distinction between *operational* and *performance* reliability, the scope focused on *unconditional* estimates of reliability and failure estimates in terms of *fail-dangerous* outcomes. A discussion of these terms is provided later in the paper.

Scope

This paper provides a review of reported operational reliability and performance estimates for (1) fire detection, (2) automatic suppression, and to a limited extent (3) construction compartmentation. In general, the reported estimates for fire detection are largely for smoke detection/fire alarm systems; automatic sprinklers comprise most of the data for automatic suppression, and compartmentation includes compartment fire resistance and enclosure integrity. It should be noted that in some cases the literature did not delineate beyond the general categories of "fire detection" or "automatic suppression," requiring assumptions regarding the specific type of fire protection system.

Several studies reported estimates of reliability for both fire detection and automatic sprinkler system strategies. However, very little information was found detailing reliability estimates for passive fire protection strategies such as

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compartmentation. A limited statistical based analysis was performed to provide generalized information on the ranges of such estimates and related uncertainties. This latter effort was limited to evaluation of reported data on detection and suppression. Insufficient data were identified on compartmentation reliability to be included.

This paper addresses elements of reliability as they relate to fire safety systems. The literature search that was performed for this analysis is reviewed and important findings and data summarized. The data found in the literature that were applicable to sprinkler and smoke detection systems reliability were analyzed, with descriptive estimates of the mean values and 95 percent confidence intervals for the operational reliability of these in situ systems reported.

ELEMENTS OF RELIABILITY ANALYSIS

There is considerable variation in reliability data and associated analyses reported in the literature. Basically, reliability is an estimate of the probability that a system or component will operate as designed over some time period. During the useful or expected life of a component, this time period is "reset" each time a component is tested and found to be in working order. Therefore, the more often systems and components are tested and maintained, the more reliable they are. This form of reliability is referred to as *unconditional*.

Unconditional reliability is an estimate of the probability that a system will operate "on demand." A *conditional* reliability is an estimate that two events of concern, i.e., a fire and successful operation of a fire safety system occur at the same time. Reliability estimates that do not consider a fire event probability are *unconditional* estimates.

Two other important concepts applied to *operational* reliability are *failed-safe* and *failed-dangerous*. When a fire safety system fails safe, it operates when no fire event has occurred. A common example is the false alarming of a smoke detector. A fire safety system fails dangerous when it does not function during a fire event. In this study, the *failed-dangerous* event defines the *operational* probability of failure (1- reliability estimate). A sprinkler system not operating during a fire event or an operating system that does not control or extinguish a fire are examples of this type of failure.

The overall reliability of a system depends on the reliability of individual components and their corresponding failure rates, the interdependencies of the individual components that compose the system, and the maintenance and testing of components and systems once installed to verify operability. All of these factors are of concern in estimating *operational* reliability.

Fire safety system performance is also of concern when dealing with the overall concept of reliability. System performance is defined as the ability of a particular system to accomplish the task for which it was designed and installed. For example, the performance of a fire rated separation is based on the construction component's ability to remain intact and provide fire separation during a fire. The degree to which these components prevent fire spread across their intended boundaries defines system performance.

Performance reliability estimates require data on how well systems accomplish their design task under actual fire events or full scale tests. Information on performance reliability could not be discerned directly from many of the data sources reviewed as part of this effort due to the form of the presented data, and therefore, it is not addressed as a separate effect.

The cause of failure for any type of system is typically classified into several general categories: installation errors, design mistakes, manufacturing/equipment defects, lack of maintenance, exceeding design limits, and environmental factors. There are several approaches that can be utilized to minimize the probability of failure. Such methods include (1) design redundancy, (2) active monitoring for faults, (3) providing the simplest system (i.e., the least number of components) to address the hazard, and (4) a well designed inspection, testing, and maintenance program.

These reliability engineering concepts are important when evaluating reliability estimates reported in the literature. Depending on the data used in a given analysis, the reliability estimate may relate to one or more of the concepts presented above. The literature review conducted under the scope of this effort addresses these concepts where

appropriate. Most of the information that was obtained from the literature in support of this paper were reported in terms of *unconditional operational* reliability, i.e., in terms of the probability that a fire protection strategy will not *fail dangerous*.

LITERATURE REVIEW

A literature search was conducted to gather reliability data of all types for fire safety systems relevant to the protection strategies considered: automatic suppression, automatic detection, and compartmentation. The objective of the literature search was to obtain system-specific reliability estimates for the performance of each type of fire safety system as a function of generic occupancy type (e.g., residential, commercial, and institutional).

Sources of information included national fire incident database reports, US Department of Defense safety records, industry and occupancy specific studies, insurance industry historical records and inspection reports documented in the open literature, and experimental data. Reports on experimental work and fire testing results were utilized only when fire detection, automatic suppression, or compartmentation strategies were explicitly evaluated. Tests of systems used for qualification, approval, or listing were also reviewed for information on failure modes. Published data from the United Kingdom, Japan, Australia, and New Zealand were included.

General Studies

Several broad based studies were identified that reported reliability estimates for fire detection and fire suppression systems as well as construction compartmentation. These included (1) the Warrington Fire Research study [1996] in the United Kingdom, (2) the Australian Fire Engineering Guidelines [Fire Code Reform Center, 1996], (3) a compilation of fire statistics for Tokyo, Japan [Tokyo Fire Department, 1997], and (4) results from a study of in situ performance of fire protection systems in Japan [Watanabe, 1979].

The Warrington Fire Research study addressed the reliability of fire safety systems and the interaction of their components. A Delphi methodology was used to develop discrete estimates of the reliability of detection and alarm systems, fire suppression systems, automatic smoke control systems, and passive fire protection (e.g., compartmentation).

The Australian Fire Engineering Guidelines were developed as the engineering code of practice supporting the new performance-based Building Code of Australia. Following the methods in this guide, building fire safety performance is evaluated for smouldering, flaming non-flashover, and flaming flashover fires. The performance (i.e., probability of detecting, extinguishing or controlling a fire event) of fire safety systems is predicted, accounting explicitly for the operational reliability of the particular system. Reliability estimates from an expert panel rather than from actual data are provided in the Guideline for this purpose.

Finally, operational reliability data were reported in two separate studies in Japan. One study involved evaluation of fire incident reports from the city of Tokyo during the period from 1990 to 1997 [Tokyo Fire Department 1997]. The other study involved review of fire incident reports throughout Japan during an earlier time period ending in 1978 [Watanabe 1979].

Table 1 provides a summary of the reliability estimates provided in these studies. Significant differences exist in the individual reliability estimates depending on the parameters used to develop these estimates. Depending on the required accuracy in predicting future operational performance of fire protection systems, dependence on the range of estimates from these studies could significantly alter the results. In addition, the uncertainty associated with a single estimate of reliability or the existence of potentially important biases in the methods used to derive these estimates may limit their direct usefulness in addressing either operational or performance reliability of fire protection systems.

Table 1. Published Estimates for Fire Protection Systems Operational Reliability (Probability of Success (%))

Protection System	Warrington Delphi UK (Delphi Group)		Fire Eng Guidelines Australia (Expert Survey)		Japanese Studies (Incident Data)	
	Smoldering	Flaming	Smoldering	Flaming/ Flash Over	Tokyo FD	Watanabe
heat detector	0	89	0	90 / 95	94	89
home smoke alarm	76	79	65	75 / 74	NA	NA
system smoke detector	86	90	70	80 / 85	94	89
beam smoke detectors	86	88	70	80 / 85	94	89
aspirated smoke det.	86	NA	90	95 / 95	NA	NA
sprinklers operate	95		50	95 / 99	97	NA
sprinklers control but do not extinguish	64		NA		NA	NA
sprinklers extinguish	48		NA		96	NA
masonry construction	81 29% probability an opening will be fixed open		95 if no opening 90 if opening with auto closer		NA	NA
gypsum partitions	69 29% probability an opening will be fixed open		95 if no opening 90 if opening with auto closer		NA	NA

NA= Not Addressed

Review of Available Reliability Data

Due to the limited applicability of the reliability estimates published in the general literature, the literature review was extended in an effort to (1) develop an improved understanding of the elements of each of the three strategies under consideration that influence reliability, and (2) identify and evaluate quantitative data regarding individual system operability and failure rates.

Automatic Suppression Systems (i.e., sprinkler systems)

Table 2 provides a summary of reported operational reliability estimates from several studies that evaluated actual fire incidents in which automatic sprinklers were present. As a group, these studies vary significantly in terms of the reporting time periods, the types of occupancies, and the level of detail regarding the types of fires and the sprinkler system design.

The estimates presented in Table 2 generally indicate relatively high operational reliability for automatic sprinkler systems. While some of the references include fire "control" or "extinguishment" as part of the reliability assessment, the reported data were not consistent. Therefore, operational reliability was assumed to be limited to sprinkler operation. The estimates also indicate a range of values, suggesting that it would be inappropriate to assign a single value for sprinkler system reliability without attention to biases in the data sources and general uncertainty associated with combining data from different databases.

Table 2. Reported Automatic Sprinkler Reliability Data (percent)

Occupancy	Reference	Reliability Value
Commercial	Milne [1959]	96.6/97.6/89.2
	Automatic Sprinkler [1970]	90.8-98.2
	Miller [1974]	86
	DOE [1982]	98.9
	Maybee [1988]	99.5
	Kook [1990]	87.6
	Taylor [1990]	81.3
	Sprinkler Focus [1993]	98.4-95.8
	Linder [1993]	96
General	Building Research Est. [1973]	92.1
	Miller [1974]	95.8
	Miller [1974]	94.8
	Powers [1979]	96.2
	Richardson [1985]	96
	Finucane et al. [1987]	96.9-97.9
	Marryat [1988]	99.5
Residential	Milne [1959]	96.6
Institutional	Milne [1959]	96.6

The "raw" estimates in Table 2 range from a reliability estimate of 81.13 percent [Taylor] to 99.5 percent [Maybee, Marryat]. The relatively low value of 81 percent associated with Taylor's study as well as the somewhat higher estimate reported by Kook (87.6%) appear to reflect significant biases in the databases used in these studies. In both studies, the number of fire incidents was relatively small, and the database did not differentiate between automatic sprinklers and other types of fire suppression systems. The high end estimates of 99.5 percent reported by Maybee and Marryat reflect sprinkler system performance in occupancies where inspection, testing, and maintenance activities were rigorous and well documented.

Another important limitation in the available sprinkler reliability data is that most of the sprinkler systems involved in the documented incidents included standard spray sprinklers. Limited incident data existed in these references regarding quick response or residential sprinkler technology. Of particular concern in attempting to estimate the reliability of residential sprinkler systems are several factors, including (1) permitted coverage limits, (2) lower water supplies, and (3) the potential for no remote alarm or notification in the event of a fire. These, as well as other factors associated with this technology (e.g., level of maintenance) could directly affect the operational reliability of these types of sprinkler systems. Additional field data are necessary for any attempt to address these issues, but based on this latter observation that residential systems in general are less likely to be maintained properly, some decrease in expected operational reliability for residential sprinkler systems may be warranted.

Fire Detection/Alarm Systems

Table 3 shows a summary of operational reliability estimates for selected occupancy groups. The estimates, including the mean reliability and 95 percent confidence limits, were calculated based on data provided by Hall [1995]. The mean reliability estimates range from approximately 68 to 88 percent. These values correspond roughly with the reliability figures presented in the Warrington Delphi study. However, the general range associated with the 95 percent confidence limits is 66 to 90 percent.

Table 3. Reliability Estimates for Smoke Detectors [Hall, 1995]

Occupancy	Property Use	Mean Reliability (%) n = 10	95% Upper Confidence Interval	95% Lower Confidence Interval
Residential	Apartments	69.3	69.9	68.7
	Hotels/Motels	77.8	79.3	76.4
	Dormitories	86.3	88.4	84.3
Commercial	Public Assembly	67.9	69.8	65.9
	Stores & Offices	71.7	73.5	69.9
	Storage	68.2	70.0	66.3
	Industry & Manufacturing	80.2	81.3	79.1
Institutional	Care of Aged	84.9	86.6	83.3
	Care of Young	84.0	86.3	81.6
	Educational	76.9	79.6	74.1
	Hospitals & Clinics	83.3	85.4	81.2
	Prisons & Jails	84.2	85.9	82.5
	Care of Mentally Handicapped	87.5	90.3	84.8

Compartmentation

Compartmentation relies on the functioning of various types of devices such as doors (including hold open devices), walls, floor/ceilings, penetration seals, glazings, fire dampers, smoke dampers, and construction units. While compartmentation is considered a key fire protection strategy, very little data were found in the literature regarding the performance of the individual elements that influence compartmentation. Discrete estimates for construction and partition operational reliability were provided in the Warrington study and the Australian guidelines, but these estimates were based solely on expert judgement. Therefore, no further analysis is provided.

STATISTICAL INDICATIONS AND UNCERTAINTY ESTIMATES

The literature search summarized in the previous section provided general information and data representing estimates for both automatic sprinkler system and smoke detector reliability. The automatic sprinkler system reliability data came from several sources. The smoke detector reliability estimates came from a single reference, Hall [1994], which contained reliability estimates for a ten-year period (1983-1992) and presented the most comprehensive reliability study found in the literature. One of the initial goals of this paper was to provide an overview of operational reliability estimates for the systems studied. For automatic sprinklers and smoke detectors, this was done by performing a statistical analysis on the available data.

Automatic Sprinkler System Analysis

The reliability estimates presented in Table 2 for automatic sprinkler systems were analyzed for each occupancy type. It should be noted that only one source [Milne, 1959] provided reliability estimates for institutional and residential occupancies, and this early data provided no information regarding the reliability of modern day residential sprinkler technology. Histograms illustrating the distributions for each occupancy's reliability estimates are presented in Figure 1. The mean values and the 95 percent confidence limits were calculated for the general (a category reported in some studies that did not distinguish among commercial, residential, and institutional occupancies) and commercial occupancies, and for the combination (commercial, institutional, residential and general occupancies) of reliability estimates. These results are presented in Table 4.

Table 4. Reliability Estimates for Sprinkler Systems

Residential	Institutional	Commercial	General	Combined
n = 1 96.6	n = 1 96.6	n = 9 88.1 < 93.1 < 98.1	n = 7 93.9 < 96.0 < 98.1	n = 18 92.2 < 94.6 <97.1

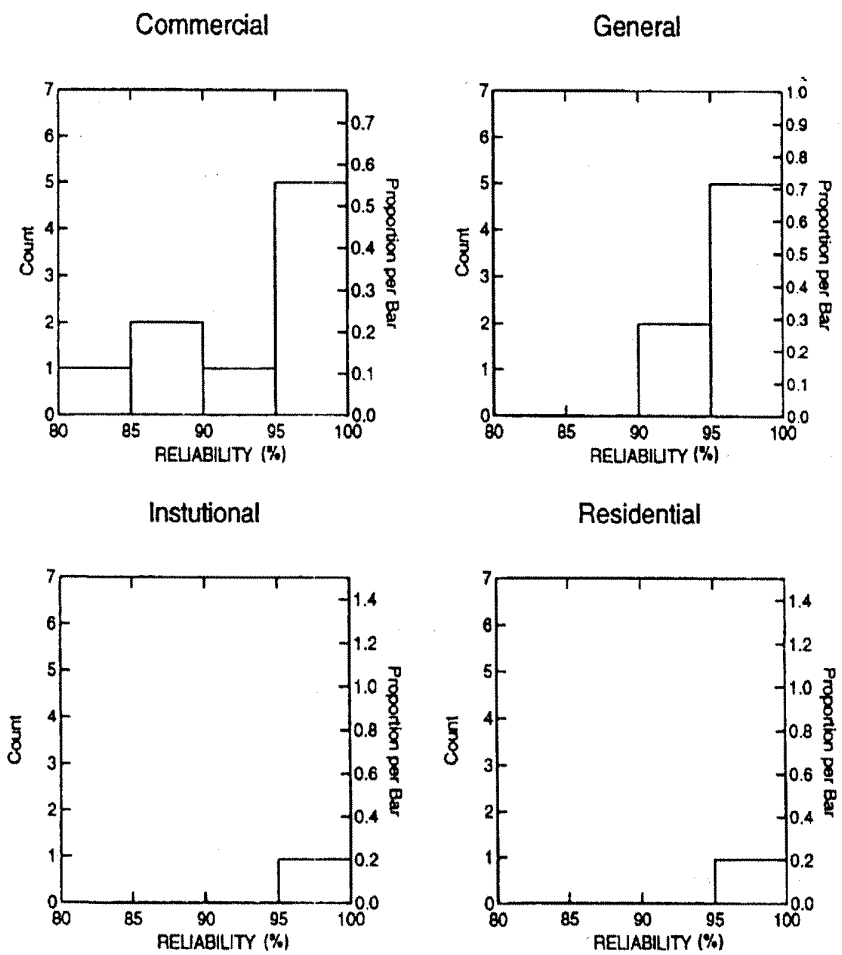

Figure 1. Automatic Sprinkler Reliability Estimates by Occupancy

The mean operational reliability estimates for commercial and institutional occupancies are contained within the 95 percent confidence intervals of the other reported occupancies. The single point estimates for residential and institutional occupancies added somewhat to the usefulness of the combined operational reliability estimates by increasing the size of the overall database, using 18 estimates for the four individual categories. However, the individual point values for residential and institutional occupancies should not be used alone to draw any conclusions.

The reliability estimates for commercial, general, and the combined occupancies provide some useful information. Based on the data available for this analysis sprinkler systems were estimated to have an operational reliability above ~88 percent, and if commercial occupancies are not being considered, sprinkler system reliability can be assumed to be above ~92 percent. However, it is important to determine if the particular sprinkler system being compared to these estimates is similar to the referenced systems. The range for "commercial" buildings was estimated at 88 to 98 percent, and for "general," the range was 94 to 98 percent.

Smoke Detector Analysis

The data located for smoke detector reliability estimates was comprehensive. The data set spanned ten years and reported reliability estimates (as reflected in Table 3) for each year. This was done for several property uses. The analysis presented here examined the property use descriptions and divided them into occupancy classifications. The data from each property use were then used to calculate reliability estimates for each occupancy type. Figure 2 illustrates the distribution for all of the smoke detector reliability estimates across all occupancies.

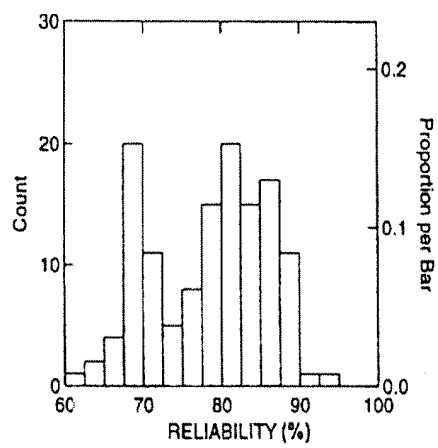

Figure 2. Smoke Detector Reliability Estimate Distribution for All Occupancies

As shown in the histogram, the data have a bi-modal distribution. Therefore, to further investigate the possibility of two distinct mean values in this data set, an analysis of variance (ANOVA) was performed. The ANOVA examined the mean reliability estimate and the influence on that estimate by a given occupancy's contribution. A graphical representation of the ANOVA in the form of a least squares means plot is presented in Figure 3.

The ANOVA results concluded, as Figure 3 illustrates, that the three occupancy classifications each have different mean reliability estimates for smoke detectors. Figure 4 contains histograms describing the reliability estimate distributions for each occupancy classification.

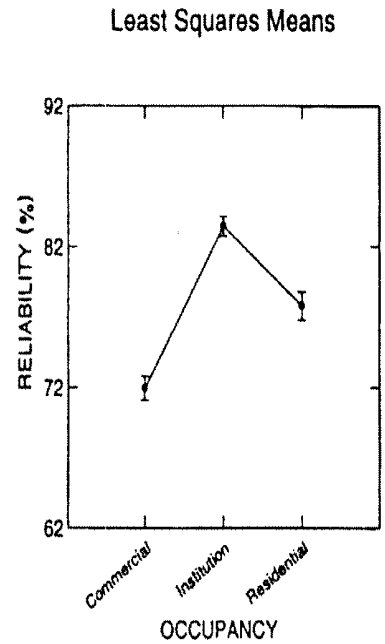

Figure 3. ANOVA Results for Smoke Detector Reliability Estimates by Occupancy

These individual occupancy distributions were analyzed separately for mean reliability estimates and 95 percent confidence intervals. The results are presented in Table 5. The results for each occupancy were significantly different. The confidence intervals between occupancy classification did not overlap as with the automatic sprinkler system reliability estimates. This could be due to the more extensive data set used in the smoke detector analysis. The estimates presented in Table 5 indicate a distinct difference in reliability for smoke detectors depending on the occupancy classifications. Determining the non-data related reasons for the difference is beyond the scope of this analysis.

Table 5. Reliability Estimates for Smoke Detectors

Residential	Institutional	Commercial
n = 30 75.1 < 77.8 < 80.6	n = 60 82.3 < 83.5 < 84.6	n = 41 70.2 < 72.0 < 73.7

The data used in this analysis were viewed as representative of the systems described in the studies and, currently, the best data available in the open literature on sprinkler system and smoke detector reliability. The representativeness of the data is an important consideration in determining the type of information that can be attained from a statistical analysis of this type. The results of the analysis should be used for making inferences only after examining the referenced studies and determining their applicability to the particular safety strategy employing the analyzed systems. However, the approach as outlined represents a significant advancement in addressing the reliability of different fire protection strategies, including attention to uncertainty and bias in reported data.

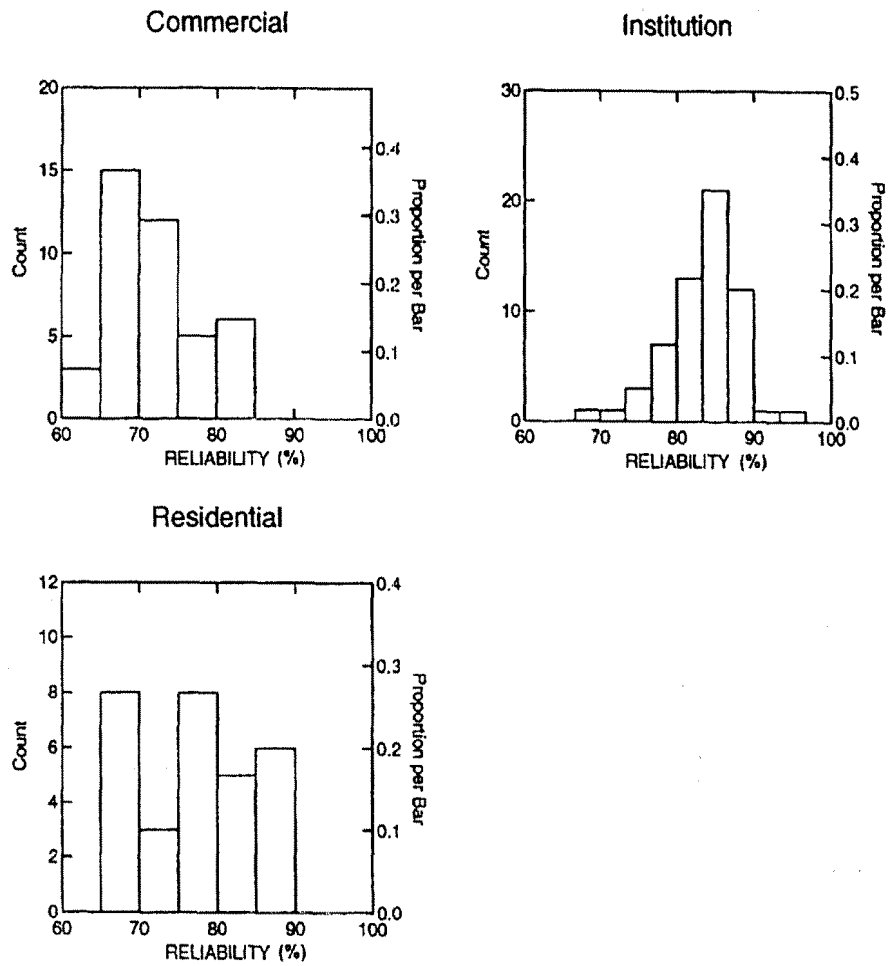

Figure 4. Reliability Estimate Distributions for Smoke Detectors by Occupancy

SUMMARY AND CONCLUSIONS

A detailed literature review and analysis of available operational reliability data were conducted to provide insight regarding the operational reliability of several fire protection strategies, including fire detection, automatic sprinklers, and compartmentation. For this study, operational reliability was defined as the estimate of the probability that a fire safety system will operate on demand. Several recent studies provide such reliability estimates, based primarily on expert judgement. These published values do not directly account for uncertainty or biases in the estimates. For compartmentation, the reliability estimates summarized in Table 1 were the only information found.

In an attempt to address uncertainty in the estimates, several relevant detailed studies of fire incidents and operational performance of smoke detectors and automatic sprinklers were reviewed, and the reported data were extracted for a more structured evaluation. Relevant data for compartmentation were not found. This evaluation included the use of conventional statistical methods to evaluate the available reliability data and provide estimates of mean operational reliability as well as the range of operational reliability values associated with 95 percent confidence limits. Tables 4 and 5 summarize the results of this analysis.

The results indicate that the use of a single value for estimating operational reliability of a fire protection strategy is not appropriate. For example, in Table 4, the operational reliability estimates for sprinkler systems in commercial occupancies range from 88 to 98 percent, with a mean estimate of 93 percent. The populations were too small (single values) to calculate mean values and confidence limits for residential or institutional occupancies, but the combined occupancy group had a calculated mean reliability estimate of 95 percent, with 95 percent confidence limits of 92 to 97 percent. The use of the mean value for reliability, based on the knowledge that the value represents the mean of a range with 95 percent confidence limits, is significantly more justified than the use of an arbitrarily derived value. In addition, the use of the entire confidence interval and not just the most probable mean value when comparing systems is significantly more informative since all similar system reliability estimates are included in the comparison. This is a generally accepted statistical approach when comparing one system to many others.

The values for smoke detector operational reliability in Table 5 have a much tighter range associated with 95 percent confidence limits. This may be the direct result of the size and quality of the database as well as the consistency in the initial interpretation of the results by Hall [1995]. Based on the results presented in Table 5, the mean value for operational reliability of smoke detectors was 72.0 percent (lower bound 70.2%, upper bound 73.7%) for commercial, 77.8 percent (lower bound 75.1%, upper bound 80.6%) for residential, and 83.5 percent (lower bound 82.3%, upper bound 84.6%) for institutional occupancies.

The ANOVA results for smoke detector reliability further indicate that the reliability estimates are occupancy type dependent (see Figure 3) for the data analyzed. The highest reliability for smoke detector systems was associated with institutional occupancies. This effect may be the direct result of more demanding maintenance and routine system certification requirements for many of the institutional type occupancies.

The methods presented in this analysis can be readily applied to evaluation of the operational reliability of other fire protection strategies. However, it should be noted that the quality of the data in the literature is an important consideration. Considerable variation in the form and detail of the data was observed in the reports and studies reviewed as part of this effort. This study provides a very broad, preliminary attempt to describe fire safety systems operational reliability. Broad data gathering protocols are needed to improve the databases. Such an effort with a focus on obtaining more specific input data for a broader population of systems could provide the basis for significant improvements in estimates of operational reliability for fire protection strategies of interest to design engineers and authorities. This technical information is also necessary for engineering based analyses associated with rapidly progressing performance based design concepts.

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APPENDIX D

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Fire Modeling: An Introduction for Attorneys

by:
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Introduction

Fire modeling is something which is often found tobe mysterious by attorneys.Yet, understanding what it is, what it can do, and what it cannot do can be vital to successful development of some types of fire cases. The purpose of this note is to present the basic ideas so that they are understandable by the non-scientist. Thus, the information should be of value also to fire investigators, claims adjusters, and other individuals involved with fire losses. Most of them are not aware of either the strengths or the limitations of the fire modeling. Thus, in this note the objective is to explain the process in simple terms, so that a clear picture will emerge how fire modeling can and cannot be used.

What is a model?

Before we can discuss fire models, we must explain what a scientist means by 'model.' The meaning of this crucial term is essential to understand. A model of anything is, simply, a systematic representation of that thing. Thus, for example, we can have

- thought models (or conceptual models)
- scale models, and
- mathematical models.

The above three examples are probably the main 'representation' which are used by scientists. A thought model is simply a proposed schema explaining how something works. Scale models are often used in structural engineering, fluid dynamics, and have occasionally been used in fire science. Model trains are familiar to all. A scale model in scientific work is simply a reduced-size object on which certain measurements will be made. The category which we want to discuss in this Note is the last type, the mathematical model. In general, a mathematical model will be a series of equations which describe a certain process. If the equations are simple enough, they can be solved on the hand calculator. More commonly, the equations are not so simple. Consequently, a computer is required for their solution. Thus, in the fire field, we would speak of "computer fire models." Nowadays, when one speaks of a "fire model," it is usually understood that one is referring to a "computer fire model." This is unnecessarily restrictive, however, and other types of models (such as scale models) remain legitimate scientific forms of model.

A "computer fire model" is normally realized as a *computer program*. This again, is most common, but not necessarily always true. A computer fire model, for example, could be realized as only a flowchart. From the above, one can understand why fire modeling is often taken to mean "use of computer programs for predicting fire," although this would be too restrictive a definition.

What do fire models do?

By now, fire modeling has been in use for more than two decades. This author's computer program COMPF was released in 1975 [1] and was the first computer program for predicting room fires to be developed in the U.S. Research in several other countries, however, goes back further. During the subsequent two decades, tremendous progress was made in the field. Today, many persons who have only a limited knowledge of fire science have already had a slight exposure to fire modeling. From this, they are apt to conclude that fire modeling is something which allows scientists/engineers to 'wave a magic wand' and to calculate the history of a fire just by working at their computer. On rare occasions, this can be true. But normally, the situation is not so straightforward.

The function of COMPF was to predict the fire history within a single room. The history was represented only after the time of 'flashover' within the room. *Flashover* is the point in a fire (it does not occur in all fires) when the room "fills with flames." The hazard greatly increases from that point on. Nowadays, various other types of computer fire models are also available to the scientist. What kind of fire characteristics, then, can a fire model predict? The list is limited only by the ingenuity of scientists, but we can cite characteristics which are already routinely being computed:

- gas and surface temperatures
- flow rates of gas through openings
- heat fluxes impinging on surfaces
- smoke obscuration
- production of certain toxic gas species
- strength reduction and structural failure of building elements
- activation times for sprinklers and detectors

It can be noted that this list is weighted towards fluid mechanics and related themes. This is not surprising, since a majority of the researchers creating fire models have been fluid mechanics specialists. Models also exist for certain human behavior aspects (e.g., exiting through corridors and stairs) although these have so far been very little used for practical problem solving; thus their validity is generally unknown.

It should be noted that certain characteristics are usually not being computed. These include:

- the ignitability of objects from small flames
- the spread of fire over surfaces
- the actual 'size' of the fire, that is, its heat release rate

A list of other fire characteristics that we cannot yet routinely predict has recently been publicized [2]. The three characteristics above are three exceedingly important aspects of fire, indeed heat release rate (HRR) has been referred to as the single most important variable in describing fire hazard [3]. Likewise, there will not be a fire without ignition and, in most cases, flame spread is also an essential trait of fire. The way that today's fire models normally solve a problem is by being given the HRR as input. The flame spread aspects are usually not made explicit. The most important role of flame spread is to progressively involve greater areas in burning, that is, to cause a growth of HRR. Thus, if we have a HRR versus time curve, the flame spread issue has already been solved. The initial ignition is, simply, assumed to have taken place, so no computation is made there either.

To make a computation using one of our state-of-the-art models, such as HAZARD [4], then requires that the modeler supply a HRR curve as input. In some cases, the HRR curve may already have been published in the literature for a 'similar' burning object. Compendia of data are available which present some useful, non-proprietary data [5]. However, the variety of items which can burn is essentially infinite, while the amount of publicly available data is quite tiny.

The situation is even more complicated when one realizes that more than one item can burn. Methods have been suggested for estimating second-item involvement [6]. However, under most conditions, such procedures entail a great deal of uncertainty. This can be due to: (a) irregular geometry of the item in question; (b) not well enough studied ignition response of the item; (c) inadequately detailed knowledge of local heat fluxes, etc. When one contemplates the uncertainties then associated with estimating the ignition for the third, fourth, etc. item, it becomes clear that the ignition sequence of a roomful of diverse items cannot be predicted with a reasonable degree of confidence.

Fire testing

The solution to the above difficulty is actually straightforward: when data are not available, run a fire test. Model development is a difficult, specialist task. Thus, one cannot expect to say "improve the models," since progress could hardly be made on a time schedule to suit fire litigation needs, even if the resources were available. What is possible to do on relatively short notice is to organize fire tests.

Fire tests have their limitations, too. The largest fire that can be conducted indoors in a laboratory, under controlled and instrumented conditions is about 20 megawatts. Physically, this corresponds to one room or a couple of smallish rooms joined together. Fire models are much less restricted in that respect. They are available for computing multi-story, multi-room arrangements, and the rooms do not have to be small enough to fit under a laboratory's exhaust hood.

Thus, the practical solution is to combine fire modeling with fire testing.

Normally, the objects, walls, etc. associated with ignition and early fire growth are directly reconstructed in the laboratory by procuring

exemplars and creating what is normally termed a *sectional full-scale mockup*. Full-scale denotes that real appliances are used, real wall thicknesses are employed, etc. Sectional denotes that only a slice out of the building is constructed in the laboratory and not the whole fire environment.

The presumed or alleged ignition sequence is then started in the laboratory test and measurements are taken of HRR, smoke production, temperatures, heat fluxes, and other fire variables. Fire modeling is then used to take the laboratory data of the initial fire stages as an input and to compute the subsequent stages of fire development. Thus, fire modeling can be viewed as a direct extension of fire testing, or vice versa.

The confidence in the results produced by the fire model is normally greater for the intermediate stages of the fire than for the late stages. During the late stages of fire, a number of additional events can happen. These include burn-through of partitions, collapse of beams, collapse of occupant goods (e.g., rack storage) and similar. Also, it may be expected that firefighting will make some difference on the outcome of the fire, and this may not be reasonable to try to predict mathematically. Models do exist which can allow the prediction of the collapse of structural members, but these require input data which may often be unavailable.

Tests vs. demonstrations

It is important to distinguish between a field demonstration and a large-scale laboratory test. Both involve setting up of an environment intended to recreate the scene of the fire origin. Both can be used to produce videos for jury viewing. However, a field demonstration does not collect HRR nor other fire data which could usefully serve as input to a fire model. Thus, demonstrations can **only** be used for video purposes.

The advantage of a demonstration is that it can be conducted in every town and city. A laboratory test, by contrast, requires use of a fire testing laboratory, and there are only a handful of such facilities in the country.

The **costs**, however, are not necessarily much lower for a demonstration. The bulk of the cost is normally associated with procuring exemplars, constructing the mockup, setting up video and other documentation, and witnessing of the test. Since a fire test laboratory already has the HRR and other instrumentation necessary, the marginal cost is small for setting up the instrumentation and collecting the necessary data. The actual laboratory test procedures [7] are, by now, quite well worked out, and time does not need to be allocated to research in this area.

Conclusions

Fire modeling can normally be considered as the prediction of fire characteristics by the use of a mathematical method which is expressed as a computer program.

The needs of fire litigation from fire modeling are specialized. Usually,

there is a great deal of specificity about the sequence of fire ignition and the materials involved in the process. This commonly precludes the use of handbook data as input to fire models. Instead, it will usually be necessary to conduct a sectional full-scale mockup to obtain appropriate data describing the initial part of the fire. This information then serves as input to a fire model, using which the later fire development can be approximately predicted.

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APPENDIX E

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The Future of Fire Simulation

By Kevin McGrattan, Ph.D., Howard Baum, Ph.D., Ron Rehm, Ph.D., Glenn Forney, Ph.D., and Kuldeep Prasad, Ph.D.

INTRODUCTION

Scientists and engineers are often asked to make predictions of the state of technology in the future and are usually laughably wrong. The best prognosticators get the trends right, but cannot possibly fill in the details. Think of Jules Verne predicting a trip to the moon, albeit in a projectile decked out in lavish red velvet, manned by champagne-sipping adventurers, and shot out of a giant cannon. Unlike Jules Verne, we dare only look 10 years into the future, rather than 100. Also, we focus on the work going on in the Building and Fire Research Lab at NIST because, even though most agree that modeling will play an increasing role in fire research, the nature of the models is a subject of intense debate. We do not presume to speak for the entire community, and we welcome the opinions of other researchers as to the direction of modeling in the future.

In the Spring 2000 issue of *Fire Protection Engineering*,[1] Howard Baum wrote a brief history of fire simulation in which he listed three major challenges facing fire modelers:

First, there are an enormous number of possible fire scenarios to consider. Second, we do not have either the physical insight or the computing power (even if we had the insight) to perform all the necessary calculations for most fire scenarios. Finally, since the "fuel" in most fires was never intended as such, the data needed to characterize both the fuel and the fire environment may not be available.

Ten years from now, these issues will remain. Certainly the wide range of fire scenarios will persist, even widening due to the constant emergence of new materials and new architectural forms. Computing power will certainly increase, but not to the point of allowing for direct numerical solutions of the governing equations. As models focus in on the small-scale combustion processes in a fire, ever-more complex challenges will emerge that are, for now, neglected. Fortunately, there is hope. The reason is that models based on fundamental principles will improve automatically as computers get faster and the temporal and spatial resolution improves. In looking towards the future, we need to adopt fundamentally sound physical mechanisms that will retain an elegance and simplicity over time, that will shift us from empirical to deterministic descriptions of fire behavior, and that will be useful to fire protection engineers and researchers alike.

BLOWING SMOKE

Even as we develop more sophisticated numerical algorithms to describe the growth and suppression of fires, the majority of design calculations will continue to address a subject for which zone and field fire models were first developed – smoke movement. Because smoke inhalation and carbon monoxide poisoning are and will remain the most dangerous actors in a fire, code officials will continue to enforce regulations designed to ensure safe evacuation of a building. Originally, two-zone fire models were developed to predict the descent of the smoke layer in a fairly simple building, but as building geometries become more complex, fire protection engineers are turning to field models to track the smoke in open-plan, multilevel buildings.

Ten years from now, engineers will still be interested in smoke movement from fires whose size and growth rate will be predefined. Current field models can handle these problems in theory, but computation times are often too long or the grid resolution is too coarse to capture important features of the flow. The solution to this problem is faster computers, better allocation of grid cells and parallelization, all of which

at NIST

are subjects of active research by computer scientists because the application of these ideas goes way beyond fire.

What we can do now is adopt models that improve automatically as numerical grids become more refined. The best example of this idea is Large Eddy Simulation (LES). We have found over roughly twenty years that good simulations result from solving the Navier-Stokes equations with as few empirical parameters as possible on grids with as many cells as possible. While we always want more, we have found that very good results are obtainable with modest calculations, allowing engineers running our models to investigate a wide variety of problems without having to worry about numerical parameters for which they have little training.

It is our belief that the LES concept will emerge as the prevailing methodology for smoke and heat transport because of its ability to render realistic, time-resolved animations of the flow of gases throughout a building. It is inevitable that as computers get faster, users of CFD models will demand more lifelike simulations rather than time-averaged or steady-state images. This is particularly true of the fire community since the audience for many of the simulations are the authorities having jurisdiction who often have little training in fire modeling. The design engineer must demonstrate to the official what is being calculated with something more than static images or time-temperature plots. Animations of smoke flow provide a visual check of the building geometry, grid resolution, and other features of the calculation that are difficult to convey any other way.

WHAT ABOUT THE FIRE?

Skeptics of fire models have complained from the outset that the fire is not really modeled in a fire model. To a large extent, this criticism is valid, and here are two reasons why. First, most engineers are usually interested in smoke movement, so there's no reason to model the fire other than as a point source of smoke and heat. Second, the combustion processes occur at length and time scales below the resolution limits of most practical calculations, so much so that information obtained from the resolvable scale, like an average cell temperature, is useless in even the most simplistic of combustion models.

Much of the future research in *fire* modeling will focus on improvements in the way small "subgrid-scale" physical processes are modeled. Examples of such processes include (but are not limited to) soot formation and growth, combustion in vitiated atmospheres, heat transfer to pyrolyzing surfaces, and radiation from gaseous combustion products. All of these phenomena occur in both laboratory-scale experiments and material test apparatus. These processes will serve as the start-

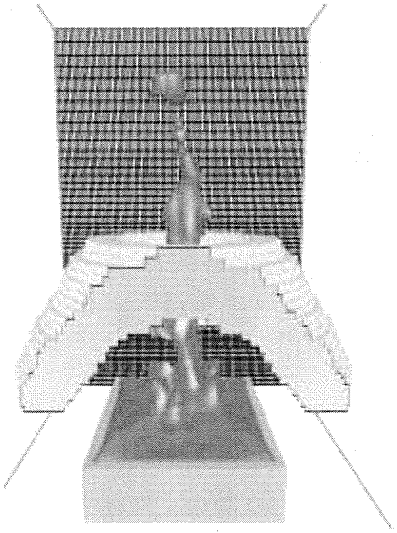

FIGURE 1. Simulation of a sample of wood burning in the cone calorimeter performed with FDS. Courtesy Simo Hostikka, VTT Building and Transport, Finland.

ing point for developing better fire submodels because they are well-controlled, relatively simple, and, most importantly, small. Because they are small, the calculations can be performed at sufficiently high resolution to capture the important phenomena directly, and then the same calculations can be performed at lower resolution to see how well the new algorithms perform on larger-scale simulations. The objective of this effort is not to produce the most detailed description of the phenomena. Very detailed submodels of most fire phenomena exist now; the challenge is to design an overall fire model that balances the accuracy of each submodel. Balance means that the level of detail incorporated into each is roughly the same. Everyone learns in high school that adding a measurement accurate to the nearest millimeter and one accurate to the nearest centimeter yields a result that is only accurate to the nearest centimeter. Similarly, a fire model will only be as accurate as the least accurate of its components.

A good starting point for a better fire model is a well-controlled test apparatus, like the cone calorimeter (Figure 1). A set of solid and gas phase models should be developed that would hopefully provide a reasonable, balanced description of the interaction of the fire with the test apparatus. In essence, this is the procedure that was followed in the development of the Fire Dynamics Simulator (FDS), a general-purpose fire field model released into the public domain in the year 2000. The approach had been to model the large-scale gas phase transport as faithfully as possible for a given numerical grid, and then introduce extra features that were consistent with the detail (or lack thereof) afforded by the smoke transport algorithm. In some sense, the fire itself was just another one of these extra features. At first, the fire was a Gaussian-distributed blob of heat superimposed on the numerical grid, then the fire was a set of hot particles ejected from the burning object, and for the time being the fire is a surface on which fuel and oxygen meet and react infinitely fast. The emerging fire model may move beyond this, but at the moment it should be possible to work with this description of the combustion while the solid phase mechanisms are brought up to par.

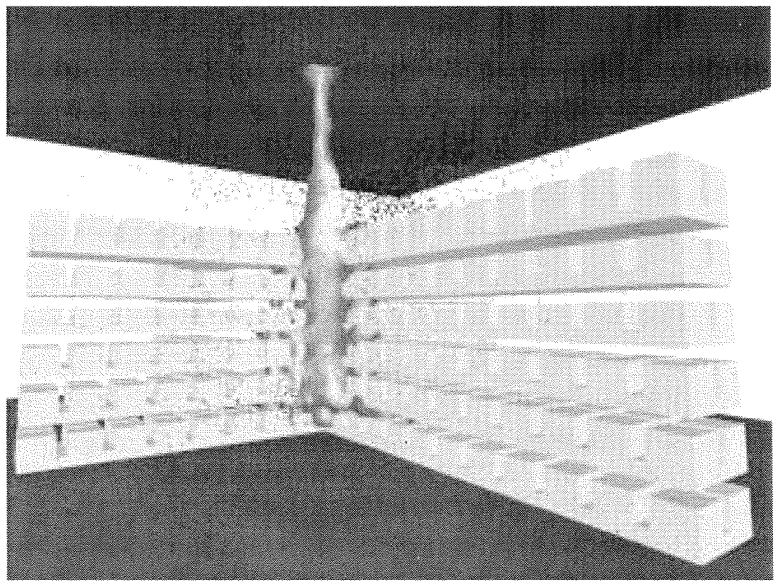

FIGURE 2. Simulation of a rack storage commodity fire. The simulation predicts the growth and suppression of a fire that originates at the floor. These types of simulations are by far the most challenging attempted to date, and it remains to be seen how much the relatively simple solid phase pyrolysis and suppression algorithms can be improved.

There are two advantages to this evolutionary strategy. First, the various submodels, even in their primitive states, have been useful to FPEs for smoke movement and simple heat transfer calculations, and to introduce the next generation to the technology. Second, all aspects of the simulation improve at the same pace – sprinklers, radiation, burning objects – so that no part of the calculation looks out of place. A good analogy is classical sculpture. The artist transforms a block of marble into a human form by painstakingly chipping away stone first to reveal the gross outlines of the head, arms, torso, etc., and only then focuses in on finer details. Consider that the most beautifully sculpted hand would look ridiculous if one arm were longer than the other.

INDUSTRIAL-STRENGTH FIRES

A few years ago, in parallel with large-scale tests, the development of FDS turned towards the problem of fire suppression in large warehouses and warehouse retail stores[2] (Figure 2). As simplistic as the combustion and heat transfer algorithms were at the time, they were not nearly as primitive as the sprinkler spray and suppression models. With the exception of the thermal activation equation, which by that time had become widely adopted, the water droplets emerging from the pipe, landing on the commodity, and eventually interacting with the fire were by far the greatest source of uncertainty in the simulation.

A series of bench-scale experiments was conducted at NIST to develop necessary input data for the model. These experiments generated data describing the burning rate and flame spread behavior of the cartoned plastic commodity, thermal response parameters and spray pattern of the sprinkler, and the effect of the water spray on the commodity selected for the tests. The missing link in the analysis was the spray characterization of the sprinkler itself; that is, the water was assumed to leave the sprinkler in a simple umbrella pattern quantified only by visual observation. What made the model work reasonably well was the fact that the spray parameters were tweaked until a match between computed and observed water density patterns on the floor was obtained. Hundreds of hours were needed to roughly characterize one fuel and one sprinkler because the characterization

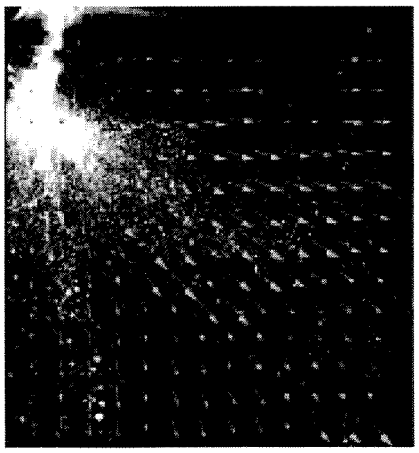

FIGURE 3. Image of a sprinkler spray created with Particle Image Velocimetry (PIV). The green arrows represent the velocity vectors of water droplets leaving the sprinkler orifice. The technique involves taking two photographs of the spray in rapid succession and backing out the velocity from the displacement of the droplets. Courtesy Dave Sheppard, Northwestern University and Underwriters Laboratories.

was almost all empirical – little of it was based on fundamental physical models because the phenomena was so very complex. As a result, users of the FDS model were not able to apply it easily to other commodities and sprinklers; a problem that persists to this day.

Sprinkler spray characterization will remain largely empirically based because each sprinkler has its own unique design that makes predicting which way the water will go difficult. To simulate the sprinkler spray, we need to know the initial distribution of the droplet size and velocity. Measuring these quantities has proven to be very difficult and still very expensive. The most promising technique for measuring droplet size is through Phase Doppler Interferometry (PDI) and droplet velocity through Particle Image Velocimetry (PIV) (see Figure 3). Both are nonintrusive, laser-based techniques that require very expensive equipment and skilled technicians with a high level of training in laser diagnostics. This is worrisome because calculations should be cheaper than experiments, or else what's the point? If high-level modeling of challenging industrial fire scenarios becomes more routine and starts to show potential benefits to sprinkler manufacturers and building owners, there ought to be more investment in the measurement techniques required for input data. The Catch-22 is that it's hard to show benefits with little data.

Understanding how various standard commodities burn and how they respond to water ought to be less empirically based than sprinkler sprays, assuming the necessary solid phase models are developed that retain enough of the fundamental physics to accommodate a better description of suppression, yet simple enough to be used in large-scale simulations. We discussed above the need for more fundamentally based models of pyrolysis, starting with relatively small-scale calculations of standard test apparatus and eventually moving to large-scale. It is unclear how to describe the burning of real commodities, which are mixtures of cardboard, plastics, woods, etc., other than with the simple lumped parameter models developed to date. It is hoped that at a minimum, we will have a way of relating the burning rate of the fuel to the heat feedback to the surface based on the thermophysical properties of the fuel rather than simply an exhaustive series of experiments that are often too expensive to perform given the wide variety of fuels burning in a single fire. This is possible now with a limited number of pure fuels, liquids especially, but hopefully this list can be extended in the future.

THE FIRE HAS LEFT THE BUILDING

The fire models with which we are familiar were developed to describe residential and commercial building fires. However, there is a different class of models developed by the forest management and agricultural communities designed to predict the spread of wildland and forest fires. These models are semiempirical and are built upon very different assump-

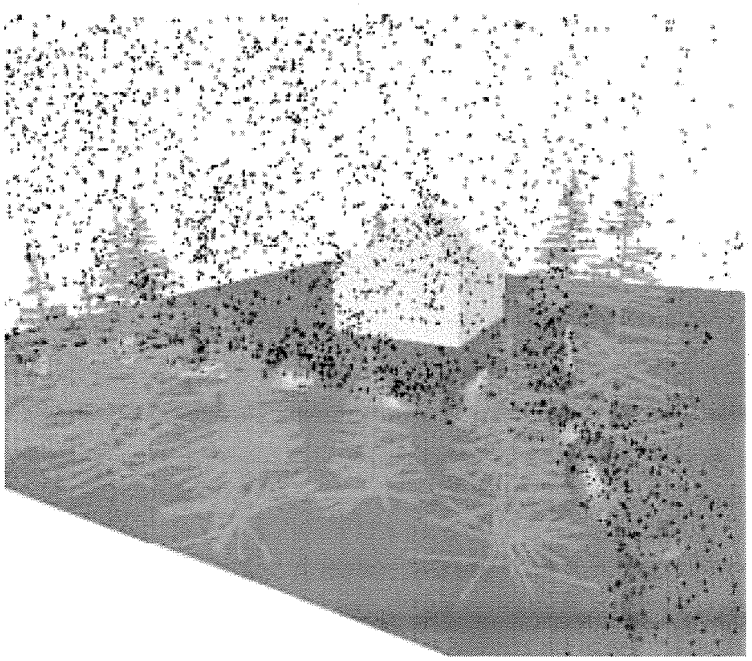

FIGURE 4. Simulation of a brush fire advancing on a house. Preliminary calculations such as these are now being performed to assess the feasibility of simulating community-scale fire spread. Here, the domain is a few hundred meters on a side, the grid cells about 1 m. The trees serve as a drag on the oncoming wind.

tions than building fire models. They are closer to zone models in philosophy since they are designed to run faster than real time so that they can be used the day of the actual fire. It would be hard to believe that field models for community-scale fire spread could be developed in ten years' time to be run in real time, but field models are being developed now, both at NIST and elsewhere, to study the behavior of large outdoor fires to aid in planning efforts.

Last year, wildland fires cost an estimated one billion dollars for just the firefighting. However, fires in the built environment are generally even more costly. The famous 1991 Oakland Hills fire in Berkeley, CA, alone did an estimated $1.5 billion in damage while killing 25 people and injuring 150 others. While large-scale models of fire propagation are useful in wildland settings, corresponding models for community-scale (rural, suburban, or urban) fire spread, i.e., fires spreading between structures and natural fuel, are still in their infancy. Development of such models suffer from the following Catch-22 – validated models of community-scale fire spread are needed because experiments on that scale are almost impossible to carry out; but without experiments, how do we validate the models?

The main numerical problem to community-scale fire prediction is grid resolution. Consider a square kilometer of terrain containing both structures and dry vegetation. Any field model tracking the progression of a brush fire through the area would require several million grid cells, which, even if cleverly distributed, would provide spatial resolution of at best a meter. Existing large-scale models of wildland fires regard the fuel (vegetation) as continuous and assume the fire to propagate as a line. Resolvable-length scales for these models are tens to hundreds of meters. The technical challenge for the community-scale fire model is to develop a mathematical description for the ignition and burning of individual trees and shrubs, and to determine fire spread between wildland elements and structures. Such a mathematical description must include fire spread by brand generation, transport, and subsequent ignitions for both wildland fuels and structures. As with any useful model, these descriptions must be validated using experimental data and must then be integrated into a CFD flow solver generalized to account for an atmospheric boundary layer flow conditioned by natural topography, upwind structures, and trees.

In addition to the numerical challenges posed by community-scale fire prediction, it is often difficult or impossible to obtain meteorological and topological information in a form that can be used in the calculation. The meteorological conditions driving the fire have to be postulated or derived from a mesoscale weather model with a minimum resolution measured in kilometers and the terrain features obtained from a database that may or may not exist at the required resolution for that particular patch of the earth. Fortunately, there are now efforts within the meteorological and geographical research communities to develop and maintain models and databases that would be useful to the fire community. For example, digital elevation data from LIDAR overflight measurements is being made increasingly available and cost-effective.

PROOF BY PRETTY PICTURE

Modelers are looked upon with skepticism by the rest of the fire community because of the perception that they all too often hide behind an eye-catching image or animation without understanding the physics underpinning the model. In fact, some have started to refer to CFD as "colorful fluid dynamics." This is often a fair assessment, but it is short-sighted. While the rapid improvement in visualization techniques has been a boon to many in the field who use field models on a regular basis, within the next 10 years what is now gee-whiz will become ho-hum. This is good because as field modeling becomes routine, the discussion will be raised beyond the superficial level we are at now to a point where the quality of a simulation will be judged by the spatial and temporal fidelity of its images and animations. With any field model, the user chooses a numerical grid on which to discretize the governing equations. The more grid cells, the better but more time-consuming the simulation. The payoff for investing in faster computers and running bigger calculations is the proportional gain in realism manifested by the images.

As the community at large becomes accustomed to looking at various pictures and animations, model developers will find new ways to dazzle. Up to now, most visualization techniques have provided useful ways of analyzing the output of a calculation, like contour and streamline plots, without much concern for realism. A rainbow-colored contour map slicing down through the middle of a room is fine for researchers, but for those who are only accustomed to looking at real smoke-filled rooms, it may not have as much meaning. Visualization in the next 10 years will turn towards providing as much information as the rainbow contour map but in a way that speaks to modelers and nonmodelers alike. Take, for example, Figure 5. Presented are two ways of visualizing the same calculation, each figure made for a different audience. The trend in scientific visualization is to combine the features of each into one to reach both groups of people.

A good example is smoke visibility. Unlike temperature or species concentration, smoke visibility is not a local quantity but rather depends on the viewpoint of the eye and the depth of field. Advanced simulators and games create the illusion of smoke or fog in ways that are not unlike the techniques employed by fire models to handle thermal radiation (Figure 6). It is envisioned that eventually graphics hardware and software will play a role in actually computing results rather than just drawing pretty pictures. AHJs often ask whether or not building occupants will be able to see exit signs at various stages of a fire. The fire model can predict the amount of soot in each grid cell, but that doesn't answer the question. The harder task is to compute on the fly within the visualization program what the occupant would see and not see.

CAN'T YOU MAKE IT GO FASTER?

Computational Fluid Dynamics was built around weather prediction and aerospace design. A quick browse

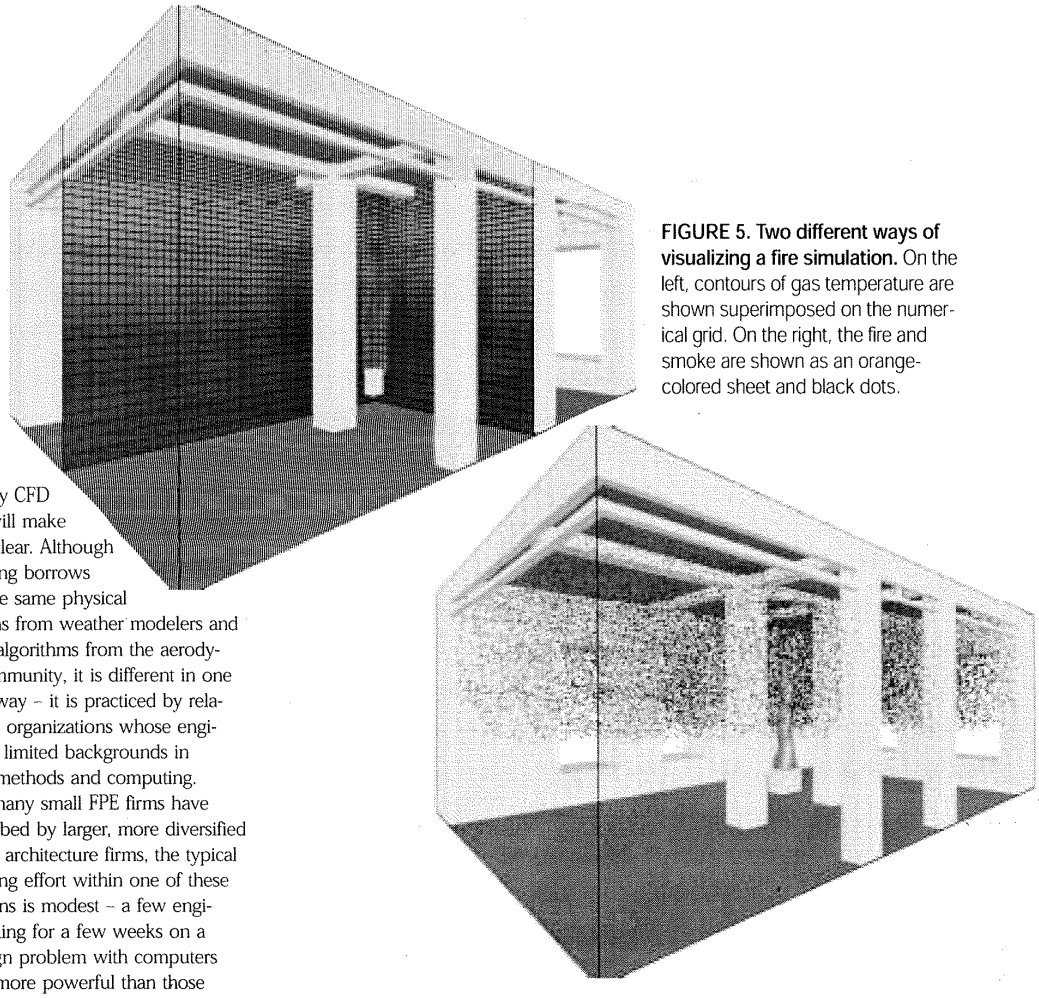

FIGURE 5. Two different ways of visualizing a fire simulation. On the left, contours of gas temperature are shown superimposed on the numerical grid. On the right, the fire and smoke are shown as an orange-colored sheet and black dots.

through any CFD textbook will make this point clear. Although fire modeling borrows many of the same physical assumptions from weather modelers and numerical algorithms from the aerodynamics community, it is different in one important way – it is practiced by relatively small organizations whose engineers have limited backgrounds in numerical methods and computing. Although many small FPE firms have been absorbed by larger, more diversified design and architecture firms, the typical fire modeling effort within one of these organizations is modest – a few engineers working for a few weeks on a given design problem with computers not much more powerful than those found in the home. The reason for this is that fire protection is but one of many features of an overall building design, and one which is typically squeezed when other items in the budget run in the red.

Because of how it is practiced, fire modeling has always emphasized simplicity and efficiency. One of the first questions that we are asked whenever we demonstrate the latest simulation is how long did it take to set up the case and how long did it take to run. The answer to both of these questions needs to be on the order of a day or less (and don't tell me I can't run it on my laptop!). If it's more, then we've lost 90% of our audience. This presents us with a bit of a dilemma – how do we stay at the forefront of CFD but still serve the community of practitioners? One way is to design the model so that one can easily start doing simple calculations with simple geometries and then systematically work up towards more elaborate appli-

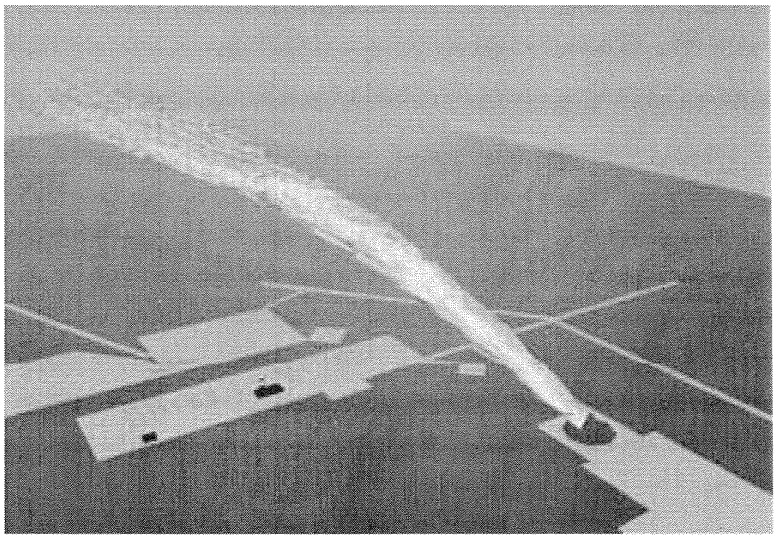

FIGURE 6. This figure is an example of how fog is used to bring more realism into the scene. Shown is a simulated smoke plume made with the ALOFT (A Large Outdoor Fire plume Trajectory) model. The plume is embedded within a fog-shrouded oil field visualized with the commercial software package SGI Performer.

cations. The trouble with many types of engineering software is that it is packed with so many features that the learning curve for even the simplest of problems is too steep. Fire modeling, especially field modeling, will advance only if there is a large enough core of users to justify the time and expense of developing and maintaining a very complex computer code. Sustaining that core of users means making the software accessible to a wide audience.

Not only must the software be easy to use, but the calculations must run as fast as possible. Veteran CFD practitioners do not find week-long calculations unusual, but fire protection engineers who only have experience with zone models find it intolerable. Faster computers have soothed some, but the demands for more-detailed calculations often negate gains made in computer speed. To keep up with demand, the fire models will need to exploit advances in computer science and numerical methods that go beyond just faster chips. Parallel processing is becoming more of a reality in certain fields, but still is a few years away for those using the current generation of personal computers. However, in the not-too-distant future, relatively inexpensive desktop computers will come with 2, 4, or 8 processors, plus the necessary hardware and software to make these chips work together effectively. Also, techniques to better distribute the grid cells will allow for greater flexibility in the design of simulations. One technique that is used by many CFD packages (but not yet FDS) is called multiblocking. An example of how this would work is a house in which every room has its own numerical grid. Those rooms requiring more spatial resolution could have finer grids, those that don't need it could remain coarsely gridded. The numerical algorithms presently used in single-block codes will not change except there needs to be extra logic built into the algorithms so that information is properly communicated across block interfaces. Such a technique is perfect for fire models because most simulations investigate buildings with relatively simple, rectangular geometries. Contrast this with the aerospace industry where simulations are performed on very complicated body shapes. These models utilize numerical grids that are far more sophisticated and difficult to construct than those needed for fire models.

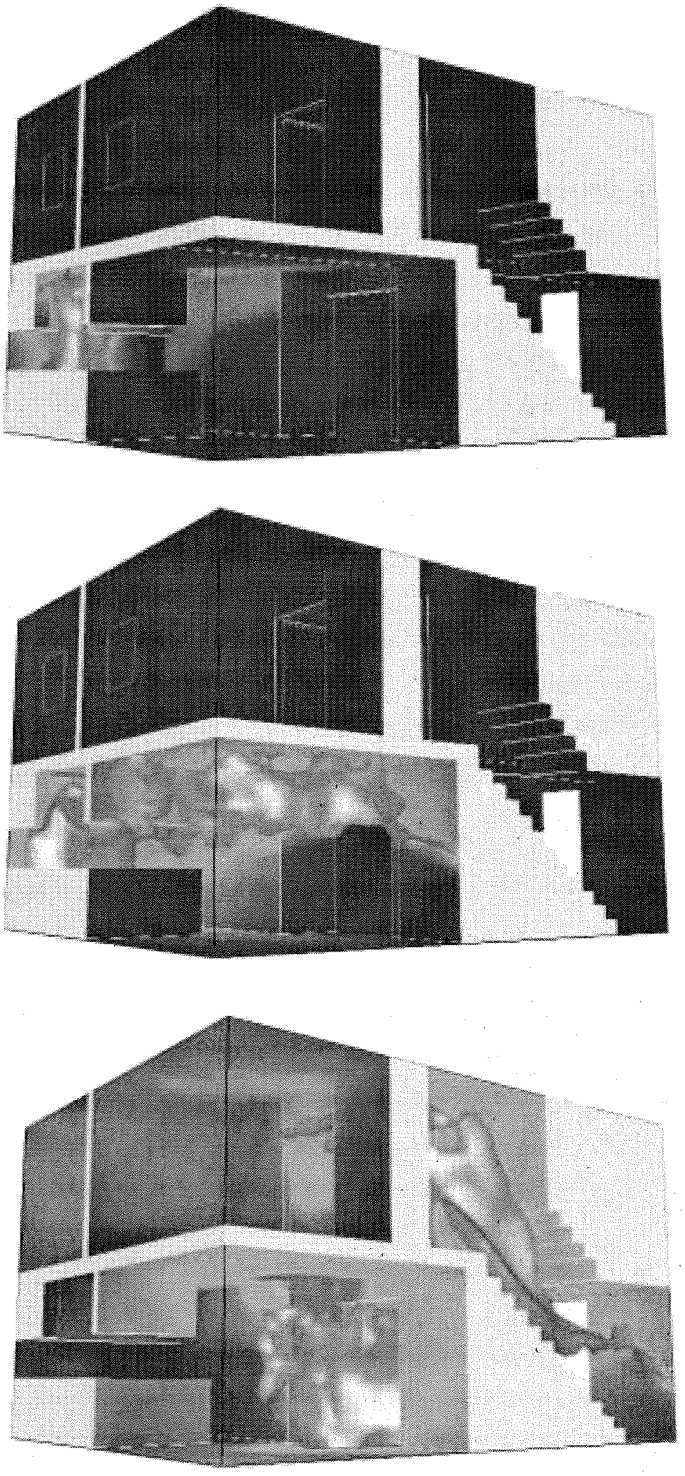

FIGURE 7. Several snapshots of a fire spreading through a townhouse. The fire originates in the kitchen area (lower left), and eventually spreads throughout the house. The front door (right) is assumed to be open, as are the windows on the second level.

WHO'S GOING TO USE FIRE MODELS?

The discussion thus far has focussed mainly on the application of fire models to design problems. This is not surprising, since fire models have traditionally worked best when the fire itself was considered merely a model input rather than a model output. However, fire models have been used as forensic tools in the past, and their use as such will accelerate in the future. In fact, much of the work to improve fire models past the point of just smoke movement has benefited the fire investigators moreso than the designers who are most often content to dial in a design fire rather than try to predict its growth and suppression.

The fire service in particular has traditionally been skeptical of any type of model, usually preferring full-scale experimental data over computer simulations. However, recent work[3] with fire models to reconstruct several fire losses has moved some in the fire service to consider the use of fire models as training tools for firefighters. If the present interest in simulation by the fire service continues, a great deal of effort will be placed on understanding the spread of fire through an entire house, not just a single room. Reconstructing a raging house fire goes way beyond simple smoke and heat transport because, as the fire spreads from its point of ignition to envelop entire rooms in flame, the response of the wall materials becomes tightly coupled to the progression of the fire in a way that up to now fire models have largely neglected. Presently simulations of entire house fires are being performed to roughly scope out the grid resolution and physical mechanisms necessary to at least capture *qualitatively* the sequence of events from primary ignition to second-object ignition to room flashover to room-to-room fire spread (Figure 7). It is difficult to validate such calculations, but at least we are starting to understand what we're up against. Validation will come from more controlled single-room experiments, like the ISO 9705 room corner test, and from simulations of test apparatus.

Ultimately, the users of fire models, whether they be researchers, design engineers, firefighters, or litigators, will drive the development of new features. The challenge to developers is to create fire models that can be used and understood by all of these groups. Even if some do not need the entire set of model features, their use of the models will speed the development and acceptance of them because much of the skepticism associated with modeling will diminish as more people grow comfortable with the capabilities and limitations.

ACKNOWLEDGMENTS

The work described in this article is the contribution of many people at NIST and beyond. We are indebted to a number of guest researchers and post-doctoral associates who have contributed to the modeling effort over the past 10 years, including Dike Ezekoye, Ruddy Mell, Javier Trelles, Francine Battaglia, Jason Floyd, and Simo Hostikka; in addition, our colleagues at NIST for input data, validation experiments, and software testing: Jason Averill, Dave Evans, Paul Fuss, Bill Grosshandler, Anthony Hamins, Dan Madrzykowski, Rick Peacock, Bob Vettori, Doug Walton, and John Widmann. Finally, thanks to the many users of our various fire models, for useful feedback, suggestions, and critiques.

The authors are with the National Institute of Standards and Technology.

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APPENDIX F

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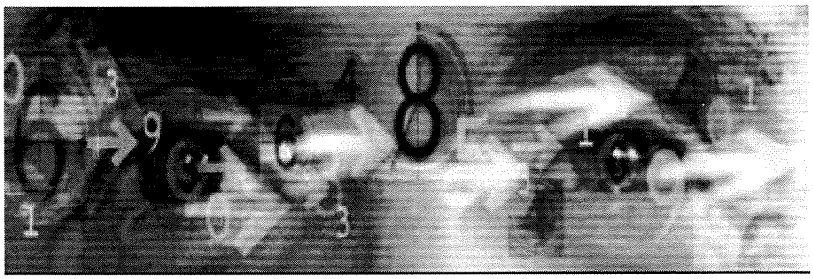

The RIGHT TOOL for the JOB

By Frederick W. Mowrer, Ph. D., P.E.

INTRODUCTION

A master builder wouldn't use a framing hammer for finish work or a tack hammer for framing. The master builder knows what tools are available for different tasks, knows how to properly use each tool, and understands which tool is appropriate for the task at hand. If not qualified for a particular task, the master builder either develops the skills to perform the necessary tasks to complete the project, or, more likely, hires another professional with the required skills and expertise.

The practice of virtually any trade or profession demands a similar approach. We all have a limited set of skills and expertise. Consequently, we must all understand our limitations as well as our capabilities. This demands that we understand the appropriate uses and limitations of the tools that are available to us as well as our own competencies in applying the available tools. Where our competencies are lacking, we need to either enhance our skills or obtain the services of people with the required skills.

In the field of fire protection engineering, the "toolbox" of models and calculations available for quantitative fire hazard analysis has expanded greatly over the past two decades. We have gone from "slide rule estimates of fire growth"[1] and other hand calculations and correlations embodied in many chapters of the *SFPE Handbook of Fire Protection Engineering*,[2] through computer-based single- and multiroom two-zone fire models,[3, 4] to emerging highly detailed computational fluid dynamics (CFD) models.[5, 6]

Spurred by the ever-increasing processor speeds and memory capacities of desktop computers, it is now practical to perform detailed fire dynamics calculations and visualize results in ways that were virtually unimaginable only a few years ago. While these ever-increasing computational capabilities are valuable, they are not needed for every job. Given the enormous computational needs of these sophisticated calculations, it makes sense to make use of computationally less-intensive tools where possible and save the more-detailed, computationally intensive calculations for those tasks where the simpler tools are inadequate.

One of the first things the fire protection engineer must do before performing a quantitative fire hazard analysis is decide what is the right tool for the job.

WHY FIRE MODELING?

All of the tools discussed in this article permit the calculation of one or more aspects of enclosure fire dynamics. It is important to keep sight of the objectives of such analyses. We perform calculations and other analyses to evaluate the adequacy of a proposed or existing component, system, or process to fulfill its functions. In other words, we perform calculations to support design decisions. As noted in the *SFPE Guide to Performance-Based Fire Protection Analysis and Design of Buildings*,[7] the first steps in the process involve the establishment of fire safety goals, objectives, and performance criteria.

Once the performance criteria are established, different calculations can be performed to determine whether the specified performance criteria will be achieved by a proposed design. Some evaluations may involve only a few simple calculations, while others, such as CFD analyses, may require millions or even billions of calculations. In general, there are three possible outcomes for a calculation within this context:

- The calculation clearly demonstrates achievement of the objective performance criteria;
- The calculation does not clearly demonstrate either achievement of or failure to achieve the objective performance criteria;
- The calculation clearly demonstrates failure to achieve the objective performance criteria.

It is for this reason that calculation methods ranging from "back-of-the-envelope" hand calculations through the most sophisticated computer-based CFD models all have a place in the fire protection engineering toolbox. A relatively simple hand calculation may clearly demonstrate the achievement of, or the failure to achieve, a specified performance criterion, in which case use of a more powerful tool would be unnecessary as well as uneconomical. Ideally, we would like to think that the more powerful the tool used for an analysis, the smaller would be the uncertain middle area of the possible outcomes. The perfect analytical tool would be one that eliminates the uncertain middle area, such that the results of a calculation would either demonstrate achievement of the objective performance criteria or the failure to achieve it. This concept is illustrated in Figure 1. Unfortunately, the perfect

analytical tool does not exist, so there will always be uncertainty that must be considered.

ELEMENTS OF ENCLOSURE FIRE MODELS

Before considering the analytical tools available for quantitative fire hazard analysis, it is useful to consider the elements of enclosure fires. Based on observations and measurements during real and laboratory enclosure fires, it is possible to subdivide the complex and interrelated phenomena occurring during an enclosure fire into a number of discrete elements. As illustrated in Figure 2, these phenomena include:

- The fire source
- The fire plume
- The ceiling jet
- The smoke layer
- The lower layer
- Vent flows and mechanical ventilation
- Boundary heat transfer
- Target heating and response

These are the phenomena that are addressed with varying degrees of sophistication and detail by different fire models. To a large extent, the level of detail with which a model treats these elements distinguishes one model from another. In some of the simpler models, the user must specify some or all of these elements, while in more complex models, the model calculates some of these same phenomena based on fundamental principles.

For example, most models require specification of a fire source; only a few attempt to calculate fire growth based on fundamental principles. Some of the simpler models calculate air entrainment into a fire plume based on a particular correlation while more sophisticated models calculate entrainment based on the fundamental dynamics of the fluid flow. Similarly, in simple models the ceiling jet is calculated in terms of an available correlation, while in more complex models the ceiling jet develops as a natural part of the fluid flow calculations. The simpler models can only be used reliably for conditions and scenarios where the correlation is reasonably accurate, while the more sophisticated models can be used with more confidence for a wider range of scenarios.

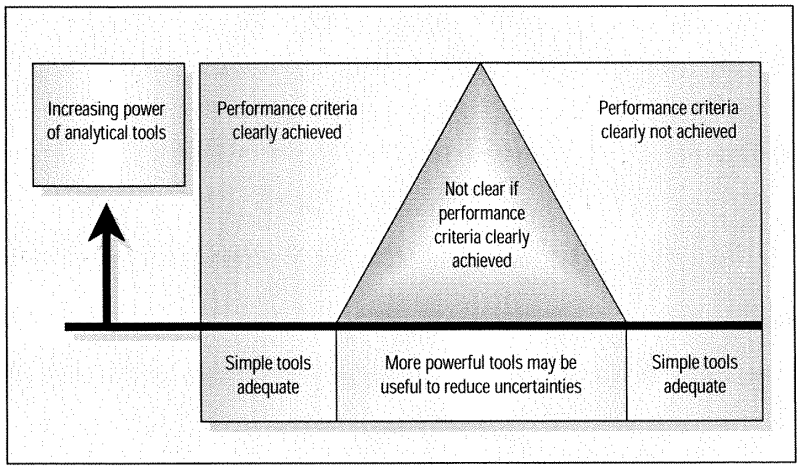

Figure 1. Ideal representation of calculation results as a function of the increasing power of the analytical tools employed.

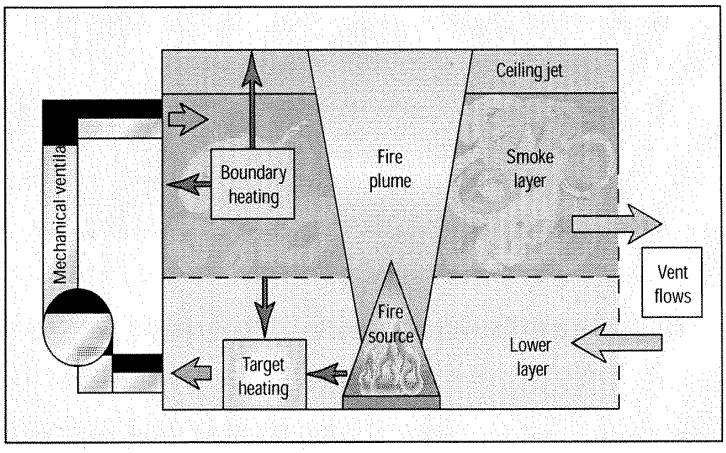

Figure 2. Elements of enclosure fire models.

TOOLS OF THE TRADE

Over the past 25 years, considerable progress has been made with respect to understanding the dynamics of fires in buildings. While models to simulate conditions in post-flashover fires have been around for even longer than this, efforts to understand and model the elements and interactions of pre-flashover fires began in earnest during the mid-1970s.

Models for evaluating the dynamics of enclosure fires can be classified in three categories, ranging from the simplest to the most complex:

- Hand calculations and correlations
- Zone models
- Field models

Hand calculations generally include "closed-form" equations that can be solved directly without the need for iteration. For example, a number of correlations have been developed that permit the calculation of flame heights, air entrainment into fire plumes, fire plume and ceiling jet temperatures and gas velocities, and smoke layer descent rates in closed rooms for fires with known energy release rates. While called hand calculations because of their closed form, these calculations typically involve the evaluation of exponents, so they are usually performed with the aid of a calculator, a spreadsheet template, or a basic computer program to make the process easier.

The best-known compilation of hand calculations in the United States is the FIREFORM (for Fire Formula) suite developed at the Building and Fire Research Laboratory (BFRL) at the National Institute of Standards and Technology (NIST). While now more than ten years old, this suite of calculations is still widely used, either within

the FPETool program,[3] as part of recent versions of the FAST program,[4] or separately. Similar suites have been developed in the United Kingdom, where ASKFRS[8] was developed at the Fire Research Station of the BRE, and in Australia, where FIRECALC[9] was developed at CSIRO.

The term "zone model" is generally applied to the many two-zone models that have been developed over the past 25 years. In a two-zone model, a room is divided into at least two thermodynamic control volumes or zones, a smoke layer of buoyant gases and products of combustion that develops beneath the ceiling, and a lower layer of relatively fresh air that remains near the floor, as illustrated in Figure 2. Conditions within each zone are assumed to be uniform, and the zones are separated by a distinct interface. Mass, species, and energy conservation equations are applied to each zone to determine the average temperature and smoke composition within each zone. While clearly an idealization of what actually occurs in room fires, the two-zone model has proven to be an effective tool for estimating room fire conditions.

A large number of two-zone fire models with varying levels of sophistication have been developed internationally. The first two-zone model to enjoy widespread use among practicing fire protection engineers was the ASET (for Available Safe Egress Time) model,[10] which calculates the descent of a smoke layer within a single closed room as a result of gas expansion and air entrainment into an axisymmetric fire plume. Today, the most widely used two-zone model is probably the FAST (for Fire And Smoke Transport) model,[4] which calculates smoke layer conditions in a multiroom building. Both of these models were developed at NIST and can be downloaded from the BFRL Web site (www.fire.nist.gov).

The term "field model" is generally applied to the types of models more generally known as computational fluid dynamics (CFD) models in other disciplines. In a field model, a space is subdivided into a very large number of cells, which may be in the hundreds, thousands, or even tens of thousands, depending on the desired resolution of the calculation and the available computational resources. The conservation equations for mass, species, energy, and momentum are then applied to each cell along with appropriate initial conditions and boundary conditions for the calculation domain.

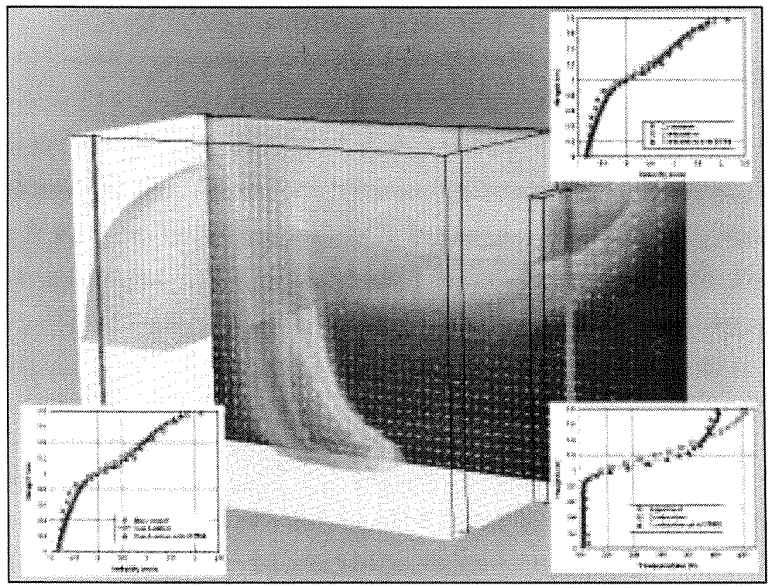

Figure 3. Results of an example SOFIE calculation.

Field models generally demand much more in the way of computational resources than zone models do. While once relegated to advanced scientific workstations, field model calculations can now be run on many personal computers. Some practical applications may take days or even weeks to run, but with the multitasking capabilities of modern computers, these calculations can be performed in the background while a computer is used for other tasks. They can also be performed over evenings and weekends, providing full employment for otherwise idle computers.

A number of general-purpose commercial CFD models have been applied to fire calculations. These models generally require some modification to deal with some of the unique aspects of fire problems, including the large temperature and density variations and gradients in the fire plume, and the significant role that thermal radiation plays at high temperatures. These commercial CFD models typically include preprocessors and postprocessors to simplify data input and visualize computed results, but the cost for these commercial packages can add up to tens of thousands of dollars per year for a site license.

At least two CFD models are being developed specifically for fire dynamics calculations. The first, known as SOFIE (for Simulation Of Fire In Enclosures), is being developed primarily by a consortium of European fire research laboratories. SOFIE is a field model of the type known as *k-epsilon* based on the way that turbulence is addressed by the model. Results of an example SOFIE calculation are illustrated in Figure 3. More information about the SOFIE program is available at the SOFIE Web site (www.cranfield.ac.uk/sme/sofie/).

The second model being developed specifically for fire dynamics calculations is known as the FDS (for Fire Dynamics Simulator) model. The FDS model is being developed at the Building and Fire Research Laboratory at NIST. FDS is based on the concept of Large Eddy Simulation (LES). A recent paper by Baum in *Fire Protection Engineering*[11] provides an overview of the FDS model. The FDS model is rapidly gaining popularity among practicing fire protection engineers. One reason for the growing popularity of FDS is inclusion of the SMOKEVIEW program that permits the results of an FDS simulation to be visualized and animated. These free programs provide capabilities normally associated with expensive CFD and visualization software packages. Results of an example FDS calculation are illustrated in Figure 4. Version 1 of the FDS model is currently available for download at the BFRL Web site (www.fire.nist.gov/fds/). Version 2 is currently in beta testing.

Field fire models, including SOFIE and FDS, require considerable knowledge and substantial computer power

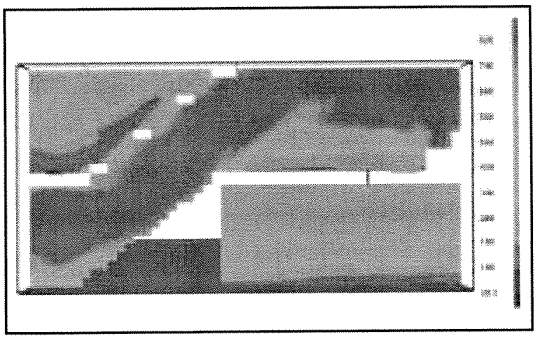

Figure 4. Results of an example FDS calculation.

to apply properly. While casual users may have some success running these models, they require a high level of expertise to use them properly. Despite these caveats, CFD models are the programs of choice for situations where adequate correlations do not exist to make use of the simpler tools.

FIRE MODELING OR FIRE CONSEQUENCE ANALYSIS?

Many, if not most, applications of fire modeling should more accurately be called fire consequence analyses because the fire itself is not being modeled, only the expected consequences of a specified fire are being calculated. Even the most sophisticated fire models have only rudimentary ability to model the actual development of a fire in an enclosure at the present time. More typically, the user specifies a fire energy release rate history, which may include an incipient period of low power output, a growth period of accelerating power output, a fairly steady period of peak power output, and a decay period of decreasing power output, as shown in Figure 5.

This approach has an obvious potential pitfall. A user can specify an incorrect fire history, resulting in an inaccurate analysis regardless of the accuracy of the actual calculation method employed. While there is not a simple solution to this problem, it is important for both fire modelers and for those reviewing fire modeling results to understand and accept the bases for the specified fire histories.

While most current fire models may not be able to accurately calculate the growth and spread of fire, many models can and do address the influence of oxygen on burning rates within an enclosure. For most typical combustibles that burn in fires, there is a direct relationship between the energy released by the fire and the amount of oxygen consumed from the atmosphere. Many fires become "ventilation limited," which means that their energy release rate becomes governed by the rate of airflow to the fire enclosure rather than by the fuel release rate. Models that do not account for this ventilation limitation on combustion can produce inaccurate results.

MODELING UNCERTAINTIES

Models, by definition, are incomplete representations of the component, system, or process being modeled. Consequently, there will always be uncertainties associated with the results of a calculation. In general, these uncertainties will be associated either with the model itself or with the input parameters. Modeling uncertainty is primarily epistemic because it relates to the level of knowledge related to the phenomena being modeled. Parameter uncertainty is primarily aleatory as it relates to random variations in the properties or attributes of the input parameters.

Enclosure fire models are a type of deterministic model because they produce the same specific set of output results for the same input parameters. Only a few enclosure fire models have attempted to address uncertainty through specification of probability distribution functions for the input parameters and in some cases for the modeling equations. The COMPBURN model[12] that is widely used for nuclear power plant fire hazard analyses is probably the best known of these models. Such models produce probability distribution functions for the output parameters by repeating the same calculations hundreds or thousands of times with the different input parameters in a process known as Monte Carlo simulation.

Whether uncertainty is addressed quantitatively or qualitatively, it is important that uncertainty is addressed. Perhaps the worst mistake a fire modeler can make is to run a model only once and then rely on those results as conclusive without considering how variations in input parameters might affect the results. One of the benefits of fire modeling is the ability to vary input parameters over expected ranges of conditions in order to evaluate the sensitivities of the results to variations in input parameters. An exception to this would be for situations where an analysis is being performed for a "reasonable worst case" scenario. In this case, a single calculation might suffice provided that the input parameters are truly representative of reasonable worst case conditions.

GARBAGE IN – GOSPEL OUT?

Most of us have heard the phrase associated with computers: "garbage in – garbage out." While this phrase has become trite from overuse, it is overused because it remains so true. While it may be appropriate to trust that a computer calculation will be performed accurately once a program has been debugged and verified, this is no guarantee that the calculation result will accurately reflect reality. If the scenario being modeled is not specified accurately, then the model will not produce meaningful results. On the contrary, results of a sophisticated computer-based calculation may provide the perception of a high level of accuracy despite producing erroneous results. This has sometimes been referred to as "garbage in – gospel out." For this reason, it is critical that the assumptions and uncertainties associated with the input parameters be clearly described and adequately justified.

Consider, for example, the practice of using a design fire heat release rate of 5 MW for the analysis and design of smoke management systems in large spaces such as atria. Such a specification is widely used in building codes (e.g., 1997 *Uniform Building Code* and 2000 *International Building Code*) and referenced in design standards (e.g., 1995 NFPA 92B). While such a specification may be reasonably conservative for the vast majority of applications, it is inadequate for those applications where larger fires might be expected to occur. Appropriate administrative controls are needed to limit fire sizes to those used for analysis. Otherwise, "garbage in – garbage out."

WHAT IS THE RIGHT TOOL FOR THE JOB?

It would be nice if there were a simple and universal answer to the ques-

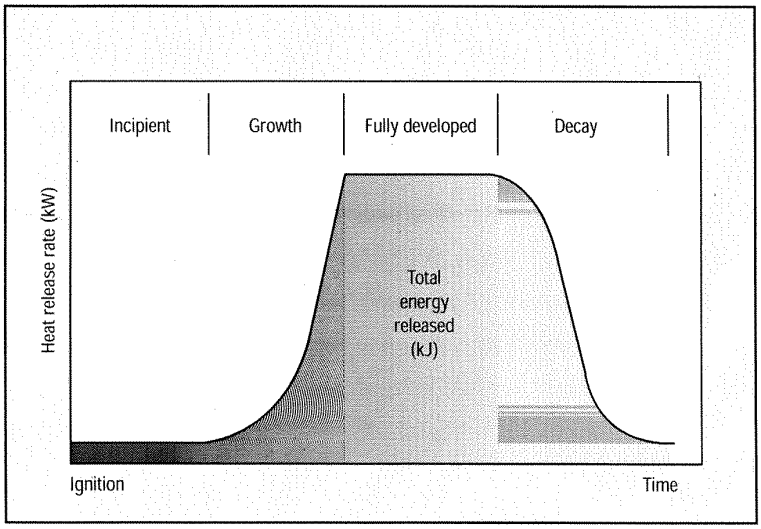

Figure 5. The stages of fire energy release rate.

tion: What is the right tool for the job? Unfortunately, there isn't one. The right tool depends on the task at hand. It is the job of the engineer to understand the uses and limitations of the available tools and to select a tool that is suitable for the task. It is equally important that the engineer understands and documents the bases and limitations for a particular analysis.

It is easier to develop a procedure that can be followed to help the engineer in the selection and application of the right tool than it would be to provide specific guidance on which specific tools apply to which scenarios. This procedure would be:

1. Identify and document the purpose of the analysis in as much detail as possible.

Fire models are generally used to demonstrate that fire mitigation strategies will be effective before unacceptably hazardous conditions develop. For example, they can be used to help demonstrate that a large space can be evacuated before occupants become immersed in the descending smoke layer. Or they can be used to evaluate when a fire detection device or sprinkler would be expected to activate in different fire scenarios. Ideally, they could be used to demonstrate the effectiveness of a sprinkler system design, although such capabilities are generally beyond the current state of the art.

For this first step, it is important that all the different purposes for which an analysis is being conducted are identified. It is equally important that the purposes are documented along with the performance criteria that will be used to evaluate the acceptability of a proposed design. Sometimes fire protection engineers take for granted the purpose of an analysis because they routinely perform such analyses. However, the purpose of an analysis may not be apparent to other stakeholders, so this documentation is important.

2. Identify modeling tools that can support the level of detail demanded by the analysis.

In order to identify appropriate modeling tools for a particular task, it is important for the fire protection engineer to understand the uses and limitations of the models that are available for a task. For example, the widely used model to predict fire detector activation, DETACT,[13] is based on unobstructed axisymmetric plumes in large spaces with smooth horizontal ceilings. The engineer needs to recognize what the effects of obstructed plumes, small spaces, and obstructed or sloped ceilings will be before applying this model to such plumes or spaces. Where it is determined that the DETACT model does not apply due to complicated geometries, other more sophisticated tools may be needed, such as a CFD model, that can address these aspects.

Many analyses include a screening step during which simple tools are used to perform conservative analyses. Dungan[14] recently provided an overview of the FIVE Methodology, a risk-based methodology used in nuclear power plant fire safety analysis that uses such a screening step. As illustrated in Figure 1, simple screening tools may be adequate to clearly demonstrate that performance criteria clearly are, or are not achieved, for many scenarios. While the ultimate objectives of an analysis may require the use of more sophisticated tools for scenarios that do not screen out with a simple tool, screening steps frequently permit many scenarios to be screened so that the more sophisticated tools can be applied only when needed.

This step should also include consideration of how the tools being evaluated have been validated and verified. Ideally, the modeling tools being considered for use will have compared favorably with experimental data for scenarios similar to those being considered. If not, some validation studies may be needed to develop confidence in the accuracy of the modeling tools for the scenarios being considered.

3. Determine what input parameters are needed for the models being considered, and identify and document the data sources to be used as bases for the input parameters.

Most of the input parameters needed for different fire models are basically the same. While they may be specified in different terms, all enclosure fire models require specification of the enclosure and ventilation opening dimensions, the boundary thermal properties, and the fire properties, either in terms of a specified energy release rate or in terms of flammability properties. While results of a simulation may be relatively insensitive to many of these input parameters, they will be relatively sensitive to others, notably the fire history.

For this step, it is important for the data sources that are used to justify the selection of different input parameters to be identified and documented. This will provide the justification for the values selected as well as provide an audit trail so that others can confirm and verify that appropriate values have been selected. This documentation of input parameter selection may also provide a basis for an uncertainty analysis.

4. Consider how model results will be used to support design decisions.

Finally, before a model is selected for use, consideration should be given to how the model results will be used. At

this step, model results must be communicated to other, generally nontechnical people. While such people may not be interested in the details of an analysis, it is important for them to understand the limitations of the analysis so that they can make better risk-informed decisions.

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APPENDIX G

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Human Behavior and Fires: An Introduction

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From a selected list of references, the author traces the developments in the research into human behavior in fire situations. This paper includes research approaches, people and design as related to the evacuation process, panic, behavioral tendencies, and decision-making, citing references from the author's paper: *Human Behavior and Fire Emergencies: An Annotated Bibliography, NBSIR 81-2438.*

THE STUDY OF HUMAN response and capabilities in fire emergencies is an essential part of a total, systematic assault on the problem of fire fatalities and losses in all types of occupancies. On the negative side, there is the human factor in ignition of unwanted fire, whether through intent or carelessness. The improper use of cigarettes and alcohol, and the prevalence of arson are particularly significant." There is also the role of people in making a situation worse through inappropriate actions, or actions which reduce the effectiveness of the installed fire safety systems. From a positive viewpoint, human capabilities can be utilized, to a degree, to enhance installed fire safety systems or compensate for shortcomings in such systems. The study of human behavior and fires is still in its infancy, although beginning with the Wood study completed in 1972, there was an intensification of interest and effort, with some major systematic studies and numerous smaller ones subsequently being carried out. This area of scientific study is beset by methodological problems - experimental subjects obviously cannot be placed in real fire situations,' after-the-fact testimony from participants in fires may contain errors,' and where samples are

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limited or not representative, conclusions must be drawn cautiously. Nevertheless, there is considerable consensus among researchers concerning certain recurrent themes which have emerged from these studies. The central perspective on human behavior in fires can be stated as follows:

> Despite the highly stressful environment, people generally respond to emergencies in a "rational," often altruistic manner, in so far as is possible within the constraints imposed on their knowledge, perceptions, and actions by the effects of the fire. In short, "instinctive," "panic" type reactions are not the norm. The historic emphasis in the press and regulatory literature on the likelihood of "instinctive" or "panic" reactions is inaccurate and counterproductive. The serious researcher might cringe at such dramatic headlines in the popular press as "Panic Kills 300"[5] or ". . . when confronted by a blaze, most people behave pretty foolishly . . ."* Such attentiongetters are either erroneous or, at best, oversimplifications.

APPROACHES

Researchers have turned their attention to the whole range of. behaviors exhibited by persons in fires, from their first awareness of a possible problem through completion of the evacuation process. The bulk of the data has been obtained through studies of actual fire incidents. In-depth case studies of individual incidents have been conducted as well as statistical, summary studies of large numbers of incidents. There has been a progression from largely descriptive studies - what was done, how often, by whom, in what order - to more complex analytical studies which attempt to extract typical behavior patterns or relate both behavior and fire development in a time sequence." Bryan has used this technique in an extensive series of case studies of health care facility fires.' Relating behavioral actions to a time frame is particularly important, since the appropriateness of an act such as "fighting the fire" is critically related to the stage of fire development at which it occurs."·" The whole behavioral process is taking place as the fire itself may be rapidly developing, and "what is an appropriate action at one stage may be quite inappropriate a minute later.""

A further direction which research can take (with implications for training and education), suggested by such researchers as Wood, Keating, and Bryan, is the exploration of the reasoning and motivation behind a participant's choice from among the alternative actions available to him. Why did he choose to perform a given act first, and how did the outcome of his actions match his expectations?

Much attention has been directed toward identifying sequences of actions followed by those involved in fires. Unfortunately, it is not as simple to prescribe the appropriate sequence of actions to follow in a fire emergency, as it is to specify a step-by-step procedure as, for example, in the assemblage of a piece of electronic equipment.

* From Parade, the Sunday Newspaper Magazine, February 10, 1980.

Lerup states the point strongly: "There are at present no officia strategies for life safety that can stipulate a correct sequence of actions t follow ... the physical environment cannot be designed to literally reflect specified sequence of actions ... no two fires are alike. . ."[2] Canter similarl makes this point." Bickman, in his study of the effectiveness of training o nursing home staff on knowledge of appropriate behavior in fire," en countered the difficulty with sequence of actions when quizzing staff on th selection of first and second actions to be performed in case of emergency The plan of the nursing home under study contained contradictory instruc tions - at one point staff were instructed to remove residents from the fir area and then pull the alarm, while further down the same page exactly op posite instructions were written. Bickman concludes that the decision o which action to perform first might be regarded as being "situationall bound," that is, dependent on the severity of the fire, number of patients i immediate danger,.distance to an alarm box, and so forth.

There are, nonetheless, some simple, critically important directive which are generally applicable to fire emergencies: for example, response t alarms should be immediate and appropriate (without time being waste seeking verification of the existence of a fire); the occupant should not at tempt to fight any but very small, contained fires; the door to the room o fire origin should be closed immediately after all persons have left; an rooms (or buildings) should not be reentered during the course of a fire t retrieve possessions. In a health care institution, frequently more then on staff member is close by, so that while one staff member is evacuating th immediately endangered patient another can be pulling the alarm, closin other doors, etc. In many instances, automatic detection devices will hav sounded the alarm.

PEOPLE AND DESIGN

EXIT SYSTEMS

The annotated bibliography contains numerous descriptions an analyses of the evacuation process. The initial physical science "carryin capacity" approach to egress assumes that occupants respond immediatel to an emergency (like water or gas particles) and are affected only by spatia configuration and density during the actual evacuation process. Th "human response" school of research also considers the influence o evacuation time of such human factors as decision-making in a ambiguous situation or organizational factors such as the presence o trained supervisors or communications systems." Stahl's compute simulations of egress behavior in building fires are notable for thei incorporation of human interaction and **decision-making variables.** [16,17,18]

Behavioral research has shown that it is erroneous to assume that behavior in fires is a simple process largely controlled by exit and alarm

Systems." From his observations of large-scale evacuations of high-rise office buildings, Pauls concluded that an exit that is not normally used will carry significantly fewer people in an evacuation. Codes currently credit exit capacity to stairs regardless of their normal use. Pauls' work is perhaps best known for exposing problems in the traditional 22-in. unit-exit-width basis for exit rules." He asserts that "even in simple, total evacuation drills, evacuation times have been observed to be as much as twice as long as had previously been predicted" and "Given ... improved awareness of the complexity of behavior in fires, we should think of evacuation time predictions - even those based on realistic conservative flow assumptions - as minimums and not maximums, as is sometimes argued.""

In one nursing home fire, perimeter stairs not normally used by residents were not used by staff to evacuate residents in a fire emergency, even though their use in the emergency would have been most appropriate. Rather, a center stairway was used, although it meant that most residents were moving toward the fire. A security alarm had been set off often in the past by residents who had attempted to leave through the perimeter exits, and some residents who were caught using these exits had been scolded."

One possible explanation for the tendency to use habitual routes during emergency evacuations may be found in the psychological research on fear and stress: ". . . under heightened anxiety, people's attention becomes narrowly focused; they are aware of only the most obvious aspects of their environment. Peripheral cues, which are usually easily processed, remain unobserved."

ALARMS

The question of the effectiveness of alarms is dealt with frequently in the bibliography, either directly and exclusively as in accounts of experimental studies or as a part of fire incident case studies. Whether or not an alarm will awaken a person is dependent on more than just the noise level of the alarm or its noise level in relation to ambient noises. Sounds that have "meaning" for the sleeping person are more likely to awaken him. Not only do individuals differ from one another as to the noise level necessary for awakening, but a given individual will require different levels at different times depending upon such conditions as sleep stage, time of night, or medication .22.2'.24

The frequency of false alarms, the possible ambiguity of meaning of the alarm, and the tendency for people to look for confirming evidence of a fire rather than to immediately evacuate, all are factors which tend to determine the effectiveness of alarms in **producing prompt evacuation.** 4.9,20,25,26

AREA OF REFUGE

There is a general consensus among researchers who have concerned themselves with high-rise occupancies that simple alarm systems are not

adequate for many such occupancies. Total evacuation within a reasonabl amount of time is not a feasible option. Comparatively complex voic communications systems have been installed in some of these buildings s that partial, selective evacuations might be conducted.'-"-" This raises th interesting question of how willing people will be to wait their turn t evacuate or simply remain in a "safe area" once they are aware of th existence of a fire emergency. The fire in the World Trade Center on Apri 17, 1975, demonstrated that even though reassurances are provide through a public address system, it may still be difficult to convinc people they are not in danger when they see an obvious problem such a smoke. In this case, a small trash fire in the 5th floor resulted in th evacuation of the 9th through the 22nd floor because of occupants concern over smoke. The firesafety director had initially urged people t return to their offices; when it became obvious they were not going to d so, he ordered the evacuation."

One aspect of partial, selective evacuations which could prove difficult is the condition where people working on the floor above a fire might be asked to go up a flight to prevent clogging narrow stairwells leading from the fire floor. It is to be expected that most people would want to go down stairs and leave the building. However, Keating, Loftus, and Groner found in several buildings that there were no instances during test drills when people failed to follow the somewhat counter-instinctive direction to go up stairways, although several occupants were to question the sense of this directive." (The occupants could not be certain that this was only a test.)

In large buildings without voice communications systems, occupants may be forced themselves to choose between using their living units as areas of refuge or attempting to evacuate."[11,12]

A recent trend has been to provide increased access to public buildings to the physically handicapped. The elevators used to provide access for these individuals under normal conditions commonly are not designed to be used in the event of a fire emergency. Thus there are increasing recommendations to establish adequate areas of refuge in these buildings. It will be necessary to inspire confidence in the adequacy of such areas."

PANIC

Why the popularity of the notion of panic as a cause of fire deaths? Keating and Loffuu" mention one possible explanation which may be found in a theory of social psychology. Attribution theory suggests that "when the failures of others threaten the stability and predictability of our own world, we try to distance those failures from ourselves. Thus we tend to dismiss accidental fire deaths as the victims' fault: they panicked, but we would not. . ." "we often want to believe that the dead or injured were victims of their own maladaptive or panic behavior."

Probably no word has been used more commonly than panic to refer to behavior in fire, nor has any word been more tantalizing or frustrating to the behavioral researcher. The basic problem lies in the diffusion of meaning

of the word. It has been used at various times to refer to emotion and/or action; to flight behavior alone, or to jumping or immobility reactions; to the initial reaction of an individual to a fire situation, or to the "stampede" of a crowd as smoke and flames rush into a room with inadequate or blocked exits. Panic can refer to actions which might be labelled maladaptive or adaptive, rational or irrational, depending upon the outcome of the actions or whose survival is being considered. With this complexity in mind, Quarantelli, as chairman of a panel on panic at an international seminar on behavior in fires, posed the following question to the assembled panel of experts: "Do you see the concept of panic as a useful one for scientific purposes?"" The feeling of the panel was that the concept was exceedingly troublesome, but its use inescapable due to the long tradition of use and its frequent appearance in press accounts.

Behavioral scientists can take a *nonscientific* word like panic and attempt to attach an operational definition to it for study purposes. But even here there are intricacies as, when one attempts to attach modifying words, like "irrational" or "maladaptive" to actions like "flight." What may seem like "irrational" behavior from the point of view of an outside observer (with his hindsight and access to more complete knowledge of the total situation) may have been rational behavior from the point of view of the participant."-[5] What is "maladaptive" for the welfare of the group (with the goal of saving the greatest number possible) may be adaptive for a given individual. Movement within a burning building against the press of an exiting crowd by a parent attempting to find a child is adaptive from the parent's viewpoint, but not for the group of people trying to get out.

Should the behavior of the two students who jumped from fifth floor dormitory windows, receiving serious injuries, be labelled as "panic?"' Note that both of these individuals before jumping had experienced unsuccessful evacuation attempts, receiving burns in the process.

The Beverly Hills Supper Club, fire in Southgate, KY, on May 28, 1977, in which 165 people died, is a case where a superficial look might lead one to ascribe many fatalities to panic. Sime quotes a British newspaper report with the headline "Panic Kills 300.'[115] Contrary to this, researchers agree that panic, in the sense of aggressive behavior which would add to the danger to self and others presented by the fire itself, did not occur. Rather "it seems reasonable to conclude that there was a maximum of altruistic behavior."" The essential behavioral problem lay in failure to appreciate the seriousness of the situation soon enough - there was a false sense of security because the Cabaret Room where most of the patrons were located was a long way from the room of fire origin. "Hence fire safety education should consider people's erroneous *conceptions* about distance being related to safety and the time needed to **escape from a fire emergency.** [1136] Some patrons initially regarded the busboy's *announcement* of fire from the stage as a part of the comedy routine.

Sime maintains that "Research of fires shows that people need sufficient information about a fire before they can, or are prepared to, leave a building.

There is growing evidence that the delay in warning people in a number of major fires has been a primary reason why people have been unable to escape in time. An emphasis on avoiding `panic' contributes to delays. "" Any hesitation to inform people of a potentially dangerous situation out of fear of causing panic may ironically lead to a situation in which panic (i.e., rapid, mass competitive flight) must inevitably occur.

A better focus of concern would be what might be considered the reverse of panic - inaction, denial, a fear of appearing foolish by overreacting, the need to investigate before leaving a burning building, reentry of it, or persistence in fighting a fire too large to control rather than promptly leaving. The Wood and Bryan surveys"-" revealed considerable reentry behavior. In *Scanlon's* study,° people reentered an apartment building to get possessions after reaching safety even after having seen smoke and flames while outside in the courtyard. The classic experimental studies of Latane and Darley'° are interesting in that they indicated that the presence of others lessens the chances of an individual reacting promptly to a potential emergency. Male undergraduate subjects found themselves in a smoke-filling room. When alone, 75 percent of the subjects reported the smoke. In the presence of two nonreacting others (confederates of the experimenters) *only* 10 percent of the subjects reported the smoke during the experimental period.

BEHAVIORAL TENDENCIES

One strong pattern identified by the literature is the tendency of people in fires to do the familiar: they use familiar exits; they assume familiar roles. Swartz found evidence in his behavioral study of the Beverly Hills fire that the people involved continued to fulfill the roles they had prior to the fire. In that fire, the staff consistently took actions to assist patrons, whereas patrons followed or took a more passive role. Staff members took care of the patrons they would normally serve. Thus Swartz concludes that "firesafety plans for places of public assembly should examine the roles that people normally play, and not seek to prescribe emergency actions that are contrary to these roles.""

Bryan's extensive study of nursing home fire incidents' showed that nursing staff perform in accordance with their roles of responsibility for patients even when at some risk to themselves.

Behaviors in accordance with traditional male/female roles have been identified by several researchers. For example, a University of Surrey study' found that the "variability of the actions which follow the encountering of smoke and fire itself is explained by male/female differences. Females are more likely to warn others and wait for further instruction (for example, if husband and wife are both present). Alternatively, they will close the door to the room of fire origin and leave the house. In both cases, females are more likely to seek assistance from neighbors. Male occupants are most likely to attempt to fight the fire. Male neighbors are more likely to search for people in smoke and attempt a rescue." The Wood study" revealed sex

differences - women were again more likely to warn others and evacuate the family while men were more likely to attempt fire fighting. Conventional sex role behavior was also found in the Bryan," Keating and Loftus," and Kobayashi and Horiuchi" studies.

Another strong behavioral pattern identified is the tendency of people to seek verification of fire cues (both those which are characteristics of the fire, and alarms) before evacuating. There is also the problem of nonresponse due to negative conditioning by false **alarms.** [4,9,24,25,26]

DECISION-MAKING

With very limited time available in which to decide on a course of action, people involved in fires often face difficult decisions. Decisions may be intellectually difficult in the context of limited knowledge of the engineered safety or of the basic configuration of the occupied structure or limited knowledge of the development of the fire itself. Decisions may be difficult because of the sometimes counter-instinctive nature of the correct response; because some additional risk to one's self is incurred by a decision to alert or assist others. Further complicating matters is the possible negative physiological/psychological effects of toxic gases or oxygen deprivation even before these factors produce severe physical symptoms."-4''[44]

In an Illinois nursing home experimental study, [4] it was found that staff were resistant to accepting the concept that ambulatory patients should be evacuated first. A group which received training on the home's fire emergency plan scored significantly better than a control group on test items regarding simple factual information relevant to firesafety, but no significant difference was found between the training and no-training groups with regard to the question of whether to evacuate ambulatory or nonambulatory patients first. A majority of both groups incorrectly indicated that nonambulatory patients should be evacuated first. The experimenters concluded that, in instances like this, where there are strong erroneous preconceptions regarding appropriate behavior in fire, more thorough training methods, including simple explanations of why such beliefs are in error, are needed.

Nursing staff in a Mississauga, Ontario, nursing home fire [45] which resulted in 25 patient deaths, were faced with the problem of trying to save a patient in the room of fire origin. When the nurse arrived at this room, several items, including the bed and chair, were on fire. She could not enter the room, but was aware of the patient still in there, lying on the floor moaning. She closed the door and reportedly went to get wet sheets and blankets to attempt to remove the patient. A supervisor returned to the room, reopened the door, but unfortunately was unable to close it again due to the great volume of fire and smoke.

The degree of altruism and capability exhibited by people in some of the case studies is perhaps surprising. Some cases in point: the behavior of the nurse's aide in the St. Joseph's Hospital fire [46] the evacuation assistance rendered by a resident of the Taylor House to another blind resident,'' and the instances of occupants assisting other less able occupants in the Georgian Towers apartment fire."

SUMMARY

RESEARCH DIRECTIONS AND PRELIMINARY FINDINGS

This introduction has served to acquaint the reader with the broad range of research done in the area of human behavior and fires, to give an overview of human response patterns to various firesafety design features, and to, wherever possible, point out some areas where various researchers have arrived at similar findings regarding behavioral tendencies in response to fire emergencies.

"Panic" behavior has been singled out for special attention. Whether or not "panic" occurred in a given situation to some extent seems to depend upon the definition one assigns to panic. However, the concept of panic is too prevalent and too important to be dismissed merely as a semantic matter. Panic is no doubt the behavior most commonly associated with fire emergencies by the public in general and historically by those with professional interests in firesafety. Institutional firesafety plans and general safety guidelines to the public routinely and repeatedly warn against panic.

Researchers now tend to discount the importance of panic as a factor which adds to the injuries or loss of life which would result from the fire itself. (An early research study" is interesting in that panic behavior is an assumption, not a condition to be defined or verified.) It is important to distinguish between panic, as an emotion, and panic, as an action with aggressive, maladaptive, or irrational components. People naturally feel strong anxiety in a fire emergency, but this strong emotion does not necessarily preclude appropriate lifesaving actions."

The consensus among disaster researchers at the human behavior in fires conference in 1978 was that the popular belief in the widespread prevalence of panic in disasters is a "myth." Some caution is perhaps in order, as Black pointed out during the discussions, when generalizing this downgrading of the importance of panic reactions in disasters to fire emergencies. Because of the extremely limited time for reaction and the possibility of sensory deprivation, fires may present a special category of disaster.

Although evidence of panic reactions should continue to be looked for by fire investigators and researchers, it has been suggested that more attention to other potentially harmful behaviors such as failure to respond to alarms or reentry of a burning building may prove more useful.

Decision-making during the various stages of a fire emergency can present a severe challenge to the participants. Since every situation is somewhat different, successful coping with a fire emergency can demand more of the participant than following a set of previously memorized correct actions. It has been suggested that analysis of the decision-making process, based on in-depth interviews with participants, is one direction which might be emphasized in future research.

PREDICTION AND RISK

An important goal of behavioral research is to understand the capabilities of people in fires and to be able to predict their likely reactions in emergencies. The extent to which human behavior is predictable (even with improved knowledge) is still an open question. Since human response in a fire emergency tends to be difficult to predict (individuals vary from one another and also a given individual's performance may vary with the time and setting), it can be argued that an ideal system of firesafety might be one in which there was no dependence on human response, and the approach could be classified as "idiot proof." In a practical sense, however, there is no safety system that cannot be enhanced by appropriate human actions or defeated by inappropriate actions. To some degree, human response can compensate for shortcomings in the physical safety of the environment and vice versa. Each, however, has an area of participation in overall safety that is not interchangeable with the other.

The appropriate balance of all safeguards, both physically installed and human response in nature, is needed. In this balance, all factors - including potential safety, reliability, failure mode and effect, cost and other impacts - need consideration. Absolute safety against fire injury and death is, of course, unattainable. Authorities must implicitly accept a certain "reasonable" level of risk when they make decisions in the area of resource allocation for firesafety. (Several references pertinent to this general topic are listed under "risk" in the index of the annotated bibliography.)

With regard to vulnerable populations - the aged, the physically handicapped, and the mentally impaired - the acceptance of a certain degree of risk is done with the intent of improving the "quality of life." Such individuals have been moved from institutional settings, with greater built-in fire protection, to smaller residences with more homelike atmospheres. (See reference number 50 for a discussion of deinstitutionalization and the major implications of this trend for firesafety.) Greater access to public buildings has been provided for the handicapped through ramps and elevators, placing them at greater risk from fire, but improving their freedom of movement. Burgun maintains that the handicapped should be allowed to take the kinds of risks we all accept as part of normal life, since if all elements of risk are denied handicapped persons, then essential developmental opportunities are also denied. He also contends that the handicapped should not have to endure more or increased risks than those who are not disabled, and that some special provisions will therefore have to be made for the handicapped."

Determination of the appropriate share of the limited funds available for social concerns to devote to life safety from fire, and consideration of the proper balance between "reasonable" safety from fire and "quality of life" are two of the complex, underlying philosophical challenges which face administrators and fire officials.

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APPENDIX H

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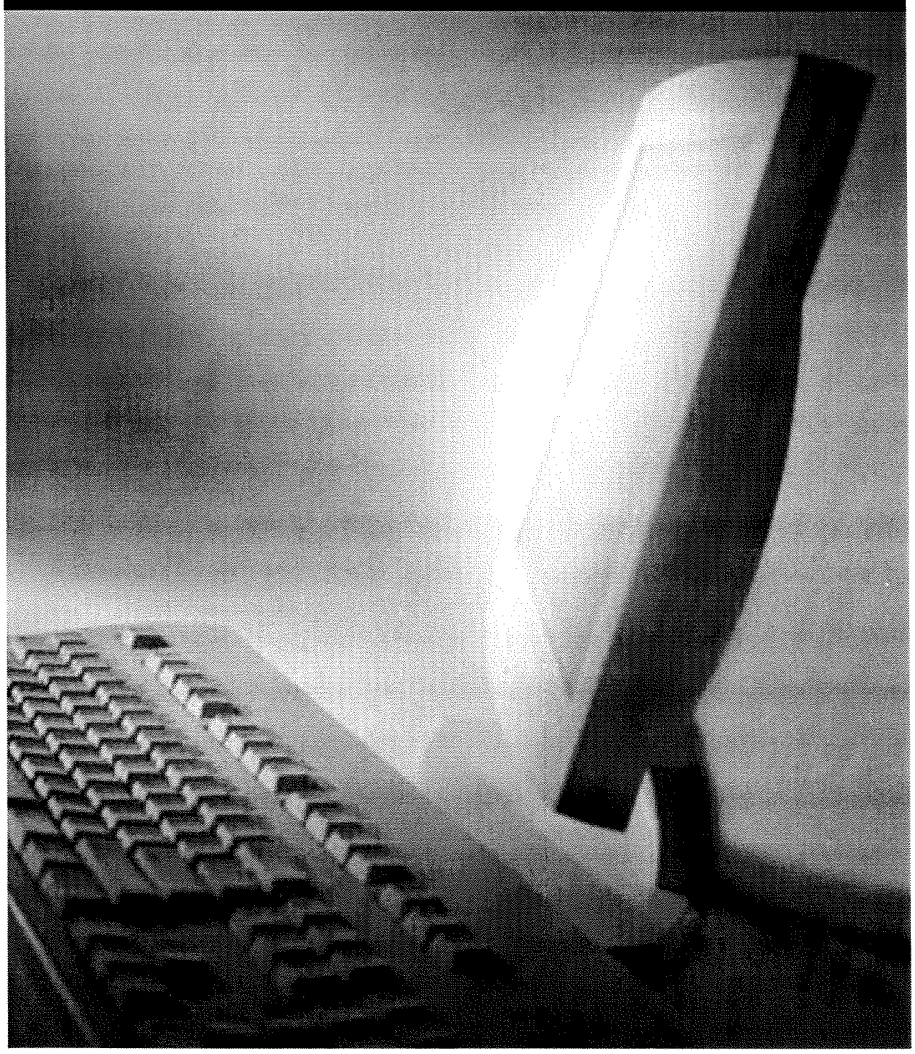
EVALUATING Computer Fire Models



By Marc L. Janssens, Ph.D.

Evolutions in fire science and technology and computing have resulted in a growing number of powerful mathematical models that are used in support of fire safety engineering design and analysis. Good engineering practice requires that a statement of uncertainty accompany all computer fire model calculations. This article summarizes a series of standard guides that help assess uncertainties in computer fire models. It also discusses application of the guides by SFPE and others.

COMPUTER FIRE MODELS

What Is a Computer Fire Model?

A fire model is a physical or mathematical representation of burning or other processes associated with fires.[1] Mathematical models range from relatively simple formulae that can be solved analytically to extensive hybrid sets of differential and algebraic equations that must be solved numerically on a computer. Software to accomplish the latter is referred to as a computer fire model.

Types of Computer Fire Models

The most commonly used computer fire models simulate the consequences of a fire in an enclosure. Zone models as well as field or CFD models are used for this purpose. Enclosure fire models have been extended to simulate the spread of fire and smoke through multiroom structures.

A second category of computer fire models predicts how materials, systems, or people respond when exposed to specific fire conditions. Sprinkler and detection activation models fall in this category. Other examples are calculation methods to assess the load-bearing capacity of structural elements and assemblies exposed to fire, and models that simulate human behavior and egress in the event of fire.

Uses of Computer Fire Models

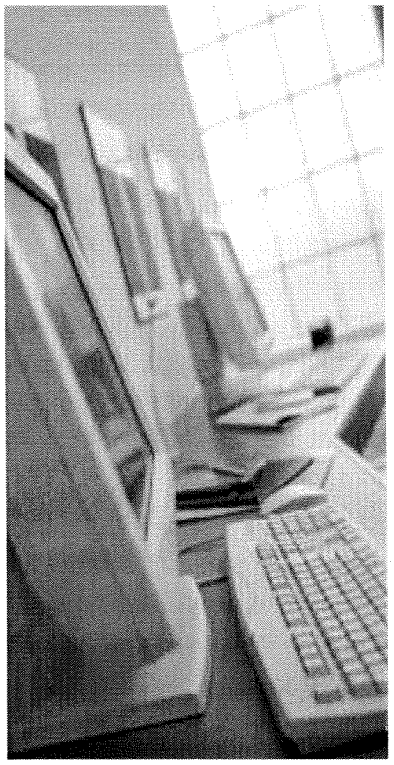
Computer fire models are used primarily for two purposes: reconstruction and analysis of a fire, and fire-safe design of a structure. The former is usually an easier task, because there is always other information available such as forensic evidence, eyewitness accounts, fire department reports, etc. A computer fire model in this case is most often used to supplement the other information in demonstrating that a particular hypothesis is or is not plausible.

ASTM STANDARD GUIDES

ASTM subcommittee E05.39 on Fire Modeling (later merged into Subcommittee E05.33 on Fire Safety Engineering in 1996) initiated the development of a set of standard guides in the late 1980s. Four guides are now available, which cover specific issues pertinent to computer fire modeling:

- *ASTM E 1355* addresses evaluating the predictive capability of fire models;
- *ASTM E 1472* provides guidelines for documenting fire models;
- *ASTM E 1591* describes procedures to obtain input data for fire models; and
- *ASTM E 1895* addresses uses and limitations of computer fire models.

Although many of the provisions in



the guides are applicable to other types of fire models, the focus is on compartment zone models.

Evaluating the Predictive Capability of Fire Models

ASTM E 1355 was first approved in 1990 and slightly revised in 1992. A major revision based on work performed at the National Institute of Standards and Technology (NIST) resulted in the current edition, which was approved in 1997. The model evaluation process, according to ASTM E 1355, consists of the following four steps:

1. Define the scenarios for which the evaluation is to be conducted.
2. Validate the theoretical basis and assumptions used in the model.
3. Verify the mathematical and numerical robustness of the model.
4. Evaluate the model, i.e., quantify its uncertainty and accuracy.

The first step of the process consists of a description of the fire scenarios for which the evaluation is to be conducted. Sufficient documentation is necessary to determine whether the model is suitable for the intended use, i.e., the simulation of fire scenarios of interest. Model documentation prepared according to the guidelines in ASTM E 1472 contains all the elements needed for a proper evaluation.

The second step consists of a detailed review of the theoretical basis of the model, and an assessment of the correctness of the assumptions that are made and the approaches that are used. An independent expert who has not been associated with the development of the model should perform this task. In practice, often only the model developer has enough incentive to conduct such a tedious and time-consuming task.

A model is then verified by assessing its mathematical and numerical robustness. Verification can be performed by comparing model output to analytical solutions of simple problems for which such solutions exist (e.g., steady-state problems), by checking the computer source code for irregularities and inconsistencies, and/or by investigating the accuracy and convergence of the numerical solutions of the model equations.

Step four is usually based on a comparison between model output and experimental data, and provides an indirect method for validation (step two) and verification (step three) of a model for the scenarios of interest (described in step one). It is generally assumed that the model equations are solved correctly, and the terms validation and evaluation are therefore often used interchangeably. Experimental data for model evaluation can be obtained from standard fire tests, ad-hoc fire tests conducted as part of the model development and evaluation process, the literature, and/or experience.

Three types of uncertainties contribute toward the accuracy of fire models when quantified by comparing model predictions with experimental data. The input uncertainty is primarily due to the errors and assumptions for the input data. Sensitivity analyses are used to identify the critical input parameters, which must be specified with much greater care than the parameters to which the model is relatively insensitive. A sensitivity analysis of a com-

plex model might involve a very large number of runs to assess the effect of all input parameters individually and of possible interactions between different parameters. Special mathematical techniques can be used to drastically reduce the number of computer model runs without losing much information.[2] The model uncertainty is primarily due to the assumptions made by the model, and can be quantified as a result of the validation process (step two of the evaluation). Full-scale fire test data are subject to experimental uncertainty. Therefore, discrepancies between model predictions and experimental data might be, at least partly, due to measurement errors. There are procedures to determine the precision of standard test methods on the basis of interlaboratory trials or round robins (e.g., see ASTM E 691 or ISO 5725). Custom, nonstandard, full-scale fire experiments are usually not repeated for cost reasons. However, the uncertainty of custom test data is probably comparable to that of standard full-scale fire tests. Round robins of standard full-scale fire test methods have shown that the uncertainty of some measurements may be as high as ± 30 %.[3]

There are many problems in comparing the results from fire model simulations to data from full-scale fire experiments. Some of the problems are due to the differences between the form of the recorded experimental data and the form needed for comparison with model predictions. For example, contrary to the assumption of pre-flashover compartment fire zone models, there often is not a clear and sharp change distinguishing the lower and upper gas layers.[4] Quantifying the agreement between a calculated and measured curve of variable expressed as a function of time also presents a major challenge. Researchers at NIST have made some recommendations, but more work is needed to address this problem.[5]

Documenting Computer Fire Models

ASTM E 1472 was first published in 1992, and reapproved in 1998. This guide requires that computer fire models be documented with a technical reference, a user's manual, and a programmer's guide. The technical documentation describes the theoretical and mathematical foundations of the model. The user's manual provides instructions for installing and operating the software. Sample runs should be included to allow the user to verify correct operation of the program. The programmer's guide includes the source code and instructions for users who want to customize the program. Model documentation prepared according to ASTM E 1472 contains all the elements that are needed for an evaluation according to ASTM E 1355.

Data for Computer Fire Models

Computer fire models typically require physical, chemical, and flammability properties of materials involved in the fire. ASTM E 1591 describes procedures to measure many of these properties, and includes numerous references to the open literature where property values can be found. ASTM E 1591 was first approved in 1994, and was slightly revised in 2000. A major revision is in progress to extend the scope to CFD codes and other types of computer fire models.

Use and Limitations of Computer Fire Models

ASTM E 1895 was approved and published in 1997. Several surveys have been published and should be consulted to determine which models are available.[6, 7, 8] ASTM E 1895 provides guidance to model users on uses and limitations of computer fire models, and thus facilitates the selection of the model that is most suitable for a particular task. The document also provides guidance to model developers and to authorities having jurisdiction that review designs based on model calculations.

APPLICATIONS OF THE ASTM GUIDES

NIST Models

NIST has been at the forefront of computer fire model development for more than two decades. Many different fire models can presently be downloaded freely from the NIST BFRL Web site (http://www.fire.nist.gov).

Although NIST has not formally applied the ASTM guides to any of its models, the contents of the ASTM guides are largely based on the pioneering work done by NIST. For example, the documentation for the CFAST and FDS models covers most, if not all, of the elements that are described in ASTM E 1472.[9, 10] Several extensive studies have been performed to evaluate the predictive capability of CFAST and its predecessors.[11]

FIRM

In 2000, the author of this article published the second edition of an introductory text on mathematical fire modeling.[12] The book describes the development of a zone fire model that predicts the consequences of a user-specified fire in a single compartment. The model is an extension of ASET developed by Cooper at NIST. It includes algorithms to determine flows through a ventilation opening in one of the vertical walls. The model is referred to as FIRM (Fire Investigation and Reconstruction Model). The revision presented a unique opportunity to use the ASTM guides. This book is the first formal application of the ASTM guides to a fire model.[13]

SFPE Task Group on Model Evaluation

In June of 1995, SFPE formed a Task Group to evaluate the scope, applications, and limitations of computer fire models. The approach used by the SFPE Task Group is largely based on the ASTM guides, in particular E 1355. The DETACT-QS model was selected as a test case. DETACT-QS is a model for predicting the response of detectors and sprinklers to a user specified fire. Despite its simplicity, it took five years to complete a draft and initiate a ballot. Efforts are currently under way to add more comparative data and to enhance or clarify some of the documentation. This illustrates how difficult and time-consuming it is to properly evaluate the predictive capability of a fire model. The SFPE Task Group is currently also evaluating the ASET model.

RECOMMENDATIONS

Over the past decade, ASTM published a series of standard guides that

facilitate the assessment of computer fire model uncertainties. So far, the application of these guides has been very limited. Model users in the fire protection engineering community are encouraged to apply the guides and share their experience with the SFPE Fire Model Evaluation Task Group and the ASTM E05.33 Subcommittee. This feedback is essential to improve the guides and increase the acceptance of computer fire modeling.

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**The SFPE Task Group and ASTM E05.33 Subcommittee are chaired by Mr. Dan Madrzykowski of NIST (daniel.madrzykowski@nist.gov) and Dr. Ron Alpert of FM Global (ronald.alpert@fmglobal.com), respectively.*

UNIT 4:
THE PROCESS METHOD

TERMINAL OBJECTIVE

Given specific life-safety criteria and non-life-safety criteria requirements, the students will be able to determine whether a performance-based building design submitted for approval would meet the safety criteria.

ENABLING OBJECTIVE

Given the Society of Fire Protection Engineers (SFPE) flowchart, the students will identify the blocks that outline the responsibilities of those who review and approve building and facility designs.

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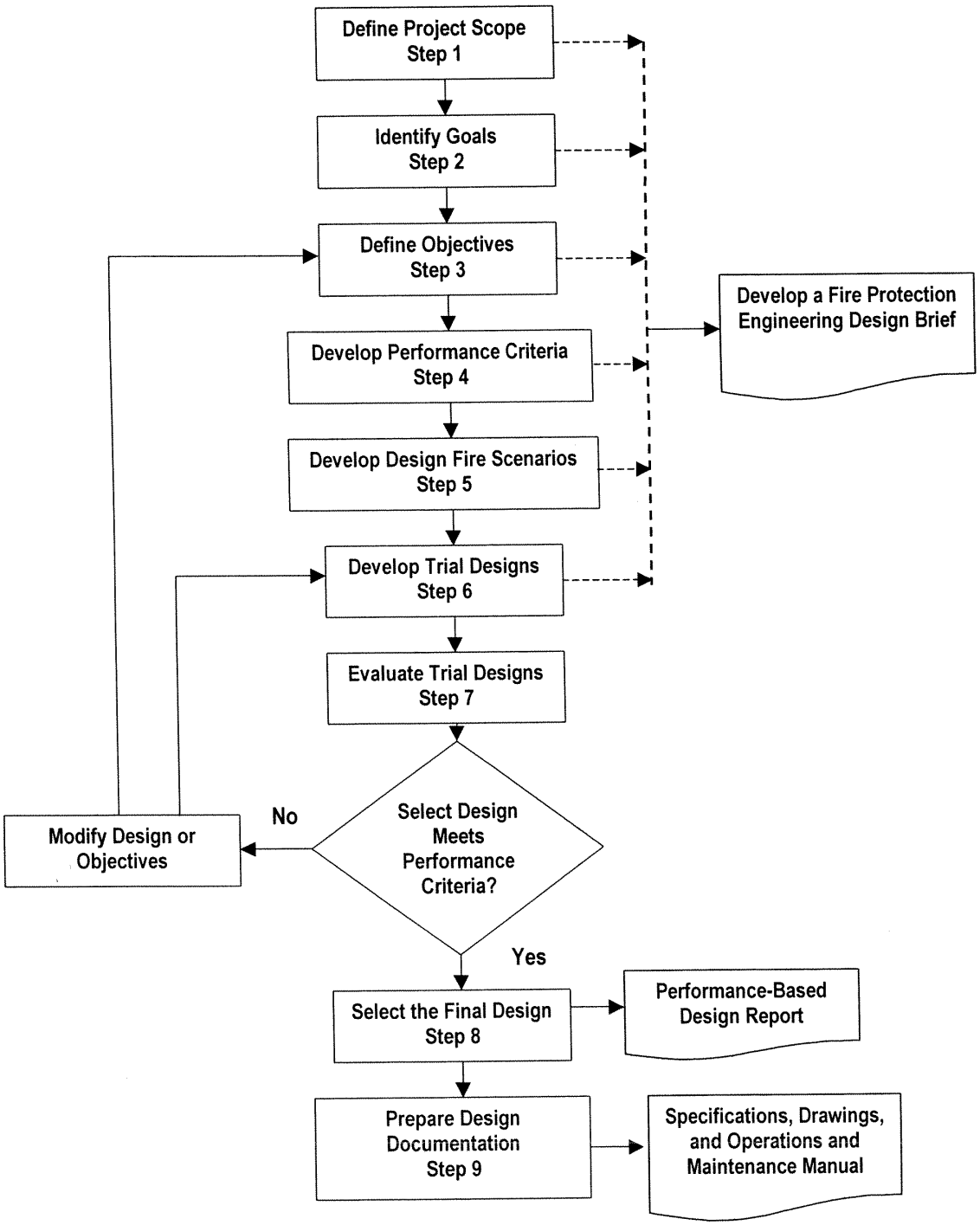

Figure 4.1
The Process Method

DEFINE THE PROJECT SCOPE

The first step in the process method for a performance-based design is clearly defining the scope of the project. Project scope is defined as an identification of the range or extent of the design matter being addressed, including any specific limits of a performance-based design. The project might be a subset of a larger development, evaluation, or design effort (e.g., one part of the building design process), or it might be a stand-alone fire safety analysis and design project. The process may be applied to new construction, renovations, change of occupancy, or repairs.

Stakeholders

The process method is best applied when it is begun during the feasibility or conceptual design stages. All stakeholders should participate in this process. Stakeholders, by definition, are anyone who has a share or interest in the particular enterprise, or a specific interest in the successful completion of a project. Reasons for the interest can be financial or safety related. Stakeholders can include

- building owner;
- building manager;
- design team;
- Authority Having Jurisdiction (AHJ) (fire, building, insurance);
- accreditation agencies;
- general contractor;
- construction manager;
- subcontractors;
- tenants;
- building operations and maintenance; and
- emergency service responders.

Designers are responsible for the project scope.

Other Factors in Defining the Scope

In scoping the project, designers should identify such factors as:

- property location, site conditions, and type and location of adjacent properties;
- fire service characteristics: location, expected response times, operating procedures, and capabilities of the responding fire department and other applicable emergency services;
- building occupant characteristics: number of occupants, their ages, mental and physical characteristics;
- intended use and occupancy of the building;
- occupancy classification;
- construction features desired by owners or tenants;
- utilities: location and capacity of site utilities, such as drainage, fuel, water, electricity;

- environmental considerations: land use planning, effluent production, wetlands, zoning classifications, and pollution considerations;
- historic preservation: requirements of local, State, or Federal laws and regulations;
- building management and security: details of management and security programs and systems;
- economic and social value of the building: tax base considerations, employment considerations, historic, public assembly or religious significance;
- continuity of service: how long a period of time the building or part thereof can be unavailable or out of service;
- the project delivery process: architect or engineering lead projects, design build, fast track, etc.;
- applicable regulations, codes, and insurance requirements; and
- budgetary parameters.

DEFINE FIRE SAFETY GOALS

Once the full scope of the project has been determined, fire safety goals can be established. Fire safety goals are the desired overall fire safety outcomes, expressed in qualitative terms. These goals may relate to:

- providing life safety for the public, building occupants, and emergency responders;
- protecting property, including cultural resources; protect the building, its contents, and historical features; and provide for the safety of adjoining properties;
- providing for continuity of operations to protect and minimize danger to occupants' ongoing mission, production, or operating capacity; and
- mitigating environmental impacts to water, soil, and air.

DEFINE FIRE SAFETY OBJECTIVES

The third step in the process method is the defining of the stakeholder and design objectives. Objectives are the safety requirements of fire, building, system, or occupants that need to be fulfilled in order to achieve a specific fire safety goal. Objectives are stated in more detail than goals, and in general they define a series of actions that make the achievement of a goal more likely. The objectives are essentially the design goals, further refined into values that can be quantified in engineering terms.

Objectives can define acceptable or tolerable levels of risk in terms of:

- dollar loss;
- loss of life;
- serious injury;
- downtime;
- extent of fire damage; and

- extent of smoke damage.

DEFINE PERFORMANCE CRITERIA

Once the stakeholder and design objectives have been established, performance criteria can be developed. Performance criteria are stated in engineering terms that will be used later in the process to evaluate the adequacy of any trial designs. Performance criteria further refine the design objectives and generally are expressed in numerical values.

Examples of Performance Criteria

Performance criteria can define

- threshold values for temperatures of materials;
- gas temperatures;
- carbon monoxide (CO) level;
- toxicity levels;
- extent of fire spread;
- smoke obscuration;
- smoke layer heights;
- thermal exposure levels;
- damage to property;
- damage to the environment; and
- behavior of occupants.

DEVELOP DESIGN FIRE SCENARIOS

The next step in the performance-based design process is the development of fire scenarios. A fire scenario is a set of conditions that define the development of a fire, the spread of combustion products throughout a building or part of a building, the reactions of people to a fire, and the effects of combustion products.

Scenarios are simply descriptions of possible fire events that might occur in a specific building. They incorporate fire characteristics, building characteristics, and occupant characteristics. The scenarios must consider all potential and typical fuel packages and ignition sources in the building. The scenarios will be refined further into design fire scenarios later in the process. For each fire scenario, information developed includes the following building, occupant, and fire characteristics:

Building Characteristics

- architectural features;

- structural components;
- fire protection systems;
- building services/process;
- operational characteristics;
- fire department response; and
- environmental factors.

Occupant Characteristics

- number of occupants;
- distribution of occupants in the building;
- alertness of occupants;
- commitment to ongoing activities;
- physical and mental capabilities;
- roles;
- familiarity with the building;
- social affiliation; and
- physical and physiological conditions.

Fire Characteristics

- ignition sources;
- fire growth;
- flashover;
- full development; and
- suppression/extinguishments.

Design Fire Scenarios

In the next step in the process, the fire scenarios are used to develop design fire scenarios. The design fire scenarios are those scenarios that are most likely to occur in the specific building. Design fire scenarios are used to evaluate the proposed design. They define or describe the critical factors for determining the outcomes of a trial design that is intended to achieve the stated fire safety goals.

The design fire scenarios must include the worst-case scenario and worst credible fire. The worst-case scenario is the one that will result in the worst consequence, as defined by the stakeholders or the code. The criteria must be explicitly stated, because worst conditions for life safety and property protection may be in conflict with each other. The worst credible fire is the one that reasonably can be expected to result in unfavorable consequences equal to, or less severe than, those resulting from the worst-case scenario.

DEVELOP TRIAL DESIGNS

Once the design fire scenarios have been properly identified and defined, they can be used to evaluate the trial designs. Trial designs are the designs that are intended to achieve the stated fire safety goals. Trial designs include the proposed fire protection systems, construction features, and operations that are necessary for a design to meet the performance criteria. The evaluation method for each of the trial designs also should be developed at this point in the process. The actual evaluation will be discussed in more detail later in this Unit.

Content of Trial Designs

The trial designs will detail how the overall design will

- manage the design fire scenarios by controlling combustion process, fuel and environment;
- suppress the design fire scenarios by detection and automatic manual suppression methods; and
- control the design fire scenarios by construction materials or methods that will vent or contain the fire.

THE ENGINEERING DESIGN BRIEF

Once the process method has reached the point of the development of the trial designs, the Fire Protection Engineering Design Brief is prepared.

While the document may not carry this title in all projects, the report summarizes the agreed-upon performance criteria and methods that will be used to evaluate trial designs.

Contents of the Design Brief

The Design Brief includes the following:

- definition of project scope;
- description of the building and occupant characteristics;
- the project goals;
- the project objectives;
- the performance criteria;
- the selected fire scenarios (fire scenarios and design fire scenarios);
- one or more trial designs;
- the levels and methods of evaluation; and
- a record of agreement by all stakeholders on the all of the above.

The design brief also should include a documentation of all project participants, documentation of the designers' qualifications, and general project information.

EVALUATE TRIAL DESIGNS

After the completion and submission of the Fire Protection Engineering Design Brief, the process moves into the next phases, which are the evaluation of the trial designs and the selection of the final design. The final design is the one that is selected from the various successful trial designs and chosen for implementation.

Each trial design is evaluated using each design fire scenario. This evaluation process will determine whether the trial design will meet the performance criteria. Only those trial design(s) that are shown to meet the performance criteria can be considered in the final design phase.

Changes to Performance Criteria

During the evaluation phase, it is possible for the performance criteria to be altered. However, it is not acceptable to change the acceptance criteria arbitrarily to ensure that a trial design is acceptable. Any changes to the performance criteria must be based on additional analysis and consideration of additional data.

Evaluation Criteria

Evaluation criteria will fall into the following areas:

Effectiveness

Does the trial design meet the established performance criteria? Does it provide for the safety of occupants and property?

Reliability

Does the design or system function as designed?

Availability

Is the design or system capable of performing the required function at a given point in time?

Cost

Is the cost of the trial design installation and life cycle in keeping with what the client is willing to expend?

Timelines for Key Fire Events

In evaluating trial designs, several timelines or fire events can be used. These can include

- ignition;
- suppression;
- detection;
- notification of occupants;
- notification of emergency forces;
- evacuation (beginning and ending);
- emergency response begins;
- untenable conditions in compartment of origin;
- window failure;
- heat release rate;
- flashover;
- spread beyond compartment of origin;
- arrival of emergency responders;
- manual suppression;
- failure of structural elements; and
- extinguishment.

The evaluation of each trial design also may incorporate the deterministic or probabilistic analysis methods that were discussed in detail in Unit 3 of this course.

Accounting for Uncertainty

During the evaluation process, the stakeholders need to ensure that uncertainty is accounted for in all trial designs. Uncertainty is the amount by which an observed or calculated value might differ from the true value. To determine to what the degree a predicted value might vary, an analysis is performed.

The uncertainty analysis is necessary, since there are always uncertainties about science and engineering, human behaviors, risk perceptions, attitudes, and values.

A sensitivity analysis also must be included in the evaluation process. This analysis is performed to determine the degree to which a predicted output will vary, given a specified change in an input parameter.

Evaluation of the Final Design

The final design must be verified, that is, there must be confirmation that the selected final design meets the established performance criteria. This verification may involve the use of the various fire modeling programs, or actual fire tests.

Using Computer Models

Evaluation of the trial designs often is undertaken by the use of the various computer models described in Unit 3: Introduction to Fire Effects and Egress Models. Using the fire models to evaluate the trial designs provides a structured approach to predicting one or more effects of the design fire scenario and determining whether or not the design meets the performance criteria.

Using Fire Tests

A trial design also can be evaluated using actual fire tests. Such an evaluation method can be used only when the "test" fire scenario accurately represents the design fire scenario. Such testing can provide output data that can be compared to the performance criteria.

While actual fire tests are possible, there are drawbacks. It may not always be possible or practical to conduct full-scale testing. Additionally, it is not possible to test human behavior factors. However, in some instances small-scale testing may be conducted to determine the actuation of detection and/or suppression systems, or to test the flammability and/or toxicity of materials.

SELECT THE FINAL DESIGN

Once all of the trial designs have been evaluated with each of the design fire scenarios, the final design can be selected.

The selection of the final design is based upon a variety of factors:

- meeting the performance criteria;
- financial consideration;
- timeliness of installation;
- system and material availability;
- ease of installation; and
- maintenance.

PREPARE DESIGN DOCUMENTATION

Once the final design has been identified, the design documentation must be prepared. This documentation will help ensure that all of the stakeholders understand what is necessary for the design implementation, maintenance, and continuity of the fire protection design.

Final Design Documentation Submission

The final design documentation submitted for AHJ review should include

- Fire Protection Engineering Design Brief;
- Performance Design Report;
- Detailed specifications and drawings; and
- Building Operations and Maintenance (O&M) manual.

The design documents that should be presented for AHJ review are discussed in more detail in Unit 5: Documentation, and the Operations and Maintenance Manual is discussed in more detail in Unit 6: Testing, Inspection, and Maintenance.

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Activity 4.1

Defining the Project Scope

Purpose

To define the scope of a performance-based building design.

Directions

1. You will form four groups.

2. Read paragraphs 1 and 2 on pages 33 and 34 of the O'Hara and Bierwerth article, located in the Unit 1 Appendix.

3. You will have 15 minutes to work in your groups.

4. Select a spokesperson from your group to present the group's responses.

    a. Group 1 will list in the space provided the most important building characteristics of the Arena.

    b. Group 2 will list in the space provided the stakeholders identified in the article.

    c. Group 3 will list in the space provided the applicable codes and regulations mentioned in the article and the fire safe design aspects that each addresses.

    d. Group 4 will list in the space provided the intended uses of the building and the types of occupants each use would be likely to involve.

5. At the end of 15 minutes, the spokesperson for your group will read the group's answers.

Group #_____

Responses:

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Activity 4.2

Defining Stakeholders' Goals

Purpose

To identify the wide variety of stakeholder goals that may exist in a project.

Directions

1. Take 15 minutes to work as a group and role play the following exercise.

2. You will be assigned the role of a stakeholder in a proposed project. Others at your table will be stakeholders who may have "competing" goals.

3. Your table group will be assigned one of the projects listed below. Based on the assigned type of project, each of you must identify at least one goal representative of your role, and be prepared to defend it.

4. List your goals on an easel pad.

5. Be prepared to share your responses with the class for discussion.

Stakeholders	Suggested Projects
Project owner Design professional Fire code official Building official Business owner Emergency responder Community advocate	Homeless family shelter in former department store. Warehouse/Shipping operation with shrink-wrap equipment. Office building with restaurants on alternating floors. Abandoned textile mill converted to artists' studios. Covered shopping mall converted to private high school. Brewery/Bottling plant with regional distribution facility. Hospital with new neo-natal intensive care wing. Auto sales dealership with body shop and tanning beds. Denatured alcohol distilling and bulk storage facility. Fire extinguisher manufacturing plant.

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Activity 4.3

Identifying Fire Scenarios

Purpose

To identify fire scenarios.

Directions

1. Go to the article by O'Hara and Bierwerth.

2. Write in the space provided below the design fire scenarios and the sizes of the design fires the designers used to test each scenario described in the article.

3. Be prepared to share your answers with the class.

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Activity 4.4

Defining Fire Scenarios

Purpose

To define fire scenarios.

Directions

1. Take 30 minutes to work as a group and brainstorm the following exercise.

2. Each table will be assigned a sample project. You are to review the project description with your group, and suggest at least four fire scenarios for it.

3. Select a spokesperson and share your responses with the class for discussion.

Project 1

Highrise hotel. The hotel is a 50-story fire-resistive building with an atrium from Floor 8 through Floor 50. The building is fully sprinklered, and the atrium and adjacent spaces are provided with a smoke management system. The atrium has four glass-enclosed elevators.

Floor 8, the lowest level of the atrium, includes an Olympic-sized swimming pool surrounded by a lounging deck. There is a combination walk-up/swim-up bar at the edge of the pool. The deck is large enough to accommodate about 850 people for receptions, and there are several cabañas that serve as rest rooms and changing stations.

Floor 7 is a full-scale restaurant with seating for about 1,000 persons. It is glass enclosed on all sides. The kitchen and pantry facilities are located on Floor 6. There are two service elevators that run from the lowest subbasement to the restaurant to provide support functions and transport foodstuffs. There are 10 open stairways between Floors 6 and 7 to accommodate the wait staff.

The hotel also has a three-level subbasement for parking, one of which is large enough to accommodate tour buses and recreational vehicles. One side of the subbasement is open to the atmosphere.

Floors 3 through 5 consist of a mixture of small, exclusive meeting rooms and suites, plus a three-story tall, 12,000-square-foot multipurpose room for trade shows and related displays. Floors 1 and 2 include guest registration, guest services, and hotel administration.

Fire protection equipment all is designed and installed in accordance with appropriate National Fire Protection Association (NFPA) codes and standards.

Project 2

Automobile manufacturing plant. The plant is intended to be state-of-the-art in the robotic production of small, hybrid gas-electric commuter vehicles. Raw materials will be delivered at one end of the plant, and finished automobiles will roll off the assembly line at the other end.

Raw materials include

- metals, consisting of steel, aluminum, magnesium, titanium, and lead;
- natural products including wood, sisal, leather, and rubber; and
- synthetic materials including rigid and foamed plastics, silicones, and phenolics.

Research and production chemicals include flammable and combustible liquids, plus a variety of hazardous materials. Already identified are gasoline, battery acid, paint, acetone, sulfuric acid, asphalt, hydrochloric acid, silane, and diesel. The owner does not anticipate the addition of any more bulk chemicals.

Occupancies in the building include administrative space, an infirmary, lunch room with commercial-scale food preparation, daycare for employee's children and parents, training rooms, rest rooms with shower facilities, physical education center, battery production and charging room, and automobile production.

The building will be entirely noncombustible: it will have tilt-up concrete exterior walls with panels ranging from 12 to 50 feet tall, an open-web steel truss roof structure and rigid metal pan roof deck covered with bituminous felt paper and gravel. Exposed steel columns throughout the building support the roof structure. Nonproduction spaces are separated from the remainder of the structure by rated assemblies made of noncombustible framing and gypsum wallboard. The production area in this 2-million-square-foot building is open from one end to the other.

Fire protection consists of wet pipe sprinklers, standpipes for occupant use and portable and wheeled fire extinguishers distributed throughout the facility. Fire protection equipment all is designed and installed in accordance with appropriate NFPA codes and standards.

As raw materials are brought into the plant, they will be converted to automobile parts. Steel and other metals will be formed into frames and parts of the automobile bodies. After fabrication, this part of the assembly is routed via conveyor belt to a 10,000-gallon dip tank where asphaltic-based undercoating materials are applied.

Sheets of rigid plastic are heated to form the remaining portions of the exterior bodies, and are stored on racks 42 feet high until they are moved to the production line. Interior components are assembled and moved via conveyor to the "merging area" where the frame, interior, and exterior bodies are attached to one another.

The engines are assembled and inserted in their mounts in the next stage of the process. High efficiency lead-acid batteries are installed in compartments formed into the automobile bodies.

When completed, the vehicles are run through a high-capacity, automated spray operation where a clear plastic finish coat is applied. The finish coat is a flammable liquid. The cars then are taken to a drying room where natural-gas-fired heaters are used to dry the finish coat.

In the final step before loading the vehicles onto trucks for delivery, the cars are "shrink-wrapped" in a thin polymer film to protect their exterior finish.

Project 3

High school. Your community's existing three-story, masonry high school is overcrowded. Your population has boomed, and the school system is unable to keep up with the growth. A study group has determined that to acquire land, develop, and build a new high school would take more than 3 years to complete.

A nationally known architect proposes a solution to the overcrowding problem that is overwhelmingly embraced by the community: add two stories of wood-frame brick veneer construction on top of the existing three-story building. An engineering analysis of the existing structure shows it is capable of supporting the new loads, so design and construction plans are underway.

The existing building was built in 1929. It is about 72,000 square feet per floor of reinforced masonry construction. One end of the building has an old boiler room in a partial basement where a coal-fired furnace was installed. The coal-fired system will be abandoned and replaced with a high-efficiency oil-fired boiler system.

Your survey of the building reveals it has open stairways between and among all floors except the basement, which is accessed only from the outdoors. The floor surfaces on each level are wood that has been varnished innumerable times since 1929. The stairs are calculated to accommodate the existing occupant capacity of the building.

While walking the building, you discover classroom doors are wood panel with plate glass in the upper half. There are operable glass transoms above every door to provide classroom ventilation.

Fire protection equipment consists of a 120-volt manual fire alarm system, some water-type portable fire extinguishers, and several abandoned hose stations for occupant use.

Since your community prides itself on historic preservation, each of these existing design elements likely will remain after the construction, and the new work may include them as well.

The existing building includes classrooms, a chemistry lab and storeroom, a library, administrative offices, nurse's office, and cafeteria/lunchroom. The gymnasium and student theater are connected to the main building by a fully enclosed walkway.

The design proposal calls for creating classrooms on the fourth floor, and using the entire fifth floor as a combination computer lab and library. The first-floor library will be converted to classrooms.

Project 4

Hospital. Due to the rapidly aging population in your area, the local hospital has been growing regularly for the past 10 years. Remodels and expansions have been regular occurrences: so regular, in fact, you can't even identify the original building in the construction.

Now, the hospital has received a Federal and State grant to expand some more. They intend to create a regional trauma and cardiac care center, plus add a wing for long-term care of the cognitively impaired.

You have been exceedingly diligent in your plan review and inspection of the existing 1.5 million square foot medical campus. The building is entirely fire-resistive construction, and all portions of the structure are fully protected by automatic sprinklers. The new work will employ these life safety features.

The new work will be added as a connection to the existing hospital. A unique design feature will be the construction of a two-story, glass-roof interior courtyard between the hospital and the cognitively impaired wing. Designed to give the appearance of an outdoor garden, the courtyard will give Alzheimer's patients a secure, pleasant environment in which to walk. Each patient will have a private room with direct door access to the courtyard, and direct door access to a corridor system surrounding the wing.

The cardiac care center will house three operating suites for emergency and planned cardiac intervention strategies. It will have its own intensive care recovery area, laundry and dietitian services, and support services including an equipment sterilization room that employs ethylene oxide and an autoclave. The cardiac care center will be connected to the new regional trauma center by a wide corridor. The corridor will have patient and family waiting rooms along either side.

The Level One regional trauma center is the "jewel in the crown" of the expansion. It will include a 24-bed emergency treatment center, a hyperbaric chamber, and a modern burn treatment facility. The one-story wing will have a large roof surface for landing helicopters ranging in size from Bell JetRangers to large military-support rotary wing aircraft. There will be an elevator from the trauma center to the roof to expedite patient transport.

There is a 64,000-cubic-foot refrigerated liquid oxygen (LOX) tank located near the east wall of the trauma center, within a three-sided, two-hour enclosure to reduce the setback distance to 18 feet. It has an indoor vaporizer/humidifier that coverts the LOX to gaseous oxygen for distribution throughout the trauma center's medical gas piping network.

APPENDIX

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Job Aid 4.1

AHJ Checklist for Initial Discussion of a Performance-Based Design

1	What is the scope of the project (One new building? More than one building? Building renovation?) What is the advantage of using a performance-based over a prescriptive-based approach?
2	What are the special architectural features of the building?
3	What type of construction will be used?
4	What fire safety codes may be applicable?
5	What fire protection systems will be employed?
6	Is the building suited to a performance-based design?
7	Where will the building be located?
8	Does the location present any obvious problems?
9	Who are the stakeholders? Are design professionals identified?
10	Are any of the stakeholders known to the AHJ from other projects? What experience in performance-based design does the team bring?
11	What are likely to be the priority goals of each stakeholder?
12	How will the proposed building or structure be used?
13	Who are the anticipated occupants of the building?
14	What is the timeframe for completion?
15	What has been the AHJ's experience with similar projects?
16	What fire safety problems can be anticipated, based on items 1 to 15?

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Job Aid 4.2

Template for Collecting Data on Stakeholders

AHJs can use this template to keep a current list of the stakeholders, updating their list as stakeholders change throughout the project life.

Organization Name:
Address:
Point of Contact:
Telephone and Fax:
Email:
Project Role (check):

- Building owner
- Building manager
- Design engineer
- Construction manager
- General contractor
- Subcontractor
- Tenant
- Building operator/maintenance
- Insurance AHJ
- Other

What are this stakeholder's goals related to:

- Safety of the public
- Safety of property
- Continuation of operations
- Mitigation of environmental impacts

How are the stakeholder goals translated into measurable safety objectives related to:

- Life safety
- "Not to exceed" threshold property loss
- Days of shutdown tolerated
- Spread of fire
- Ignition temperatures of materials used

Notes:

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Job Aid 4.3

Stakeholder Groups' Functions and Contributions to the Design Process*

Functional Group	Who They Are	Contributions
Stakeholders involved with building design and approval.	• architects • design engineers • building owners • AHJ's	Focus discussions. Establish scope, goals and objectives. Develop common language. Develop checklists of items to consider.
Stakeholders involved with building construction and supply.	• construction companies • equipment suppliers • manufacturers	Challenge builders and suppliers to think about societal issues such as equity and life-cycle performance.
Stakeholders who provide scientific data, statistical data, and tools.	• researchers • model developers • insurance industry • fire service	Quantify scientific uncertainties in the tools. Begin to think about incorporating uncertainty in tools.
Stakeholders who share the building risk.	• building occupants • the public • building owners • fire service • insurance industry • design engineers	Develop common language to discuss acceptable risk.

** Adapted from Notarianni, 2000. The Role of Uncertainty in Improving Fire Protection Regulation, p.p. 5 and 11.*

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UNIT 5: DOCUMENTATION

TERMINAL OBJECTIVE

Given an example of a performance-based design report, the students will be able to determine whether the documentation submitted is adequate, according to Chapter 12 of the Society of Fire Protection Engineers (SFPE) Guide *and this Unit.*

ENABLING OBJECTIVES

The students will:

1. *Identify the documentation that is required as part of an acceptable performance-based design submission.*

2. *In small groups, critique a set of documents for a performance-based building design to determine whether the documents include all items that are required.*

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DOCUMENTATION

While recordkeeping or documentation is an important component of any building design and code enforcement system, it is a critical element of performance-based codes and designs. Proper documentation assures that all stakeholders are knowledgeable about what is required for design implementation, testing, maintenance, and continuity of life safety and fire protection. This documentation also will help avoid any disputes during the review and approval process, construction, startup, and continual use of the building.

Results of Poor Documentation

If proper documentation is not developed and maintained, it could result in the rejection by the Authority Having Jurisdiction (AHJ) of an otherwise good design. Lack of adequate documentation also can result in improper and poor implementation of an approved design. Proper maintenance and continued reliability of the design are also dependent upon proper documentation being prepared and maintained. If the original design is not properly documented, it can make any future changes or modifications much more difficult and time consuming.

Documents Required For Authority Having Jurisdiction Review

Proper documentation must include the following information as a minimum. The actual contents of each of these items will be discussed in more detail as this unit progresses.

- Fire Protection Engineering Design Brief;
- Performance-Based Design Report;
- Specifications and drawings; and
- Operations and Maintenance (O&M) Manual.

THE FIRE PROTECTION ENGINEERING DESIGN BRIEF

The purpose of the Fire Protection Engineering Design Brief is to permit all stakeholders to review the complete the architectural and structural design, identify any potential fire hazards, define fire safety concerns in qualitative terms, identify any assumptions about who or what is being protected, and any other factors that are likely to have an impact on the performance-based design.

This document is developed best through a collaborative effort of all stakeholders, but can be developed by the project engineers and presented to other stakeholders for input and approval. The design brief ensures that the designs and evaluation methods are acceptable to all stakeholders. It also documents all agreed-upon goals and objectives and establishes a statement of understanding among all stakeholders. The Fire Protection Engineering Design Brief

generally provides the basis for the initial portions of the actual Performance-Based Design Report.

Finally, while the document (Fire Protection Engineering Design Brief) may not carry this title in all projects, the report summarizes the agreed-upon performance criteria and methods that will be used to evaluate trial designs.

Contents of the Design Brief

The design brief includes the following:

- definition of project scope;
- description of the building and occupant characteristics;
- the project goals;
- the project objectives;
- the performance criteria;
- the selected fire scenarios (fire scenarios and design fire scenarios);
- one or more trial designs and assumptions;
- the levels and methods of evaluation; and
- a record of agreement on all of the above.

The design brief also should include documentation of all project participants, documentation of the designers' qualifications, general project information, and any trademark or confidentiality agreements.

THE PERFORMANCE-BASED DESIGN REPORT

The Performance-Based Design Report also is a very important document. Because many stakeholders and others may review this report, it should be not only clear and unambiguous, but prepared for a general audience. Many of the individuals who will review the report may have only limited fire protection training. It is important that the report paint a clear picture of all of the expected hazards and risks as well as the anticipated performance of all systems during the entire life cycle of the building.

Contents of the Performance-Based Design Report

The report should contain the following items and information.

- Project scope: Definition of the project scale, including building or facility, operational, and occupant characteristics.

- Project goals and objectives: All fire safety goals and objectives that have been agreed upon by the stakeholders. Information as to how these goals and objectives were developed should be included also.

- Performance criteria: Details about how the specific performance criteria were developed, and any uncertainty or safety factors.

- Fire scenarios and design fire scenarios: Discussion of each fire scenario that was considered, the identification of the design fire scenarios, and the methods used to select them. Also includes information about the specific conditions under which these fire scenarios would be valid.

- Final design: Description of the final design, which has been selected from all of the alternatives (trial designs), as well as a discussion of how the design will meet the performance criteria.

- Evaluation: Thorough discussion of the evaluation process, including a description of all evaluation tools/methods, design tools used, and the establishment of any uncertainty and safety factors. This also should include a description of any trial designs not selected and the reasons why they were found unacceptable.

- Critical design assumptions: Includes all assumptions that must be present and maintained for the entire life cycle of the building.

- Critical design features: All design parameters that must be maintained throughout the entire life cycle of the building.

- Building codes followed, both prescriptive and performance. Fire, mechanical, plumbing, and electrical codes also should be identified by name and edition, including any local amendments.

- References: References used to support any of the design work should be included, especially those that are hard to obtain or are proprietary.

- Qualifications of engineers: Professional credentials and prior relevant experience.

- General documentation of decisions: Letters, meeting minutes, telephone logs, memoranda of understanding, etc.

- Trademark and confidentiality agreements.

SPECIFICATIONS AND DRAWINGS

The purpose of the Specifications and Drawings is to show the building and system designers and contractors how to implement the various elements of the performance-based design. Given

the unique nature of a performance-based design, the use of the standard or "master" specifications will not be acceptable. Likewise, simple references to "code" compliance, whether prescriptive- or performance-based are inadequate and unacceptable because of vagueness.

Contents of the Specifications and Drawings

The specifications and drawings will include information such as:

- sprinkler densities and coverage areas;
- bounding conditions;
- components, performance, and programming of fire alarm and detection systems;
- details of egress, fire-resistive walls and structural elements, compartmentalization;
- minimum acceptance criteria for fire protection systems;
- special hazard system, e.g., commercial cooking, spray finishing, dip tanks;
- smoke control/management systems;
- commissioning procedures and requirements for all fire protection systems and a review of their installation;
- all assumptions regarding occupants (age, mobility, familiarity with building, etc.);
- details regarding tenant spaces--size, use, contents, storage arrays, etc; and
- building construction details.

DETAILED DRAWINGS

The detailed drawings graphically represent the final results of the performance-based design and are a visual record of the final design and installation. Detailed drawings can be of several types, for example:

- civil
- architectural
- engineering
- electrical
- mechanical
- plumbing
- landscaping

Contents of the Detailed Drawings

These drawings will include

- furnishings;
- storage arrays;
- details of egress system, e.g., exit widths;

- details of all passive fire protection systems;
- design of all fire protection systems; and
- location of fire protection equipment/devices.

The AHJ should be satisfied that the detailed drawings clearly represent the agreed-upon design and bounding conditions, because these may serve as part of the permanent records for the project.

THE AUTHORITY HAVING JURISDICTION REVIEW

The AHJ is required to conduct a "knowledgeable review" of all of the design criteria. This may be a challenge for someone with little or no experience in the evaluation of performance-based designs.

In those circumstances, the AHJ may choose to retain "third party" plan review and inspection services. Costs for these services must be covered by the project proponent.

Methods of Authority Having Jurisdiction Review

This AHJ review can be accomplished by one or more of the following approaches.

- A fire protection engineer or qualified person on the AHJ staff or within the overall organization to review the fire protection proposals or to consult on the building design, such as the building department plans examiner or the fire department plans examiner.

- A fire protection engineer or qualified person whose services are shared by multiple jurisdictions.

- A "third party" fire protection engineer or otherwise qualified person or firm retained by the AHJ to conduct a peer review of the design and assist the AHJ through the entire performance-based design process.

Sources of Third Party Reviewers

The following are sources of third party reviewers:

- State, local government, or Federal experts;
- local colleges;
- consulting engineers; and
- codes and standards organizations.

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Activity 5.1

Review of Performance-Based Design Documents

Purpose

To practice reviewing documentation.

Directions

1. You will be divided into four groups, and each group will receive copies of three design documents for a performance-based building design.

2. The list of items to locate in the documents is on the following worksheet.

3. In the space beside each item on the list, provide the specific answer to the question. You may divide the documents and lists among your group members, but the group must agree on the answers.

4. Circle the items on your list that your group cannot locate.

5. Select a spokesperson to read your group's answers.

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Activity 5.1 (cont'd)

Worksheet

Design Concept Study, December 1998

1. What is the proposed construction type? _____

2. How will the proposed tenant separation walls be constructed? _____

3. What is the proposed sprinkler density for roof level sprinklers? _____

4. How many fire alarm systems are proposed? _____

5. Will the fire alarm signal be transmitted to a central station? _____

6. Where will spot smoke detectors be installed? _____

7. What controls or devices will be located in the fire control center? _____

8. Is a fire alarm system matrix provided? _____

9. What is the proposed interior finish for the "Main Street" walls and ceilings? _____

10. What type of smoke control is proposed for the "Main Street" areas? _____

Design Concept Study Supplemental Information, March 1999

1. What is the design fire size being proposed for the tenant areas? _____

2. What is the average roof deck height for the individual tenant spaces? _____

3. How many anticipated configurations are expected with respect to the demising wall and ceilings for the tenant spaces? _____

4. For the smoke control simulations, what is the total square footage of the space used in the zone model? _____

5. Will sprinkler activation be considered during the model evaluations? _____

6. What are the criteria used for determining if the space is hazardous (untenable)?

7. What modeling program is used to predict evacuation time? _____

8. What is the travel speed assumed for an able-bodied person? _____

9. What is the travel speed assumed for persons with a disability? _____

10. Does the evacuation design take into consideration persons with a disability? _____

Building Code/Fire Protection Program

1. Will most tenant spaces have full or solid ceilings? _____

2. Is the smoke control system primarily property or life safety oriented? _____

3. What is the density for the tenant area sprinklers? _____

4. What is the maximum area that a single sprinkler system will cover? _____

5. Will the main electrical switchgear and transformer vaults be protected with automatic sprinklers? _____

6. What is the occupant load factor used for the retail sales areas? _____

7. What is the minimum width of the central exit passageway? _____

8. What computer model is used to predict the production and migration of smoke? _____

9. What minimum percentage of a ceiling in a tenant space must be open? _____

10. Is an Operations and Maintenance (O&M) manual provided? _____

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APPENDIX

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Job Aid 5.1

Checklist for Reviewing Documents for a Performance-Based Design

Does the documentation submitted include

- the fire protection engineering Design Brief?
- the performance-based Design Report?
- detailed specifications and drawings of the structure and the design components?
- an O&M manual with a Tenant Manual?

The Design Brief

Does this initial document identify

- important architectural features?
- potential fire hazards?
- safety problems, in terms suitable for detailed analysis?
- assumptions about who will be protected?
- stakeholder goals and objectives, with evidence that all stakeholders agree to them?

Does the Design Brief describe

- the project scope?
- building and occupant characteristics?
- selected fire scenarios?
- trial designs and assumptions?
- evaluation methods?
- a list of all design participants?
- qualifications of the design engineer?
- documentation of all decisions made?

What is the evidence that the design will ensure occupant safety?

- Sprinkler systems.

- Smoke control systems.

- Expert opinion that supports the assumptions made in the design.

- Experience with similar designs that supports the assumptions made.

- O&M manual that describes required ongoing maintenance and includes a training program for building management and tenants.

Job Aid 5.1 (cont'd)

The Design Report

Does this final document include the following?

- An explanation of hazards, risks and expected system performance over the life of the building life cycle.
- A definition of the project scope.
- Evidence of the engineers' qualifications.
- Stakeholder and design objectives and performance criteria.
- Fire scenarios and design fire scenario.
- The final design.
- The evaluation of the design methodology, tools, inputs and outputs.
- All critical design assumptions.
- A description of all features that must be maintained for the design to function.
- A list of building codes followed.
- Important references, especially if needed to support the O&M manual.

Specifications and Drawings

Do these show:

- Sprinkler densities and spacing.
- Fire detection and alarm system components and programming.
- Special construction requirements (egress, location of fire resistive walls, compartmentalization).
- Coordination of interactive systems.
- Minimum acceptable characteristics of the fire protection systems, i.e., fire department connections, hydrants, fire extinguishers.
- Kitchen fire controls.
- Smoke controls.
- Exits and exit capacity.
- Audible and visual fire alarms.
- Size of tenant spaces.
- Building construction.
- Required quality controls.
- Commissioning of fire protection systems and review of their installation.
- Assumptions related to occupants.

UNIT 6: TESTING, INSPECTION, AND MAINTENANCE

TERMINAL OBJECTIVE

Given a change to a performance-based building design submitted for review and approval, and the fire protection Operations and Maintenance (O&M) manual sections for the original building design, the students will be able to review the revisions requested and determine what sections of the O&M manual provide direction for the change proposed.

ENABLING OBJECTIVES

The students will:

1. *Given the O&M manual for a building design, determine whether a proposed change is within the combustible load defined in the manual.*

2. *Review pictures that illustrate types of changes to the content or use of different types of buildings and describe the O&M manual sections that would apply to the changes.*

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TESTING, INSPECTION, AND MAINTENANCE

The last critical component of the performance-based design process is the Operations and Maintenance (O&M) manual. This document must establish clearly the requirement that the building operator follows to assure that all components of the performance-based design are in place, operational, and properly maintained for the life cycle of the building. Since most performance-based designs rely on fire protection systems, building systems, and fire-rated construction, it is critical that these systems function as designed if and when they are needed.

THE OPERATIONS AND MAINTENANCE MANUAL

The O&M manual must be submitted with the final design documents, and all of the stakeholders must agree on its contents. This manual contains the requirements for the testing, inspection, and maintenance of all systems; outlines restrictions on building operations; and provides guidelines on how to address any changes in occupancy or use.

This manual also must be part of the legal documents of the property so it is transferred with any change in ownership.

Job Aid 6.2 is an example of an O&M manual.

Contents of the Operations and Maintenance Manual

The O&M manual will include

- descriptions of the commissioning requirements of all fire protection systems;
- identification of all subsystems;
- descriptions of all inspections, testing and maintenance procedures and schedules;
- information on emergency electrical power systems;
- details on building operations, such as critical fuels loads, sprinkler design requirements, building use and occupancy, reliability and maintenance of fire protection systems;
- details of the maintenance plans for critical design components,
- qualifications of inspection personnel or inspectors;
- fee schedules for unique or third-party inspections required by the Authority Having Jurisdiction (AHJ) and provisions of changes to the fee schedules;
- requirements to be followed if any fire protection system is impaired or out of service; and
- testing criteria for initial acceptance, including pass/fail criteria, inspection/testing schedules, periodic testing criteria, and record-keeping requirements.

The Tenant Handbook

The O&M manual also should contain a tenant handbook. (A sample is shown in Job Aid 6.3.) This subsection informs all tenants and occupants of a specific building about any design limits of the building, and the tenants' responsibilities. The tenant handbook also serves as a guide for tenant renovations and changes. In addition, this section should spell out any requirements or restrictions, such as storage height, commodity type, or fire protection system modifications.

The Tenant Handbook also provides details for the development and submittal of modifications for review and approval by the AHJ, building owner, insurance carrier, or other appropriate stakeholders. In addition, the tenant handbook highlights actions to take if a fire protection system is out of service, and specific fire loads and their configurations.

SUMMARY

In the prescriptive code approach, the periodic testing and maintenance of a building and its systems, and the continued use and occupancy of the building follow the fixed values of the community's general building and fire codes. In the world of performance-based codes and performance-based design, the O&M manual becomes the building and fire code by which the specific building is occupied, inspected, tested, and maintained throughout its entire cycle.

BIBLIOGRAPHY

Society of Fire Protection Engineers. *SFPE Engineering Guide to Performance-Based Fire Protection Analysis and Design of Buildings.* Ch. 12. Bethesda: SFPE, 2000.

Custer, Richard L.P., and Brian J. Meacham. *Introduction to Performance-Based Fire Safety*. Ch. 10. Bethesda: SFPE, 1997.

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Activity 6.1

The Tenant Handbook

Purpose

To review contents of a sample tenant handbook.

Directions

1. The Mall at Fox Fields uses a performance-based design. The owners, Mall Management Associates, Inc., have developed a comprehensive safety handbook for its tenants to guide them in their day-to-day operations.

2. For Part I of this exercise, use The Mall at Fox Fields tenant handbook, and work individually to answer the questions. (The tenant handbook can be found as Job Aid 6.3 in the Appendix.)

3. For Part II of this exercise, work as a table group to brainstorm your answers.

4. List your answers on an easel pad.

5. Be prepared to share your responses with the class for discussion.

Part I

Review the contents of The Mall at Fox Fields tenant handbook, and answer the questions listed below. All answers must be based on information found within the tenant handbook. Identify the sections in which you found the answers.

1. Are store managers allowed to keep any storage above the level of the fire sprinklers?

   _____

   _____

2. Who is responsible for commercial kitchen hood cleaning?

   _____

   _____

3. What is the maximum storage height allowed in the tenant spaces?

   _____

   _____

4. Is indoor smoking allowed in designated areas?

_____

_____

5. What is the consequence for storage in an exit?

_____

_____

6. Are tenant improvement plans required to be stamped by a licensed architect?

_____

_____

7. What is the minimum required clearance between shelves and rounds?

_____

_____

8. Toys, Toys, Toys wants to erect a camping tent in its space to advertise coming spring sales. The tent will measure 6 feet by 8 feet. Is this permitted?

_____

_____

9. If tenants learn of a planned shut-down of the sprinkler system, they must

_____

_____

10. During a sidewalk sale in the covered mall building, one tenant wants to display a jewelry-making operation. What special requirements are needed?

_____

_____

Part II

As a group, develop a list of five potential safety or maintenance consequences that might occur in a performance-based design covered shopping mall building that does not have a tenant handbook.

1. _____

2. _____

3. _____

4. _____

5. _____

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Activity 6.2

Review of a Requested Design Change

Purpose

To review a proposed change to a performance-based design.

Directions

1. You will work in teams for this activity.

2. Read the scenario and answer the questions on the following Student Activity Worksheet.

Scenario

You are a newly appointed director of a combined building department and fire prevention bureau, with review and permitting authority, under the direction of the municipal fire chief.

The owner of a local residential lowrise building (six stories) wants to add six stories to the existing structure. Five new floors will be residential, and the top floor, which has a unique and magnificent, unobstructed view of the ocean and mountains, will be a combination nightclub and casino.

During the initial project discussions, you learn that the original design was a performance-based product that included the capability of the equipment and crews at Station 24, located three blocks from the building.

In your review of the file, you learn your predecessor approved a performance-based design that allowed narrow egress stairs in exchange for fire sprinklers and the prompt response of Quint* 24, Quint 242, and two engine companies. According to the records and models that were submitted, the fire companies were expected to respond within 6 minutes, and by then all upper floor occupants should have been within two stories of the ground.

Your new fire chief, recently hired to streamline the suppression operations and provide better service to your fast-growing community, has determined that relocating the two quints to low-density suburban neighborhoods is a more effective use of that resource.

* A "quint" is a specialized type of fire apparatus that combines the function of an aerial ladder and pumper.

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Activity 6.2 (cont'd.)

Questions

1. Do you think you are a stakeholder in this decision? Why or why not? List your reasons in the space below.

2. Do you have any concerns or recommendations about this proposal? Write your response in the space below.

3. Describe briefly in the space below how you would approach the fire chief with your concerns or recommendations.

4. Describe briefly in the space below how you would approach the building owner or architect with your concerns or recommendations.

5. The owner decides to abandon the expansion project, but the fire chief still intends to relocate the facilities and personnel. What steps do you take to assure the agreed-upon level of life safety and fire protection are maintained?

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Activity 6.3

Stakeholders and Change

Purpose

To review the impact of change and decisionmaking without involving all stakeholders.

Directions

1. Discuss the news article with your group.
2. Answer the questions, and put your responses on an easel pad.
3. Select a spokesperson to present your group's responses.

Scenario

After your challenging day at work trying to make the "right" decision regarding your recommendation to the fire chief and this project, you go home to unwind and consider your options.

You pick up the newspaper, and see the following story on the front page:

NEW PROJECT KICK-OFF
Fire Chief Credits Creative Design Method

The long-anticipated construction of The Reserves, a 500-unit upscale highrise condominium, retail, and sports complex, will begin next week after city officials today gave the go-ahead for its fire protection plan.

The project--expected to provide more than 1,500 local jobs--had been hung up in city review while emergency fire protection details were worked out.

Fire Chief Henry "Hank" Lansing signed off on the plan this morning after developers presented him a "performance-based" design for the building and adjacent facilities.

"We're treading on new ground here," Chief Lansing said. "This is the first project in our community where the fire department has contributed its two quints to the successful fire protection of this multi-million dollar effort."

Lansing explained that as part of the performance-design for the buildings, the fire department's two specialized combination ladder-pumpers, called "quints," will be relocated from Station 24 to a new Station 31 which will be built by ArcNow, the project developers.

"We predict we should be able to respond to all of the sites within 2 minutes of getting any alarm," Lansing said. "With that sort of response time--and with the capacity and training of our staff--we should be able to control any fire before it gets out of the room where it starts."

ArcNow owners credited Chief Lansing--who has been on the job only 3 months--with the creative solution to get the project moving.

"We've never employed a performance-based' design," Chief Lansing said. "Historically, we have insisted building construction comply with rigid 'prescriptive' codes that limited a designer's options and specified how buildings must be constructed. This option will give ArcNow greater design freedom while meeting fire safety requirements."

Lansing said that since performance-based design is a new concept, he/she will brief his/her staff--especially in the combined building and fire prevention bureaus--on its merits.

ArcNow, the nation's third largest developer of "high end" projects, said the highrise building will have 500 luxury condominiums, a food court with gourmet presentations, exclusive shopping outlets, and a 6,000-seat sports complex for tennis and other indoor games. The project is located in the middle of the city's low-density suburban housing, giving homeowners a choice of living styles.

If approved by the State Legislature, the site eventually will have a 800,000-square-foot, $123 million casino/entertainment center.

Questions

1. What concerns do you have about this new information?

_____

_____

_____

2. Describe how you would approach the fire chief with your concerns.

_____

_____

_____

3. How might you get all the stakeholders together to discuss this matter?

_____

_____

_____

4. As a code official stakeholder, what recommendations do you have now?

_____

_____

_____

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APPENDIX

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Job Aid 6.1

Checklist for Reviewing an O&M Manual for a Performance-Based Building Design

Does the O&M manual contain

- requirements for initial testing, and for inspection and maintenance of all building systems;
- inspection and maintenance regimes and schedules;
- restrictions on building operations related to critical fire load, sprinkler design, building use and occupancy, reliability, and maintenance of all systems;
- a maintenance plan for all critical design components;
- guidelines on dealing with changes of occupancy;
- commissioning requirements;
- a description of interactions of system interfaces;
- identification of all subsystems; and
- information on emergency/standby electrical power?

Does the **tenant manual** included in the O&M manual contain

- information for tenants and building occupants on their responsibilities in respect to the building design limits;
- maintenance schedules;
- guidelines on tenant renovations and changes;
- fees for required inspections;
- information on actions to take if the fire protection system is out of order;
- definition of storage heights;
- criteria for initial acceptance, including pass/fail criteria;
- requirements for periodic testing and inspection; and
- recordkeeping requirements?

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Job Aid 6.2
Sample of an O&M Manual

BLUE MOUNTAIN PRODUCTS
WAREHOUSE No. 16
1234 Industrial Drive
Fountain Valley, MT

FIRE PROTECTION OPERATIONS AND MAINTENANCE

SAVE

THIS DOCUMENT MUST NOT BE DESTROYED

Submittal Date: August 14, 2001 Version: A-1.01

BACKGROUND

BLUE MOUNTAIN PRODUCTS is the owner/operator of a 386,000 sq. ft. state-of-the-art warehouse for storing a variety of consumer products that await distribution to our retail outlets throughout the United States, Canada and northern Mexico.

Because of the need for rapid product turnaround in the warehouse, our 24-hour-a-day operations and the value of our employees, merchandise, operations and facilities, several special requirements are in place to assure the highest level of employee and materiel safety.

Our patented, computerized product handling methods are outside the scope of traditional warehousing practices, so our specially designed warehouse reflects our unique needs. Modern building and fire codes do not address our one-of-a-kind methods, so our architects employed "performance-based design" to satisfy the local building and fire officials that Warehouse No. 16 is safe.

This Fire Protection Operations and Maintenance (O&M) Manual is required by the City of Fountain Valley as part of our building and fire code permit conditions.

BLUE MOUNTAIN PRODUCTS is committed to maintain a fire-safe workplace while fulfilling the company's mission of on-time, undamaged and well-displayed merchandise storage and delivery.

All employees and staff are expected to read and familiarize themselves with this document within 30 (thirty) days of their employment with BLUE MOUNTAIN PRODUCTS.

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BLUE MOUNTAIN PRODUCTS WAREHOUSE NO. 16
FIRE PROTECTION OPERATIONS AND MAINTENANCE MANUAL

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STAKEHOLDERS

The following persons are stakeholders in this project, and have concurred with the life safety and fire protection features included in the building. The agencies they represent and the date of their approval is listed in the table.

Name	Representing	Approval Date
Roscoe Barnett, President	Blue Mountain Products	3/7/2000
Sharen M. Britt	Anderson & Lewis, Attorneys	8/13/2001
Aaron Willsley, Jr., AIA	WillsleyYoung Architects	3/7/2000
Henry Adamson, CBO	City of Fountain Valley Building Dept.	6/14/2000
Robert Brick, Fire Marshal	Fountain Valley Fire Protection District	6/14/2000
David Medaris, P.E.	City of Fountain Valley Department of Public Works	4/1/2000
Lois Martinson, P.E.	AMAN Fire Protection Engineers	6/14/2000
Alonzo M. Hernandez	$C^2$4 Property and Casualty Insurers	8/24/2000
Warren "Hank" Hewitt	Mid-Montana Construction	6/23/2000
Jared Smith	NoFire Sprinkler Systems, Inc.	12/14/2000
Anna Rice-Dillard	Early Detection Fire Alarm Company	3/2/2001
Lyndon Croydon	Local 102, International Association of Materials Handlers	6/12/2000
Louisa Apodaca	Blue Mountain Products, Warehouse No. 16, Safety Team Manager	8/12/2001

All stakeholders, or their designated representatives, shall participate in the review and approval of operational or building construction changes that affect life safety or fire protection as described on Page 7.

APPLICATION

This O&M Manual is a condition of the City of Fountain Valley Building Department, Construction Permit No. BLD00-031, issued June 14, 2000, for the construction of 386,000 sq. ft. warehouse occupancy at 1234 Industrial Way in Fountain Valley, Montana.

This O&M Manual is a condition of the City of Fountain Valley Building Department, Certificate of Occupancy Permit No. OCC01-044, issued March 4, 2001, for a Performance Group II (IBC Occupancy Classification Group S, Division 1) occupancy as described in the International Code Council *Performance Code for Buildings and Facilities.*

This O&M Manual has been recorded with the plat of Miller's Industrial Annex to Fountain Valley, Lots 16-21, Vol. 2, Page 4, Plats of Bison County, Montana, and is thereupon recognized as a condition to said plat. Upon granting transfer of the real property and all improvements upon it, grantor shall comply with said O&M Manual in full force and effect.

THIRD PARTY INSPECTION SERVICES

In the unlikely event of a dispute between or among stakeholders regarding the outcome of inspections, tests or maintenance, the stakeholders have agreed that third party evaluation will be performed by

PQM Fire Protection Engineers 87 N. State Street Chicago, IL 60012
Telephone: 241-555-8763 Fax: 241-555-8421
E-mail: consult@pqm.com

The findings of the third party inspection service shall be binding upon the stakeholders, and incorporated as part of this Operations and Maintenance manual.

RESTRICTIONS ON USE AND OCCUPANCY

BLUE MOUNTAIN PRODUCTS Warehouse No. 16 is designed with the latest technological advances in fire protection to provide life safety for our staff, and asset protection for our customers.

This section describes the general building construction, and special limitations on storage within the warehouse.

Warehouse No. 16

Warehouse No. 16 consists of 386,000 sq. ft. of floor space within the perimeter walls of the building. The space is allocated as follows:

Function/Operation	Square Feet
Warehousing	357,000
Shipping/Handling	12,500
Administration	6,500
Staff Lounges/Restrooms/Workout Facilities	10,000
Total	386,000

The exterior walls are poured-in place concrete (tilt-up) with open web steel trusses and a metal roof system 48 feet above the floor. The roof is supported by steel columns that are not protected with fire resistive materials.

The warehouse operations are separated from the remaining spaces by construction that has a two-hour fire resistance rating. All door openings between the warehouse and the rest of the building have 1-1/2-hour fire doors with smoke gaskets on them.

Emergency exit and access doors for the fire department are located every 125 feet around the exterior perimeter.

Except for the loading docks and rail spurs, there is a 60-foot wide grassy landscaped around the entire building. The fire lane surrounds this grassy area, and includes the truck loading and unloading access area.

Utility service is provided as follows:

Telephone	Mid-Continent Bell
Water/Sewer	Fountain Valley Department of Public Works
Electricity	Montana Power and Light
Natural gas	Cascadiana Gas
Data transfer	Verizon Wireless Services
Waste handling	3-Guys Garbage and Recycling Services

The warehouse and loading dock are heated by ceiling-mounted natural gas-fired 175,000 BtuH input unit heaters. A one-inch (1") black iron natural gas line runs around the perimeter walls and services each unit heater. Each heater has its own gas shut-off valve near the heater. The main gas meter is located on the north wall of the warehouse.

The remaining spaces are heated by wall-mounted photovoltaic solar panels that generate electricity for the forced air heater units throughout the office (administration) and employee facilities.

Electrical service is provided by an underground service cable and transformer at the south side of the building. The Electrical Room in the southwest corner of the warehouse contains all electrical distribution equipment.

The Electrical Room is kept locked at all times because of the dangerous high voltages inside. Only authorized personnel are permitted to enter. (See the BLUE MOUNTAIN PRODUCTS Lock Out/Tag Out procedures manual for additional details.)

Fire protection consists of the following elements:

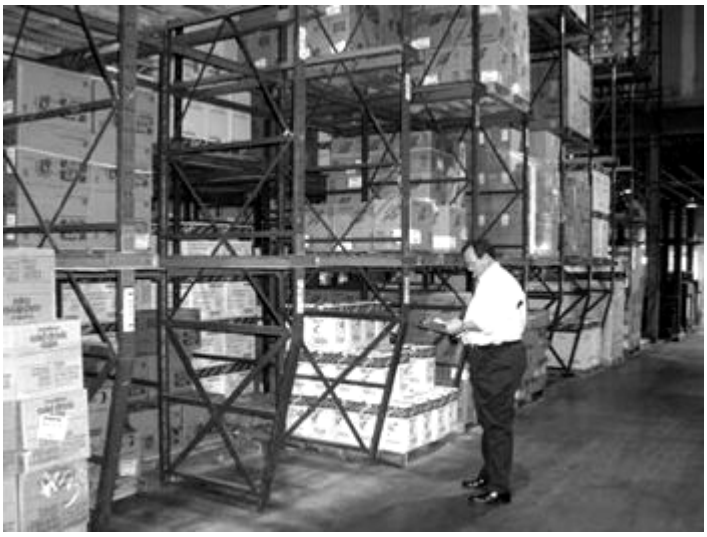
1. All areas are protected by a wet pipe automatic fire sprinkler system.
2. All areas within the warehouse are within 75 feet of a hose station outlet for a fire department standpipe system.
3. There is an underground "bladder tank" holding 1.2 million gallons of water for fire protection beneath the grassy area, and two 1,250 gpm fire pumps to supply water to the sprinkler system.
4. All areas--except the warehouse--are equipped with an automatic smoke detection system.

5. The warehouse roof is equipped with skylights that function as smoke vents in the event of a fire in the warehouse. There also are 76 high-volume fans located throughout the roof to draw smoke out of the warehouse. Louvered air intakes are installed in the warehouse perimeter walls.
6. The computer room is equipped with a "clean agent" fire suppression system that "floods" the room with an invisible gas.
7. All fire protection systems send a signal directly to the Fountain Valley Fire Department in the event of an emergency.
8. There is an Onan® 600 kW diesel-powered generator to provide standby power for the smoke fans and fire pumps.

FIRE SAFETY REMINDERS

- In the event of an emergency, always dial 9-1-1.
- Report any equipment malfunctions or safety feature damage to the maintenance department right away. *Use the BLUE MOUNTAIN PRODUCTS intranet mail server to document all maintenance requests.*
- Do not prop open any fire doors.
- The grassy area around the building must be free of storage at all times.

Our founder, Roscoe Barnett, reviews storage in one of our other warehouses. Warehouse No. 16 uses an entirely new and unique distribution method.



Storage Configuration(s)

NOTE: THIS IS PROPRIETARY INFORMATION AND SHALL NOT BE DISCLOSED

Storage with Warehouse No. 16 consists of closely spaced steel racks that operate on a moving floor system. Unlike traditional carousel racks where the product moves on a track to the picker, in Warehouse No. 16 the entire multiple-row rack series moves to the front of the warehouse as needed.

Individual steel racks are designed to the highest tolerances allowed, and average 2-3/4-inches clearance between them. Eight (8) individual racks make up a "rack array". The rack/floor systems are 36 feet wide and 560 feet long. The moveable multiple-row rack/floor system was designed and engineered by Fumojitsu-AMI Storage Solutions, Ltd. of Osaka, Japan. It takes approximately 216 seconds for a rack array to make a complete circle.

Due to customer demand to keep products moving in and out of the warehouse, the racks are not equipped with a "deadman" or "auto-stop" feature found on many carousel rack storage systems. This means that in the event of a fire in the racks, the rack assemblies will continue to rotate with the potential of carrying a fire throughout the storage array.

The racks are 40-feet high which allows material to be stored up to 44-feet above the floor. The top row of the rack is designed to hold only one unit load of commodity so it will not be within 36 inches of the ceiling sprinklers. The racks are entirely open with no decks. There are no fire sprinklers within the racks because of the movement.

The 36-foot wide rack arrays are located three feet, eight inches (3' 8") apart, to allow hand-controlled, powered service and inspection trucks to move between and among them.

Depending upon our client needs, commodities on racks may be non-combustible, limited combustible or highly-combustible. Unit loads may be encapsulated, banded or open. In order to accommodate their wide range of needs, the ceiling fire sprinkler system is designed to handle a small fire in any type of products that might be shelved there. *Polystyrene and other rigid plastic material handling systems (pallets) may not be used anywhere in the warehouse.*

FIRE SAFETY REMINDERS

- In the event of an emergency, always dial 9-1-1.
- Report any equipment malfunctions or safety feature damage to the maintenance department right away. *Use the BLUE MOUNTAIN PRODUCTS intranet mail server to document all maintenance requests.*
- Smoking or other open flames are not allowed within the warehouse area.
- In the event of a fire within a rack, notify the fire department by dialing 9-1-1, and then report the emergency to the building engineer to shut-down the moving rack/floor system.

OCCUPANCY CHANGE PROCEDURES

Generally, the fire protection systems have been designed to handle any fire challenge presented in the building. However, changes in storage arrays, rack configuration, fire protection systems, building layout or emergency plans must be approved by the local fire and building departments prior to initiation.

If we make any changes, we must provide:

- Drawings and specifications of the existing space configuration, including accurate dimensions.
- Drawings and specifications of the proposed space configuration, including accurate dimensions.
- Details of any modifications to heating, ventilation and air conditioning equipment that affects the space.
- Drawings of any and all storage arrangements, including aisle widths and product storage heights.
- Details of any modifications to security or fire protection systems, including fire sprinklers, smoke detectors or standpipe outlets.
- A sign-off "consensus" report by all stakeholders and/or their representatives.

All plans must be stamped by our licensed fire protection engineer.

FIRE PROTECTION EQUIPMENT DESCRIPTIONS

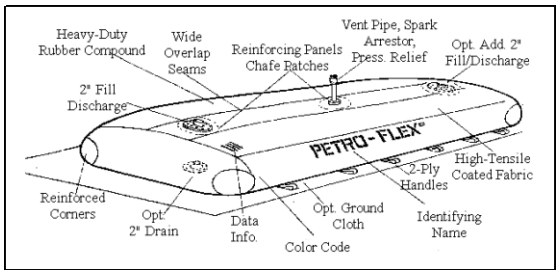
This section details the type of fire protection equipment installed in the building, its design criteria, commissioning requirements, and inspection, maintenance and testing requirements.

Water Mains

The water supply for Warehouse No. 16 is provided from two sources:

- City of Fountain Valley Department of Public Works.
- A 1.2 million gallon underground tank with two fire pumps.

The city water supply provides potable (drinking and sanitation) water plus approximately 785 gallons per minute of fire flow at 63 psi residual pressure.[1] The city has provided one (1) fire hydrant on each side of the building, supplied by a 8-inch water main that completely loops the building. Fire hydrants provided on the city water main are painted yellow.



Our private water tank is identical in design, and called Aqua-Flex™ by Moore-Grant Goodyear Manufacturing.

The private water tank is a rubberized bladder that holds 1.2 million gallons of water. It is located underground on the west side of the building. It is kept full by a connection to the city room on the water main (4-inch), and discharges through a fire pump(s) that is located in a fire

[1] Fire flow test, March 13, 1999. 1200 block Industrial Way. Source: Fountain Valley Fire District.

protected west wall. The fire pump(s) supply the private fire hydrants on a 12-inch water main around the building, and the fire sprinkler systems. The private fire hydrants are painted light blue.

Fire Sprinklers

Warehouse No. 16 is protected with wet-pipe automatic fire sprinklers.

There are eleven (11) sprinkler risers located in the fire-protected riser room along the west side of the building. On the outside wall, there is a four-way fire department connection that enables the fire department to supplement the pressure and flow from the two water main systems. Each riser is equipped with its own shut-off valve in the form of a wall indicating valve.

The fire sprinkler systems are "hydraulically" designed to provide an adequate water supply in the event of a fire. This means the fire protection has been matched to the available water supply to assure an adequate level of protection. Maintaining an adequate water pressure is essential to proper sprinkler operation.

These designs have been reviewed and approved by our fire protection engineering firm. Any changes in the warehouse configuration require a review of the sprinkler design.

Riser No.	Sprinkler Zone	Design Density	Area of Application
1	Warehouse, NW Center Zone	.415	2800
2	Warehouse, NE Center Zone	.415	2800
3	Warehouse, NW Outer Zone	.415	2800
4	Warehouse, NE Outer Zone	.415	2800
5	Administration offices/Lounges	.230	2600
6	Loading dock	.285	2000
7	Warehouse, SW Outer Zone	.415	2800
8	Warehouse, SE Outer Zone	.415	2800
9	Warehouse, SE Inner Zone	.415	2800
10	Warehouse, SW Inner Zone	.415	2800
11	Warehouse, Center Core Zone	.415	2200

Note: The water pressure on the sprinkler supply gauge should read not less than 75 psi at all times.

Standpipes/Fire Extinguishers

Fire hose outlets (standpipes) are provided approximately every 75 feet within the warehouse. *These must be protected from physical damage.* The standpipe hose outlets are designed so fire fighters can connect their fire hoses in the event of an emergency, and not have to drag fire hoses long distances through the warehouse.

Each hose station outlet is designed to flow 500 gallons of water per minute at 125 psi residual pressure, with a maximum of four standpipes flowing simultaneously.

Each hose station is equipped with two 2-1/2-inch gated hose outlets with 2-1/2-inch to 1-1/2-inch reducing caps.

There are two water-type portable fire extinguishers at each hose station. In the event of a fire, these are the preferred first aid fire appliances.

Fire pumps for standby fire protection.

Fire Pumps

There are two, 1,250 gpm fire pumps located in a fire-protected room in the warehouse. They are powered by the regular electric service, and connected to the standby power supply in case of an electrical failure.

The fire pumps are plumbed in "parallel" so if one is not capable of supplying the fire protection and fire hydrant systems, the other will operate. Also, if one pump fails to run, the other will perform until repairs can be made.

The fire pumps are outfitted with a "bypass" that allows a small amount of water to get through from the bladder tank in the event the pumps and/or electrical systems all fail. *The bypass valves must remain in the "open" position at all times.*

Fire Alarm/Smoke Detection

All areas--except the warehouse--are equipped with an automatic smoke detection system. The smoke detectors are intended to discover a fire in its early stages and report it before it can cause too much damage.

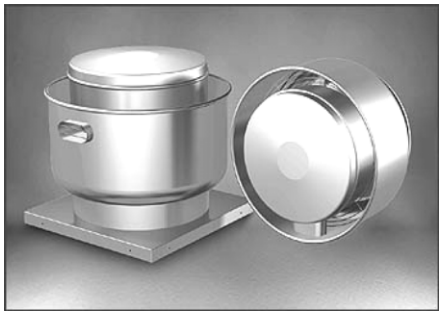
The smoke detection system is "addressable", each smoke detector and manual pull station has a unique identifying number so the source of the alarm can be found quickly. Each exit door from the warehouse has a manual pull station next to it.

The main fire alarm control is located in the Electrical Room next to the southwest corner of the Administration area. There is a remote annunciator at the south entry. In the event of an alarm, it will identify the specific device (smoke detector/water flow alarm/manual pull station) which has caused the alarm.

Smoke Venting

The warehouse roof is equipped with skylights that function as smoke vents in the event of a fire in the warehouse. There also are 76 high-volume fans located throughout the roof to draw smoke out of the warehouse.

The skylight vents are designed to shrink and fall to the floor when they reach 376°F. They are made of plastic, and can be cut open with the fire department's power-operated saws.



The high-volume fans are controlled manually with switches located at the remote annunciator at the south entry. Each fan is capable of exhausting about 28,000 cubic feet per minute, and they are used to clear smoke and other fire by-products from the warehouse. *In the event of a fire, only the Fountain Valley Fire District is authorized to operate the smoke exhaust fans.* There is a map next to the annunciator that shows which fans cover which area.

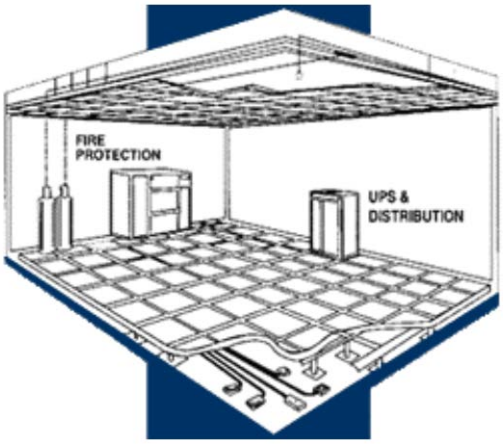
Exterior perimeter walls of the warehouse have louvered openings to let in "make-up" air when the electric fans are operated. This allows the exhaust fans to operate more efficiently. *Do not place any obstructions over these intake louvers.*

Computer Room

The computer room is equipped with a "clean agent" fire suppression system that "floods" the room with an invisible gas. The clean agent is FM 200.

In the event of a fire in the computer room, the computers are programmed to shut down immediately. (Data is backed up off site). Computer room doors will close, ventilation fans will shut off, and the fire suppression gas will be discharged into the space. ***Once the fire system operates, do not open the door until told to do so by the Fountain Valley Fire District.***

You may also operate the fire suppression system from a manual pull station located on the outside of the computer room door. There is a portable fire extinguisher mounted on the wall beneath the manual pull station. In the event of a fire, it is the preferred first aid fire appliance.



Emergency and Standby Power

Emergency egress lighting is provided throughout the building. In the event of a power failure, these lights will operate within 10 seconds to light exits.

There is an Onan® 600 kW diesel-powered generator to provide standby power for the smoke fans and fire pumps. In the event of a power failure, it will start automatically. It is designed to provide power for at least 24 hours in the event of a power failure from the power company.

The generator is located outdoors on the south lawn. There is a 5,000-gallon concrete encased tank next to it that contains diesel fuel to run the generator.

Alarm Reporting

All fire protection systems send a signal directly to the Fountain Valley Fire Department in the event of an emergency. The fire department is expected to respond right away, but may be delayed by other emergencies.

FIRE SAFETY REMINDERS

- In the event of an emergency, always dial 9-1-1. When you leave the building, activate a manual pull station.
- Report any equipment malfunctions or safety feature damage to the maintenance department right away. *Use the BLUE MOUNTAIN PRODUCTS intranet mail server to document all maintenance requests.*
- Report any identified changes in the water pressure to the maintenance department right away. *Use the BLUE MOUNTAIN PRODUCTS intranet mail server to document all maintenance requests.*
- Protect all hose station outlets from obstructions or physical damage.
- Only the fire department is authorized to operate the electric smoke exhaust fans.
- Keep perimeter wall louvered vents clear at all times.
- Do not open the computer room door until authorized by the fire department.

FIRE PROTECTION EQUIPMENT COMMISSIONING

Prior to occupancy, all fire protection and emergency systems had to be designed, installed, inspected and tested in accordance with recognized standards. Those standards specify the commissioning or "acceptance" criteria for the equipment or systems.

All inspections and tests were witnessed by representatives of BLUE MOUNTAIN PRODUCTS and the local fire or building departments. The table on the next page(s) describes the commissioning requirements.

System	Standard	Commissioning Requirements
Fire Hydrant Systems/Water Mains	NFPA No. 24	• Underground hydrostatic test o 200 psi/2hours • Underground flush o 3520 gallons per minute • Exercise all hydrant valves • Confirm thread sizes
Fire Sprinkler Systems	NFPA No. 13	• Underground hydrostatic test o 200 psi/2hours • Aboveground hydrostatic test o 200 psi/2hours • Main drain test (baseline) • Inspector's test
Fire Standpipe Systems	NFPA No. 14	• Underground hydrostatic test o 200 psi/2hours • Aboveground hydrostatic test o 200 psi/2hours • Flow performance test o 500 gpm per outlet/125 psi o Maximum 2000 gpm
Fire Alarm Systems	NFPA No. 72	• Circuit integrity inspection/test • Battery load test • Voltage drop test • Audibility performance check • Visual signaling check • Auxiliary signal transmission check • Certificate of Completion • 25% random test o 50% on AC power o 50% on secondary power

System	Standard	Commissioning Requirements

Fire Pumps	NFPA No. 20	• Aboveground hydrostatic test
		  o 200 psi/2hours
		• Aboveground flush
		  o 2350 gallons per minute
		• Electrical service arrangement checked
		• Flow performance test
		  o Run time minimum one hour
		• Electrical demand checked
		  o Automatic transfer
		• Loads start test
		• Phase reversal test
		• Controller acceptance test
		• Primary and standby power supply test

Clean Agent Suppression System		• Mechanical component review
		• Enclosure integrity test
		• Electrical component review
		• Functional test
		  o Preliminary
		  o Operational
		  o Remote monitoring
		  o Control panel power source

Standby Power Supplies	NFPA No. 110	• On-site installation test
		  o Cold start
		  o Automatic transfer
		• Full load test
		• Cycle crank test

Mechanical Smoke Exhaust	International Mechanical Code	• Electrical hardening inspection • Control function test • Air volume (manometer) test o Min. 28,000 cfm/fan

ACCEPTANCE CRITERIA

All equipment and devices listed in the table above shall meet all of the minimum requirements of the design, installation and maintenance standards listed above to be considered acceptable for service. Failure to satisfactorily complete any portion of any described test shall be considered a failure of the entire system and/or equipment, and it shall not be placed into service until such time as satisfactory repairs or replacement has/have been completed.

INSPECTION AND TESTING REQUIREMENTS

All fire protection equipment and systems, including standby power systems, shall be inspected and tested on a basis as prescribed in design, installation and maintenance standards listed above, in accordance with NFPA Standard No. 25 and the requirements of the BLUE MOUNTAIN PRODUCTS corporate property and casualty insurer, whichever is deemed to be the most restrictive by the local fire and building official.

Note: The City of Fountain Valley is responsible for inspecting and testing its own water supply and fire hydrants.

Inspection and test schedules shall be in compliance with the latest edition of these standards now or as ever adopted in the future, and as approved by the local fire and building official.

Copies of the inspection and test schedules generally can be found within the standards themselves. The BLUE MOUNTAIN PRODUCTS WAREHOUSE No. 16 safety team shall be responsible for maintaining inspection and test records as described below.

INSPECTOR QUALIFICATIONS

Only persons or corporations who have met the requirements of the BLUE MOUNTAIN PRODUCTS corporate property and casualty insurer and the following certifications shall be permitted to inspect or test fire protection equipment and systems.

System	Certification
Fire Hydrant Systems/Water Mains	• Montana State Department of Health and Human Services o Backflow Prevention Technician o Water Quality Supervisor • American Water Works Association o Hydraulic Systems Maintenance Tech-level III

System	Certification
Fire Sprinkler Systems	• National Institute of Certification of Engineering Technology o Automatic Fire Sprinklers Level III
Fire Standpipe Systems	• National Institute of Certification of Engineering Technology o Automatic Fire Sprinklers Level III
Fire Alarm Systems	• National Institute of Certification of Engineering Technology o Fire Alarm and Detection Level III
Fire Pumps	• National Institute of Certification of Engineering Technology o Automatic Fire Sprinklers Level III • Manufacturer-certified installation and service technician
Clean Agent Suppression System	• Manufacturer-certified installation and service technician
Standby Power Supplies	• Montana State Department of Electrical Safety o Journeyman Level 2 card-holder • Manufacturer-certified installation and service technician
Mechanical Smoke Exhaust	• Manufacturer-certified installation and service technician

MAINTENANCE

Fire protection equipment and system maintenance is paramount to proper emergency performance. All equipment shall be maintained in accordance with the manufacturer's requirements, and shall be performed only by qualified persons.

The BLUE MOUNTAIN PRODUCTS Warehouse No. 16 building engineer shall be responsible for tracking manufacturer's maintenance requirements, and shall assure work is performed only by qualified persons.
Records of all maintenance shall be maintained by the building engineer as described on the following page(s).

RECORDKEEPING

Accurate and detailed records are an important part of any safety and maintenance program.

The BLUE MOUNTAIN PRODUCTS WAREHOUSE No. 16 safety team shall be responsible for maintaining inspection and test records in the schedule described on the following page(s).

System	Standard	Recordkeeping Requirements
Fire Hydrant Systems/Water Mains	NFPA No. 24	• PERMANENT o Underground hydrostatic test o Underground flush • TEN-YEARS o All prescribed inspection and testing records • TWENTY-FIVE YEARS o All manufacturer's required maintenance
Fire Sprinkler Systems	NFPA No. 13	• PERMANENT o Underground hydrostatic test o Aboveground hydrostatic test o Main drain test (baseline) • TEN-YEARS o All prescribed inspection and testing records • TWENTY-FIVE YEARS o All manufacturer's required maintenance
Fire Standpipe Systems	NFPA No. 14	• PERMANENT o Underground hydrostatic test o Aboveground hydrostatic test o Flow performance test • TEN-YEARS o All prescribed inspection and testing records • TWENTY-FIVE YEARS o All manufacturer's required maintenance
Fire Alarm Systems	NFPA No. 72	• PERMANENT o Certificate of Completion • TEN-YEARS o All prescribed inspection and testing records • TWENTY-FIVE YEARS o All manufacturer's required maintenance

System	Standard	Recordkeeping Requirements
Fire Pumps	NFPA No. 20	• PERMANENT o Aboveground hydrostatic test o Aboveground flush o Electrical service arrangement checked o Flow performance test o Electrical demand checked o Automatic transfer o Controller acceptance test • TEN-YEARS o All prescribed inspection and testing records • TWENTY-FIVE YEARS o All manufacturer's required maintenance
Clean Agent Suppression System		• PERMANENT o Functional test • TEN-YEARS o All prescribed inspection and testing records • TWENTY-FIVE YEARS o All manufacturer's required maintenance
Standby Power Supplies	NFPA No. 110	• PERMANENT o On-site installation test • TEN-YEARS o All prescribed inspection and testing records • TWENTY-FIVE YEARS o All manufacturer's required maintenance
Mechanical Smoke Exhaust	International Mechanical Code	• PERMANENT o Control function test • TEN-YEARS o All prescribed inspection and testing records • TWENTY-FIVE YEARS o All manufacturer's required maintenance

OCCUPANT ACCOUNTABILITY/EVACUATION TRAINING

BLUE MOUNTAIN PRODUCTS, INC. is committed to maintaining a safe environment for workers and visitors. In the unlikely event of an emergency, we will give highest priority to evacuating all persons from the building except those specifically involved in emergency operations as designated by the Safety Team and this plan.

No one is exempt from participation in evacuation procedures or drills.

EVACUATION PLANS

Building floor plans/evacuation plans are posted throughout the facility. Emergency egress routes are marked with red arrows directing occupants to the nearest exit and an alternate exit.

The evacuation plans also detail specific meeting locations for workers and visitors.

EVACUATION PROCEDURES

1. In the event of a fire or other emergency, all persons except those specifically involved in emergency operations as designated by the Safety Team and this plan shall leave immediately.

2. All employees and visitors shall report to their designated meeting area where shift supervisors will conduct a "head count" to assure all persons have escaped.

3. In the event a person is not in his/her designated meeting area, the shift supervisor shall designate a "runner" to report that information to the Fountain Valley Fire District upon their arrival. The "runner" shall return to the designated area after completing this task.

4. After consultation with the Incident Commander of the Fountain Valley Fire District, the most senior manager on site shall determine if employees and visitors will be allowed to re-enter the facility or shall be dismissed until further notice.

EVACUATION TRAINING

Evacuation drills shall be conducted quarterly. Records of those in attendance shall be maintained by each shift supervisor and forwarded to the Safety Team where they will be kept on file for not less than five (5) years from the date of the drill.

EMPLOYEE ACKNOWLEDGEMENT

All staff and employees are required to read and acknowledge this operations and maintenance manual. Upon completion of their review, employees shall sign this log to verify they have reviewed the manual.

Employee Name (Print)	Employee Signature	Review Date

Job Aid 6.3
Sample of a Tenant Handbook

The Mall at Fox Fields

Management by:
Mall Management Associates, Inc.
1400 Executive Drive
Suite 1411
Anytown, MD 21777
Telephone: 301-555-1212
Fax: 301-555-1213
E-mail: tenantsupport@foxfields.com
Web: http://www.foxfields.com

TENANT FIRE SAFETY HANDBOOK

Welcome to The Mall at Fox Fields, Anytown's premier shopping experience. We hope you find your time with us to be profitable and rewarding. According to our marketing surveys, more than 28,000 people per day visit The Mall at Fox Fields, giving you a chance to share your dreams with each and everyone who comes here.

While retail is our business, public safety and property protection also are important to us. This information is provided to you so you understand the rules and regulations regarding the operation of your tenant space. These guidelines have been established to provide safety for you and our customers, and to minimize the risk of fire or other calamity within our mall.

These rules have been prepared in conjunction with the Anytown Fire Department and are incorporated as part of your Lease Agreement. If you have any questions, please feel free to contact **Mall Management Associates, Inc.** at the number listed above. If you have an emergency, please contact Mall Security or dial 9-1-1 from any telephone.

Our goal is to provide you the best environment for building business success. We hope you will join us.

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EMERGENCIES

(Fire, Medical or Police)

- For any emergency, dial 9-1-1 from any telephone.
  - Tell the emergency operator your name, the nature of the emergency, the address of the emergency and a call-back telephone number.
  - Remember your tenant space address is located above the door into the mall walkway, and on the outside of the door to the parking lot.
- Contact Mall Security at 301-555-1111.
- For contingent emergency actions, see the last item of this manual.

SECURITY CONCERNS THAT ARE NOT EMERGENCIES

- Contact Mall Security at 301-555-1111.
- Contact Mall Management Associates, Inc. at 301-555-1212.
- Contact the Building Engineer via pager at 715-555-3222, and enter your tenant space number at the tone.

PROPERTY DAMAGE (Flood, air conditioning, refrigeration failure)

- If you have a problem within your tenant space related to water leaks, air conditioning or heating, lights, other electrical, telephone, data communications, uninterruptible power supplies or related non-emergency systems, contact:
  - Mall Management Associates, Inc. at 301-555-1212.
  - Contact the Building Engineer via pager at 715-555-3222, and enter your tenant space number at the tone.

SMOKING

- Smoking by employees, staff or mall guests is permitted only in designated areas outdoors next to mall entrances.
  - If your employees or staff are observed smoking in other than designated areas, there will be a $50.00 (fifty dollar) fine per occurrence assessed onto your monthly lease payments.
  - If you observe someone smoking in violation of this rule, contact Mall Security at 301-555-1111.

EXITS

- Your tenant space is provided with at least two exits, one onto the covered mall walkway, and the other to the outdoors or a protected fire exit corridor.
  - It is your responsibility to maintain clean and clear walking paths through and to the exits.

  - There must not be any storage at anytime in the protected fire exit corridor. If storage or waste materials from your tenant space are left in other than designated areas, there will be a $50.00 (fifty dollar) fine per occurrence assessed onto your monthly lease payments.

  - It is your responsibility to maintain the light bulbs in light EXIT signs, and the light bulbs in emergency lighting units within your tenant space. You should check these items monthly to make sure they are working properly.

- You may not attach any new or additional locks or latching devices to the exit doors without first obtaining approval from Mall Management Associates, Inc. and the local building and fire departments. This includes chains, deadbolts, security alarms, flush bolts, slide bolts and other locking mechanisms.

FIRE PROTECTION

The fire protection system for The Mall at Fox Fields has been designed to provide the latest in state-of-the-art protection and reporting. It includes a fire sprinkler system and a smoke detection system that detects fires, alerts occupants and operates smoke control features.

- **Do not make any modifications to fire protection systems without prior approval from Mall Management Associates, Inc. and the local building and fire departments.**

  - This includes moving smoke detectors or disconnecting any air conditioning devices.
  - Keep all storage at least 18 inches below sprinklers.
    - You may store items above the sprinklers, but **only** on metal shelves along the outer perimeter of your tenant space.

- There is at least one portable fire extinguisher in your tenant space, and one nearby in the covered mall walkway. You should be familiar with their locations.
  - If a small fire occurs, and you have been trained properly,

    - Have someone dial 9-1-1 to report the fire.
    - Identify the fire and use a portable fire extinguisher.
    - Remember PASS: Pull-Aim-Squeeze-Sweep.
    - If you cannot control the fire, leave the area immediately and wait for the fire department.

- Portable fire extinguisher maintenance for that equipment within your tenant space is your responsibility.
- If the fire sprinkler system is inoperable *for any reason* (damage, repairs, maintenance, expansion, modification, etc.), you must employ the contingent emergency procedures described in the last item of this manual.

RETAIL DISPLAY/STORAGE

- All retail storage must be on solid shelves, cubes, metal rounds, glass/metal display islands or otherwise secured to prevent falling onto customers.

- Clear aisles at least 36 (thirty-six) inches wide must be provided between shelves and rounds. Aisles must be unobstructed to exits and the covered mall walkway.

- You may display products in the covered mall walkway under the following conditions:

  - Items must be on a rectangular solid or folding leg table not more 24 inches wide nor more than 84 inches long.
  - The long dimension of the table must be parallel to the front (covered mall walkway) side of your tenant space, and may not interfere with the public walkway.
  - Products on the table may not include:
    - Flammable or combustible liquids (perfumes, alcohol, paraffin, candles, Sterno®),
    - Papier-mâche, untreated crepe paper,
    - Synthetic stuffed toys or animals greater than 3 (three) pounds,
    - Pressurized cylinders (helium, compressed air, propane), or,
    - Expanded foam plastics (Styrofoam®).

Open flame devices are not allowed in the mall.

- You may not have any displays using open flames (candles, burners, incense, metal working or related activities) without getting express permission from Mall Management Associates, Inc. and the local fire department.

The Mall at Fox Fields was designed with the latest retail techniques in mind to improve your bottom line. We rely on JIT (just in time) delivery so your products arrive from your distributor, and put immediately on the sales floor.

Unfortunately, on rare occasion, excess stock arrives that cannot be displayed right away. In those infrequent circumstances:

- **Do not** store materials or waste packaging in or near exits. If storage or waste materials from your tenant space are left in other than designated areas, there will be a $50.00 (fifty dollar) fine per occurrence assessed onto your monthly lease payments.

- **Do not** stack boxes of any materials more than 8 (eight) feet high. The fire sprinkler system is not designed to control a fire when boxes are stacked higher than 8 feet.

- **Do not** stack or store materials on or above ceilings or beneath the stairs leading to mezzanines.

SALES/SPECIAL EVENTS/HOLIDAY DECORATIONS

Several times during the year, The Mall at Fox Fields sponsors special mall-wide sales and special events. Likewise, President's Day, Valentine's Day, Mother's/Father's days, Fourth of July, Labor Day/Back-to-School, Halloween, Thanksgiving and Christmas may need special sales to honor them properly.

- You may not have any displays using open flames (candles, burners, incense, metal working or related activities) without getting express permission from Mall Management Associates, Inc. and the local fire department.

- All decorations that are not permanently attached to the walls, floors or ceilings and have already been approved by Mall Management Associates, Inc. and the local fire department, must be flame retardant or flame resistant.
  - You must provide a Certificate of Flame Resistance to Mall Management Associates, Inc.
  - Mall Management Associates, Inc. reserves the right to order immediate removal of any decorations or finishes that are not proved to be flame retardant or flame resistant.

- You may not erect any tent, canopy, air-supported structure, or parasol greater than 6 (six) feet in diameter, or any retail display with a roof, ceiling, cover, top or other horizontal obstruction without prior approval by Mall Management Associates, Inc. and the local fire department.

TENANT SPACE MODIFICATIONS

Your tenant space was designed with your convenience and safety in mind.

- If you plan to make any material changes (move walls, install new carpet or wall treatments, remove or install ceiling tiles, abandon doors, etc.), you must obtain approval from Mall Management Associates, Inc. and the local building and fire departments.

- When submitting proposed changes, you, your architect or your parent company must provide:

  - Drawings and specifications of the existing space configuration, including accurate dimensions.
  - Drawings and specifications of the proposed space configuration, including accurate dimensions.
  - Details of any modifications to heating, ventilation and air conditioning equipment that affects your space and the adjacent covered mall walkway.
  - Details and specifications on new carpet and wall treatments, permanent or temporary decorations (especially fabric and plastic materials, including temporary "Sale" signs).
  - Drawings of any and all storage arrangements, including aisle widths and product storage heights.
  - Details of any modifications to security or fire protection systems, including CCTV, infrared motion detection, fire sprinklers, smoke detectors or standpipe outlets.

- All plans must be stamped by a licensed fire protection engineer.

FIRE PROTECTION EQUIPMENT MAINTENANCE

In order to assure its proper operation in an emergency, fire protection is inspected and tested on a regular basis. This section outlines the inspections, tests, frequencies and responsibilities.

- **Inspections** are visual checks to assure the item or equipment is in its place in a ready condition and is not damaged, obstructed or otherwise rendered inoperative.
- **Tests** are performed by qualified contractors to assure the item or equipment operates within their prescribed limits.

For guidance in selecting at qualified contractor:

- Contact Mall Management Associates, Inc. at 301-555-1212.
- Contact the Building Engineer via pager at 715-555-3222, and enter your tenant space number at the tone.

Item	Inspection	Test	Responsible Party
Sprinkler Obstructions	Monthly		Tenant
Smoke Detector Obstructions	Monthly		Tenant
Fire Alarm Pull Box Obstructions	Monthly		Tenant
Fire Hose Outlet Obstructions	Monthly		Tenant
Fire Sprinkler System		Annually	Mall Management
Smoke Detection System		Annually	Mall Management
Standpipe System		Annually	Mall Management
Smoke Control System	Quarterly	Quarterly	Mall Management
Portable Fire Extinguishers	Quarterly	Annually	Tenant
Kitchen Hood Cleaning	Daily	Clean As Needed	Tenant
Hood Fire System	Quarterly	Semi-annually	Tenant
Outdoor Fire Hydrants	Quarterly	Annually	Mall Management

CONTINGENT EMERGENCY PROCEDURES

- In the unlikely event of an unplanned or planned shut-down fire protection systems (sprinklers or smoke detectors connected to the mall smoke control system), the following contingent plans become effective immediately for all tenants:

    - A uniformed fire watcher will be provided by Mall Management Associates, Inc., who shall patrol the interior and exterior of the premises in such manner as to completely encircle The Mall at Fox Fields once per hour.
    - Tenants shall notify their property and casualty insurers that one or more fire protection systems are inoperative.
        - Special requirements established by the property and casualty insurers shall prevail unless in conflict with these rules and regulations or the policies of Mall Management Associates, Inc.

All merchandise, stock or display deliveries shall cease immediately until the affected fire protection system is returned to service.

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APPENDIX A

BIBLIOGRAPHY

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APPENDIX B

GLOSSARY

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GLOSSARY

ADA	Americans with Disabilities Act.
AHJ	Authority Having Jurisdiction, an organization, office, or individual responsible for approving designs, equipment, installations, or procedures.
Autoignition	Ignition that occurs when fuel is heated sufficiently for the vapors to ignite without the presence of any outside arc, spark, ember, or open flame.
BOCA	Building Officials and Code Administrators International, Inc.
Ceiling Jet	The horizontal flow of hot gas and smoke at the upper strata of a compartment.
Bounding Conditions	Conditions which, if exceeded, invalidate the performance-based design.
Buoyancy	The upward force exerted on a body, fluid, or gas by the fluid or gas surrounding it.
Compartmentaliz-ation	The building code practice to divide larger buildings into smaller areas and volumes by the construction of fire-resistive barriers such as walls, floors, or ceilings.
Competent Ignition Source	An ignition source that has both sufficient temperature and energy to raise a fuel to its ignition temperature during the contact period.
Computational Fluid Dynamics Model (CFD)	A fire model that divides a compartment into small rectangular control volumes or computational cells.
Conduction	Transfer of heat within solids or between solids in contact with each other.
Conductivity	The ability of material to conduct heat. Represented in formulas by the term "*k*."
Cone Calorimeter	A tool for measuring heat energy.
Consequence Ranking	A ranking of the consequences of each type of loss predicted, including life, monetary loss, business interruption, or environmental damage.

Convection	Transfer of heat energy by the movement of heated liquids or gases.
Design Fire Scenario	Descriptions of possible fire events.
Design Objective	A description of the performance benchmark against which the predicted performance of a design is evaluated.
Deterministic Analysis	A methodology based on physical relations derived from scientific theories and empirical results that for a given set of initial conditions will always produce the same result or prediction.
Diffusion Flame Process	The combustion process where pure fuel vapors are released by pyrolysis and mix with the surrounding air (oxygen). See "Premixed Flame Process."
Engineering Design Brief	A document that describes the project scope, the project goals, the stakeholder and design objectives and related performance criteria, the design fire scenarios, and the trial designs in a performance-based design.
Engineering Design Report	The final document produced in the performance-based design process. Written in clear, unambiguous language, it contains the final report of the performance-based design process provided to reviewers.
Equivalent Compliance	From NFPA 101®, *Life Safety Code*: Alternative systems, methods or devices approved as equivalent by the authority having jurisdiction shall be recognized as being in compliance with this *Code*®.
Established Burning	The point in fire development when the size of the flame is large enough that flaming combustion will continue without a separate ignition source, and is limited only by the amount of available fuel.
Explosive Range or Limits	The upper and lower limits in which the ratio of flammable vapor to air will support combustion. See also "Flammable Limits or Range."
Field Model	A model that uses computational fluid dynamics (CFD), divides the fire compartment(s) into thousands of small rectangular cells, and predicts the density, velocity, temperature, pressure, and concentration of fire gases in each cell.

Fire Dynamics Simulator (FDS)	A National Institute of Standards and Technology (NIST) fire effects model that uses large eddy simulation techniques to predict the thermal conditions resulting from a compartment fire.
Fire Plume	Expansion of hot gases in a vertical direction.
Fire Safety Goals	Desired overall fire safety outcomes expressed in qualitative terms.
Flameover or Rollover	Occurs when underburned smoke and gases accumulated in a compartment ceiling layer ignite.
Flammable Limits or Range	The range in which the ratio of flammable vapor to air will support combustion. See also "Explosive Range or Limits."
Flashover	The point at which room temperature at the ceiling of a compartment reaches 1,100°F (593°C) or higher and all combustible materials within the compartment ignite nearly simultaneously.
Flashpoint	The temperature at which a liquid fuel--when ignited--will flash momentarily, but not sustain combustion.
Flux	A condition of continuous movement or flow.
Frequency Ranking	An estimate of the number of times a fire event will occur within a specified time, measured on a scale from "Anticipated" to "Beyond Extremely Unlikely."
Fully Developed Fire	Steady or postflashover fire at peak heat release rate.
Geometry of Fuel	Placement of fuels within a building.
Geometry of Structures	The ceiling height and configuration, construction materials, interior finish flammability, and location of the structure on the site.
Hazard	Chemical or physical condition that has the potential for causing damage to people, property, or the environment.
Heat	The energy needed to maintain a change in temperature.
Heat Flux	The rate of energy transferred to the surface.
Heat of Combustion	Energy produced when a unit of fuel is completely burned with pure oxygen. See "Latent Heat of Combustion."

Heat Release Rate	Mass heat loss rate times the heat of combustion and combustion efficiency (portion of the mass actually converted to energy).
HPR	Highly Protected Rate (or Risk). An insurance policy rate that provides a cost incentive based on the degree of fire protection available.
ICBO	International Conference of Building Officials.
ICC	International Code Council.
Ignition Temperature	The minimum temperature to which a substance must be heated to ignite and sustain combustion.
Latent Heat of Combustion	Energy produced when a unit of fuel is completely burned with pure oxygen.
LRC	Learning Resource Center.
Life Safety Criteria	Criteria that address survivability of persons exposed to fire and its products.
NFPA	National Fire Protection Association.
NIST O&M Manual	National Institute of Standards and Technology Operations and Maintenance Manual. A manual included in the design documentation that provides details for owners and tenants outlining inspection, testing, and maintenance required to ensure that the building is constructed to the design and continues over time to conform to the design assumptions.
Oxidizing Agents	Air or other material that yields oxygen or other oxidizing gases or reacts to promote or initiate combustion or combustible materials.
Performance-Based Code	A code or standard that specifically states its fire safety goals, and references acceptable methods that can be used to demonstrate compliance with its requirements.
Performance-Based Design	An engineering approach to fire protection design based on established fire safety goals and objectives, deterministic and probabilistic analysis of fire scenarios, and quantitative assessment of design alternatives against the fire safety goals and objectives, using accepted engineering tools, methodologies, and performance criteria.

Performance Criteria	Criteria stated in engineering terms with which the adequacy of any developed trial designs will be judged.
Piloted Ignition	Ignition that occurs when an arc, spark, ember, or open flame ignites fuel vapors.
Premixed Flame Process	The combustion process where pure fuel vapors and air or oxygen are mixed before ignition. See "Diffusion Flame Process."
Prescriptive Codes	A group of codes which provide specific design, construction, and maintenance requirements for buildings, fire prevention, mechanical systems, plumbing systems, energy conservation, barrier-free access, and the like.
Prescriptive Design	An option within a code where compliance is achieved by demonstrating compliance with specified construction characteristics, limits on dimensions, protection systems, or other features.
Probabilistic Analysis	An evaluation of the fire losses and fire consequences that includes consideration of the likelihood of different fire scenarios and the inputs that define those fire scenarios.
Project Scope	Identification of the boundaries of the performance-based analysis or design, including building use, design intent, project constraints, design and construction team organization, project schedules, and applicable regulations.
Pyrolysis	Transformation of a material into one or more other substances by heat alone.
Pyrolyzate	The products of pyrolysis, including volatile and inert gases, and particulate.
Radiation	Transfer of heat energy from a hot surface to a cooler surface by electromagnetic waves.
Radiation Feedback	The condition of electromagnetic waves reflected from one heated surface to another.
Risk	Mathematical probability that an event or sequence of events involving hazards will result in varying degrees of damage to people, property, or the environment.
Risk Binning	In risk analysis, the practice of measuring the consequences of the most severe events and matching them with their approximate frequency.

Rollover or Flameover	Occurs when underburned smoke and gases accumulate in the ceiling layer of a compartment and ignite.
SBCCI	Southern Building Code Congress International, Inc.
SFPE	Society of Fire Protection Engineers.
SI or SI Units	*System International*, the units of measurement based on a decimal system, including meters (length), liters (volume), newtons (energy), pascals (pressure), etc.
Spontaneous Ignition	Ignition in which certain fuels become self-heating.
Stack Effect	The natural, vertical air movement in buildings caused by temperature differences and densities between indoor and outdoor air.
Stakeholder	Anyone who has a share or an interest in an enterprise and is therefore interested in its successful outcome.
Steiner Tunnel Test	A standard test apparatus to measure surface flammability of materials.
Temperature	The measurement that expresses the degree of molecular activity of a material compared to a reference point such as the freezing point of pure water. Temperature is described in English units as degrees Fahrenheit, in SI units as degrees Celsius, and in scientific texts as degrees Kelvin.
Trial Designs	A variety of engineering and architectural solutions developed to meet the client's needs and fire protection/life safety requirements.
T^2 Fire	A fire where the heat release rate increases proportionately to the square of the time since ignition.
Uncertainty	In risk analysis, those factors or conditions--if altered--affect the anticipated outcome.
Ventilation-Controlled Fire	Fire that is controlled by the amount of oxygen.
Zone Model	A fire effects model that divides a compartment into a hot gas upper zone and a lower, cooler zone. In a few zone models there also is a fire plume zone.

APPENDIX C

STUDENT FINAL PROJECT

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PERFORMANCE-BASED DESIGN ANALYSIS OF A SHOPPING MALL

U.S. Approach

Prepared for the Third International Conference on Performance-Based Codes and Fire Safety Approach Methods

Lund, Sweden
June 2000

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PERFORMANCE-BASED DESIGN ANALYSIS OF A SHOPPING MALL
(U.S. Approach)

INTRODUCTION

The Society of Fire Protection Engineers (SFPE) has recently published the *SFPE Engineering Guide to Performance-Based Fire Protection Analysis and Design of Buildings* (GUIDE). As a guide document, it provides a methodology for conducting performance-based designs. It is the intent of this exercise to follow this methodology in performing a case study of a mixed-use shopping mall.

The scope of this study is to follow the steps in the GUIDE, including participation by stakeholders. Further, it evaluates the GUIDE as a matter of course for its usefulness as a reference document for conducting a performance-based design analysis of a specified building. Underlying this evaluation is an assessment of three trial designs which must meet defined performance goals. The trial designs are also compared to a prescriptive design solution in terms of equivalent life safety, property protection, cost/benefit, and relative risk.

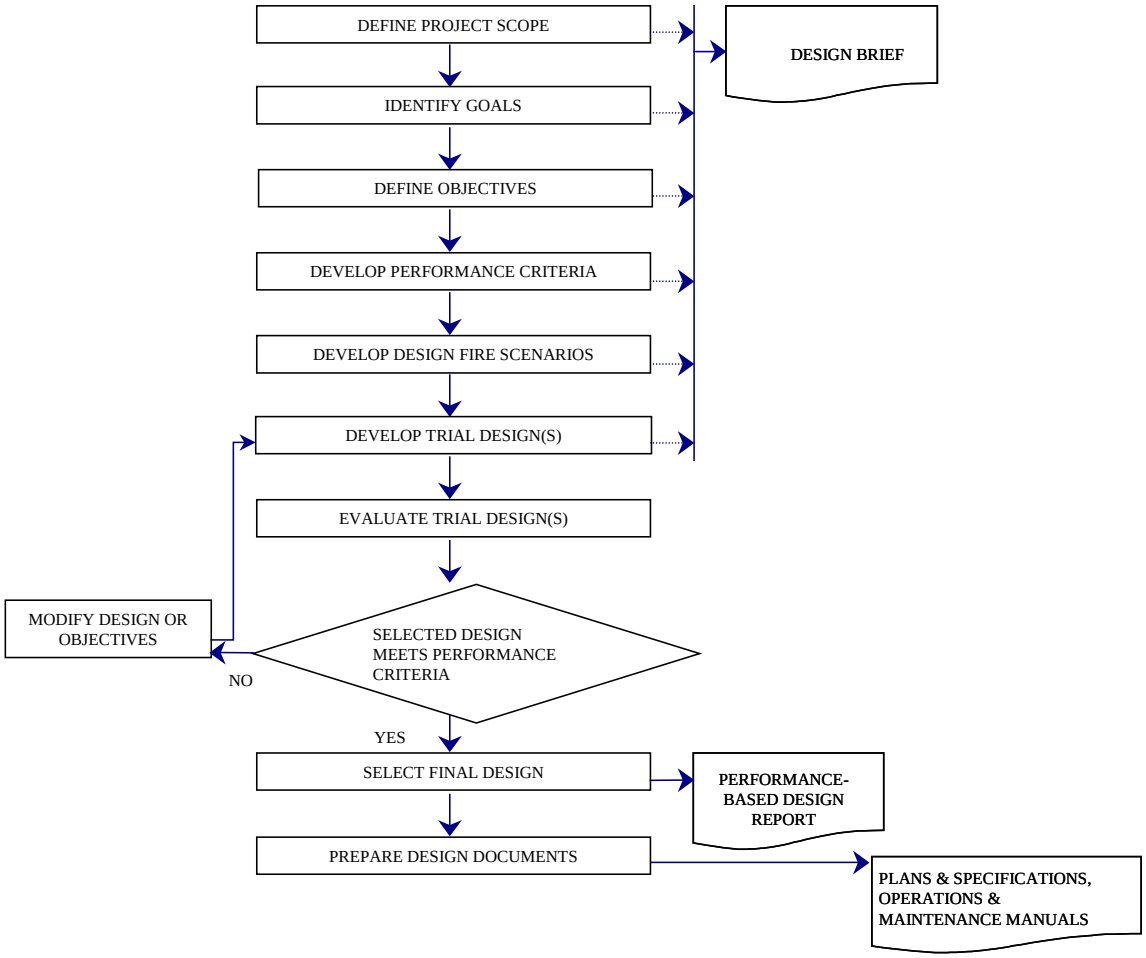
Several representative stakeholders participated in this study. They were an architect, a building official, a fire official, and a fire protection engineer. The stakeholders undertook a mock approval process to discuss the relevant aspects of the study, including the goals and objectives, engineering tools and methods, assumptions, factors of safety, and design fire scenarios.

All aspects of the performance design were documented in a design brief that was reviewed and accepted by the stakeholders. This report includes the information presented in the design brief along with the results of the trial design evaluation.

Method--SFPE Design Guide

The GUIDE was developed, in a consensus process by the membership of SFPE, as a guidance document for qualified engineers and authorities having jurisdiction "to determine and document the achievement of fire safety goals for a particular project over the life of a building."[1] It provides a logical framework (see Figure 1) for conducting performance designs and recognizes both deterministic and stochastic approaches to evaluating performance of various buildings or similar structures.

Figure 1: Performance-Based Design Flow Chart



Building Description

The building is designed to meet the specifications of the case study in the following manner. The shopping mall has four floors with a footprint of approximately 28,000 square meters (m^2). Inside the building there is one atrium interconnecting all three interior levels.

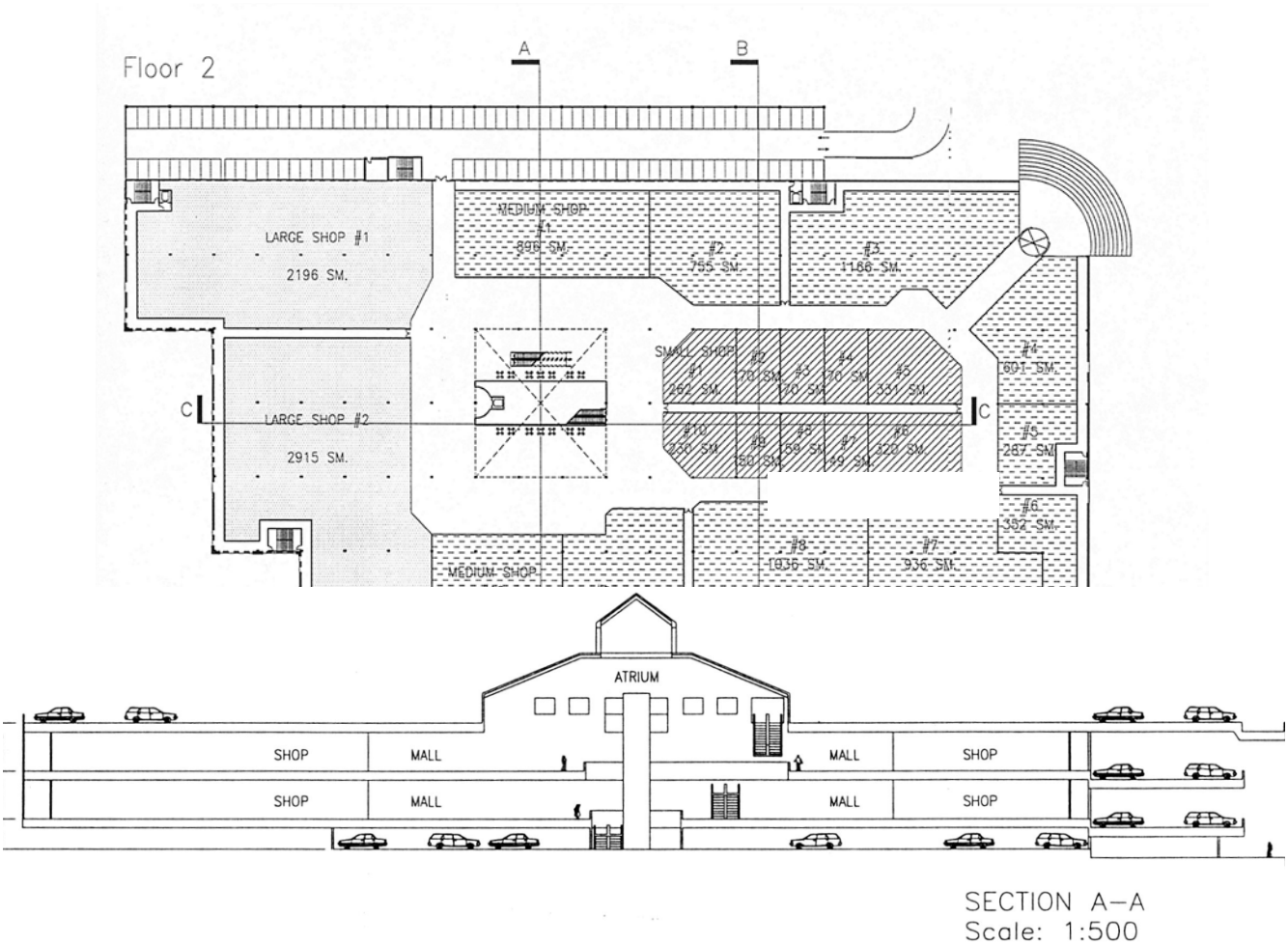
The building contains the following sizes and number of shops which are used for selling clothes, electronics, cosmetics, provisions, books, liquor, etc. All shops are equipped with some kind of display window, with unprotected openings into the common mall circulating paths.

- Four large size shops (2,000 to 3,500 m^2)
- Twenty medium size shops (600 to 1,300 m^2)
- Twenty small size shops (100 to 300 m^2)

There is a parking garage on the first floor and rooftop parking on the fourth floor. The building contains two restaurants; one on Floor 2 and one on Floor 3. Each of the restaurants have seating

for 200 people. In the atrium, there is a food court with seating for 50 people at each of Floors 2 and 3. The plan for Floor 2 and a cross-section through the atrium are shown in Figure 2.

Figure 2: Retail Floor Plan and Detail Section



Prescriptive Design

The prescriptive design is based upon the application of the 1997 Edition of the Uniform Building Code (UBC). The UBC is widely adopted in jurisdictions throughout the western half of the United States. Although the case study does not explicitly fit the code definition of a covered mall building, many of the mall provisions have been applied to the building design as a best-fit solution.

CONSTRUCTION

The building will be built with a fireproofed steel structure which qualifies as Type I Fire-Resistive construction. This requires a three-hour, fire-resistive structural frame, with two-hour, fire-resistive, floor-ceiling assemblies and shaft enclosures.

The mixed uses: mercantile (M), assembly (A-3), and parking (S-3), require fire-resistive occupancy separations as follows:

- M/A-2.1 (one-hour)
- M/S-3 (one hour)
- A-3/S-3 (two-hour)

Included is a one-hour separation between the first-floor garage and mall escalator lobby which opens into the building core. This maintains the occupancy separation at the atrium interface.

The non-structural exterior walls will be non-rated, as it is assumed that a nominal 40-foot setback to all property lines and any other structures exists.

The mall circulation area on Floors 2 and 3 will have non-rated, unprotected openings at all the storefronts, which is consistent with the covered mall provisions of the UBC. The back-of-house corridors and passageways will have a one-hour, fire-resistive rating.

EXITS

The occupant load for the two-story mall portion is based upon an occupant load factor of 1 person per 3.7 m^2 of gross leasable area (GLA). The parking levels have occupant loads based upon 1 person per 18.58 m^2 of gross floor area. This results in a population distribution and required exit widths shown in Table 1.

Table 1: Population and Exit Widths

Floor	Occupants	Required Exit Width
1	915	4.6 m
2	4,175	31.8 m
3	4,256	32.5 m
4	1,321	10.1 m

The required exit width is determined by the product of the occupant load and a factor of 5.08 mm/occupant for level travel, and 7.62 mm/occupant for stairs.

Maximum travel distance to an exit from within the mall and from within any tenant space to the mall is 61 meters. The maximum travel distance in the parking levels is 76.2 meters. In all cases, dead-end travel cannot exceed 6.1 meters.

FIRE PROTECTION SYSTEMS

An automatic fire sprinkler system will be provided throughout the building. In addition, suppression activities will be supported with standpipe valves located at each floor within the

stairwells at the entrance to exit corridors from the mall, and at other locations in the building, to allow the reach of a 45-meter hose line.

A fire alarm system will be provided throughout the building which monitors sprinkler waterflow devices, tamper switches, and smoke detectors. The system will be monitored by a central station service. A public address system will be accessible to security and fire service personnel.

A mechanical smoke control system will be provided within the two-level common mall and three-level atrium core. This system will exhaust smoke from the top of the atrium at a rate of 59 m^3/s. This is based upon a 5 MW design fire located at the first level landing of the escalator core. The system is sized to maintain the upper smoke layer at least 3.05 meters above the third floor, which is open to the atrium, as is required by UBC Section 905. Make-up air is mechanically supplied at the base of the atrium and into the common mall at a location remote from the atrium.

The smoke control system will be automatically activated based upon waterflow within the mall/atrium zone or smoke detection within the mall/atrium zone. All the mechanical systems and controls will be provided with emergency power with a standby generator.

PERFORMANCE DESIGN

Define Project Scope

The first step in the process is to define the scope of the project. The project scope is the problem definition and contains information about the building itself, project stakeholders, project peculiarities, budgets, timeliness, and applicable regulations.

An analysis of alternate trial designs will be undertaken to document the cost/benefits of each design strategy which represents deviations from the prescriptive solutions. The performance of each design will be measured against established goals and objectives agreed upon by the stakeholders.

For comparison to the prescriptive solutions, this analysis assumes that a design which meets the minimum prescriptive requirements of the UBC will meet the life safety, firefighter safety, and property protection goals and objectives of the performance design. This is implied by the wide acceptance of this code as a means of addressing society's concern of protecting the well-being of the community.

The shopping mall has a trained security force on duty 24 hours a day. They are trained to immediately respond to the location of any fire reported in the building in order to initiate evacuation and to communicate with the firefighting first responders. The shopping mall is located in a jurisdiction that is protected by an ISO-rated, "Class I" Fire Department with a maximum response time of six minutes.

IDENTIFY GOALS

The second step in the process is to identify the project goals. During the stakeholders' meeting, stakeholders state what their goals are for the project and the importance of each goal relative to the project. The stakeholders, as a whole, decide on the final ranking of project goals. Project goals are generated in reaction to the specifics of each project, such as building type, intended use, intended occupancy, and site location. For the case study, the goals are as follows:

GOAL A--Minimize fire-related injuries and prevent undue loss of life;

GOAL B--Minimize fire-related injury to the firefighters;

GOAL C--Minimize fire-related damage to the building and its contents;

GOAL D--Reduce construction costs while maintaining fire/life safety and property protection as defined in goals a, b, and c;

GOAL E--Increase return on investment by increasing GLA while maintaining the level of fire/life safety and property protection defined in goals a, b, and c.

DEFINE OBJECTIVES

The third step in the process is to define project objectives. These objectives are developed to define each goal qualitatively in a manner which can then be more easily quantified for the analyses. The following are the objectives for each goal:

Goal A

- **Objective A-1**--provide adequate time for those people not intimate with the first materials burning to reach a place of safety without being overcome by the effects of fire and fire effluents.

- **Objective A-2**--provide adequate time for those people outside the room or compartment of fire origin to reach a place of safety without being overcome by the effects of fire and fire effluents.

- **Objective A-3**--provide adequate time for those people outside the floor of fire origin to reach a place of safety without being overcome by the effects of fire and fire effluents.

Goal B

- **Objective B-1**--prevent structural failure of the building during fire suppression activities.

- **Objective B-2**--provide means of identifying the location of the fire upon arrival at the building.

- **Objective B-3**--provide means of supporting manual fire suppression activities.

Goal C

- **Objective C-1**--limit fire spread and thermal damage to the floor of fire origin.

- **Objective C-2**--limit smoke damage to the fire floor and the floor above.

Goal D

- **Objective D-1**--measure initial and 20-year life cycle cost savings.

- **Objective D-2**--determine that the design remains within an "acceptable risk" for occupants, firefighters, and property.

- **Objective D-3**--meet minimum fire/life safety and property protection objectives for goals a, b, and c.

Goal E

- **Objective E-1**--measure 20-year revenue difference from increased leasable area.

- **Objective E-2**--determine that the design remains within an "acceptable risk" for occupants, firefighters, and property.

- **Objective E-3**--meet minimum fire/life safety and property protection objectives for goals a, b, and c.

DEVELOP PERFORMANCE CRITERIA

The fourth step in the process is to develop performance criteria. It is these criteria or requirements that the proposed designs are judged against for failure and success. A proposed design that meets the performance criteria is, in turn, viewed as having successfully met the stakeholder objectives. Performance criteria further quantifies the design objectives by assigning numerical descriptors to the objectives.

This analysis examines the performance requirements of the proposed design with respect to occupant life safety, firefighter safety, and property protection. The following **occupant life safety performance criteria** are considered:

- **Thermal Effects**. The impact of the thermal effects on occupants is driven by the effects of convective and radiative heating. The convective criteria is related to the temperature of the air that the occupants will be breathing, and the radiative criteria is based on exposure to either a hot gas layer or energy source. The criteria used in this analysis are based on the assumption that occupants cannot breathe "wet" air at more than 100° C, and "dry" air at more than 220° C[2]. These criteria were developed for skin burns, but may be used to determine general tenability, as damage to the respiratory tract has not been observed without coincident damage to the skin[3].

  The criteria for tenability related to radiative effects assumes that the occupants will not be exposed to a heat flux greater than 2.5 kW/m^2. This value is derived from experiments conducted by Perkins et al[4] using searchlights, and is suggested by Babrauskas[5] for use in modeling applications.

  Progressive ignition and its impact on egress is examined. Based on the likely fuels and configuration, point-source radiation modeling and ray tracing is employed. Furthermore, temperature ignition criteria are examined in the context of fire spread and its impact on smoke production in the common egress areas of the mall.

- **Visibility.** In addition to the consideration of irritant and narcotic chemicals found in fire products, it is important to consider the psychological impact of smoke in the context of visual obscuration. Depending on whether occupants are familiar with the space, as well as the nature of the space, different obscuration criteria can be established. Two criteria have been established for this analysis. For occupants in the tenant spaces, a criteria of OD/m = 0.5, as suggested by Babrauskas[6] is used. This value for smoke obscuration will allow for about 2 meters, which should be sufficient to allow for occupants in an involved tenant space to find their way out of that space. Alternatively, in the more vast areas of the mall, where substantial distances exist between exits, a value suggested by Rashbash[7] of OD/m = 0.08 is used, corresponding to about 10 meters of visibility. This value also corresponds with values used by others for occupants unfamiliar with an escape route.

- **Toxicity.** Toxicity criteria is based on the Fractional Equivalent Dose, where unity represents either impairment or death, depending on the relationship being used. Specifically, the analysis considers the presence of outlying toxic gases such as CO and HCN. Fire Dynamics Simulator (FDS) is used to determine species concentrations in those areas immediately adjacent to the fire source in order to ascertain whether toxicity adversely impacts the ability of occupants to safely and reasonably evacuate. Percent of CO in the bloodstream is determined using the following equation:

$$\%COHb = (3.317x10^{-5})(ppm\ CO)^{1.036} RMV\ (t)$$

Loss of consciousness occurs at approximately 34% COHb.[8] Depending on the concentration of HCN in the air, two equations are used, as follows:

Concentration 80-180 ppm

$$(t_{Icn})(min) = (185\text{-}ppm\ HCN)/4.4$$

Concentration >180

$$(t_{Icn})(min) = exp(5.396 - 0.023 \times ppm\ HCN)$$

These equations represent the time to incapacitation based on HCN concentration in parts per million.[9]

The following **firefighter safety performance criterion** is considered:

- **Structural Failure.** The integrity of the steel structure, when exposed to the fire, must be considered. The critical temperature of steel (T_s) for this analysis is 538°C, as described in ASTM E-119, "Standard Test Methods for Fire Tests of Building Construction and Materials." The protected steel temperature is calculated by iterating the equation:

$$\Delta T_s = \frac{K_i}{C_{sh} \, W/D} \left(T_f - T_s\right) \Delta t \; ^{10}$$

  The thickness of the fireproofing is per the manufacturer's specification and the thermal capacity of the insulating material is to be neglected. Temperature of the fire (T_f) will be estimated in the modeling calculations.

The following **property protection performance criteria** are considered:

- **Fire Spread.** The effect of fire spread on property is studied for two cases. First, fire spread from a tenant space is examined. Within this area, fire spread is assumed to be confined to the zone of origin if the average temperature of the upper layer can be maintained such that flashover does not occur. To calculate this phenomenon, methodologies proposed by Thomas[11] are referenced. Thomas uses an upper layer temperature of 577° C for flashover criterion. Second, fire spread from a fire originating outside a tenant space will be bounded by an upper layer temperature of 325°C which is the average temperature at which most organic solids undergo pyrolysis.[12]

- **Smoke Spread**. Smoke spread for property protection is defined differently than for life safety. Smoke of any quantity or quality can cause damage to property, depending upon the property's specific sensitivity. Since temperature is considered a signature of fire and smoke spread, the boundary for smoke migration is defined as areas of temperature increase greater than 20°C from ambient conditions.

DEVELOP DESIGN FIRE SCENARIOS AND DESIGN FIRES

The fifth step in the process is to develop design fire scenarios and design fires from all of the possible scenarios. Design fire scenarios are descriptions of reasonable yet severe fires that could possibly threaten a building or its occupants. Design fire scenarios are described by elements such as building geometry, available fuels, potential ignition sources, fuel

configurations, etc. The nature of the design fire scenarios is also influenced by fire suppression systems, mechanical and natural ventilation systems, and other environmental factors.

Design fires are typically quantified in the form of a heat release rate, mass loss rate, smoke production rate, and species yield. These design fire descriptions are arrived at based upon an examination of the combustible contents, the proximity and likelihood of ignition sources, as well as the likely failure mechanisms and supporting history for failure that would result in a fire event.

Several major assumptions are made with respect to narrowing the field of design fire scenarios:

1. The case for multiple simultaneous fires will not be examined.

2. The case for a thoroughly executed arson will not be used.

3. The suppression systems will be assumed to be in working order and operating according to their respective designs.

4. Simultaneous occurrence of fire and other natural disasters such that passive and/or active systems are compromised will not occur.

Of those fire scenarios examined, two were deemed both likely and severe in the context of those goals previously identified in this document:

1. **A Fire Located in a Typical Tenant Space.** It is assumed that sprinklers would actuate and control heat release rate while simultaneously cooling the smoke. This scenario was chosen because of the large fuel loads, as well as the numerous potential ignition sources. Based on research performed by Law[13], it was determined that a typical footprint for this scenario would be approximately 9 m^2, limited by sprinklers and/or fuel configuration. Typical fuels include, "…miscellaneous cellulosic combustibles and foamed plastics to represent a display in a typical [hardware store]...". The total weight of the materials was assumed to be about 100 kg, most of which was comprised of plywood.

   It is important to note that sprinklers used in Law's research, though assumed to operate, were obstructed, thereby reducing their effectiveness. The steady state heat release rate was estimated to be about 5 MW, growing at a rate corresponding with a fast fire as defined in the SFPE Handbook of Fire Protection Engineering where $\alpha = 0.0469$ in the equation $\dot{Q} = \alpha t^2$.[14] Figure 3 depicts the severe-case tenant space heat release rate history used in this analysis.

2. **A Fire Located in the Common Egress Areas (or Mall Areas) of the Retail Center.** It is assumed that sprinklers will actuate in a delayed fashion, such that the maximum heat release rate will likely be fuel limited prior to sprinkler actuation. Two locations for this fire are considered: at the main court, and at the remote end of the "horseshoe" section of the mall. Regardless of the location, the primary ignition sources are assumed to be electrical in nature, originating within the kiosk display.

The fuel in question was assumed to be a generically represented vendor kiosk (50% cellulosic, 50% plastic) approximately 1.22 meters in height, 2.44 meters long, and 1.22 meters wide. The weight of combustible fuels was assumed to be 200 kg and the effective heat of combustion was assumed to be approximately 20 MJ/kg. The unbounded heat release rate depicted in Figure 4 assumes a fast fire growth rate followed by a period of steady state heat release, finally terminating in fast decay once the fuel mass has had a chance to burn away completely. It is assumed, and can be demonstrated, that adjacent fuels have sufficient distance such that they will not ignite as a result of convective or radiant exposure to the fuel item in question.

Figure 3: Heat Release Rate History

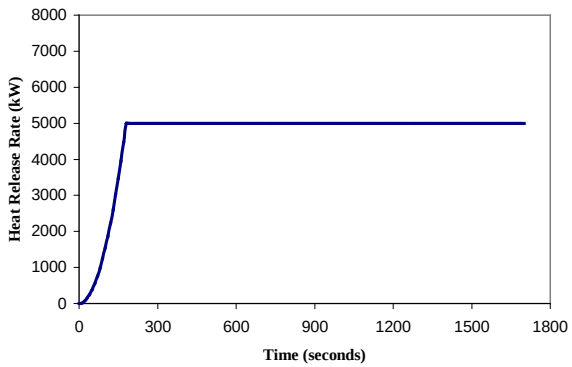
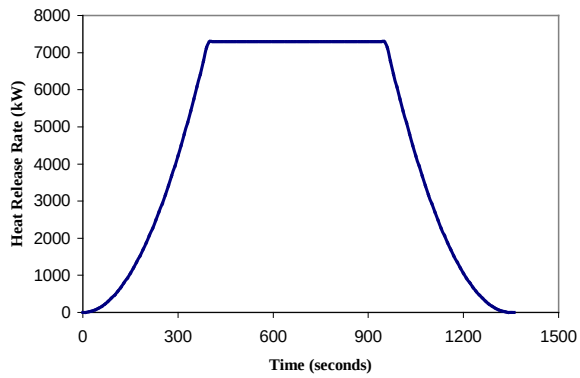


Figure 4: Heat Release Rate History

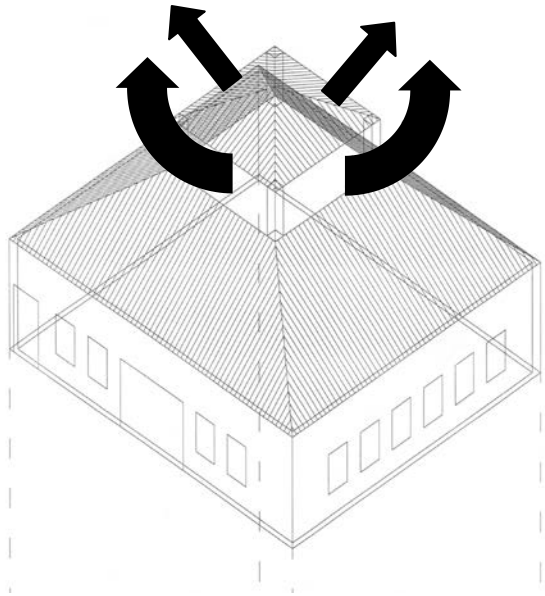


DEVELOP TRIAL DESIGNS

The sixth step in the process is to develop trial designs. Trial designs are possible solutions to meeting the project design objectives defined in Step 3. There will be three trial designs for this study. Each one will be compared to the prescriptive design.

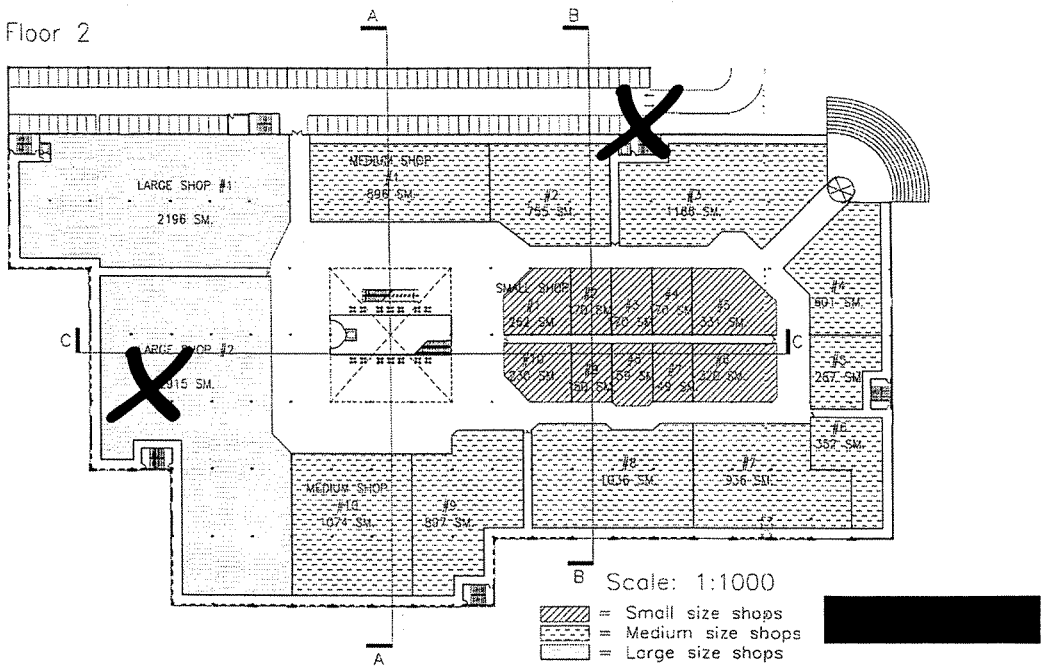
The first trial design will meet all of the prescriptive design requirements except that the mechanical smoke control system will be replaced with a natural ventilation system. Smoke is vented at the top of the atrium through four rooftop openings as shown in Figure 5. Gravity intakes for make-up air are provided at the base of the atrium and at the end of the mall remote from the atrium. The system has mechanical dampers which open upon smoke or fire detection within the building. The dampers fail open in the event of a power failure. This design is being tested to determine if it meets the objectives for Goals A, B, C, and D. There is no expected reassignment of space to GLA as desired by Goal E.

Figure 5: Natural Ventilation Detail--Top of the Atrium



The second trial design will meet all of the prescriptive design requirements except that the capacity of the exiting system will be reduced by removing two stairs as shown in Figure 6. This design is being tested to determine if it meets the objectives for Goals A, B, C, D, and E.

Figure 6: Deletion of Stairs



The third trial design will meet all of the prescriptive design requirements except that the fire resistance of the structural elements and floor-ceiling assemblies will be reduced to one-hour from the prescribed three-hour and two-hour ratings respectively. Additionally, the sprinkler system will be provided with a second point of connection to the municipal water supply. An administrative requirement for monthly inspection and testing of the sprinkler system will be employed. This design is being tested to determine if it meets the objectives for Goals A, B, C, and D. There is no expected reassignment of space to GLA, as desired by Goal E.

EVALUATE TRIAL DESIGNS

The seventh step in the process is to evaluate the trial designs. Trial designs are evaluated against performance criteria for failure or success. The goals of the trial design evaluations are to quantify the response of the design fire to the trial design, determine if the designs meet the performance criteria, and select the final design.

The evaluations are performed with the aid of engineering tools, including computer programs, manual calculations, and empirical data. For this evaluation, three deterministic computer models, EVACNET4, DETACT, and FDS will be used.

Egress Evaluation--EVACNET4

The purpose of the timed egress analysis is to demonstrate that occupants within the building could exit before conditions in the building become hazardous to life, as defined previously. The proposed arrangement has occupants exiting from tenant spaces into the mall and into back-of-house corridors that eventually lead to stairs and the exterior.

In calculating the egress time for occupants, hazardous conditions are determined for the entire length of egress travel where necessary. Thus, if fire or combustion products spread outside the area of origin, their effect(s) on exiting occupants can be evaluated. Successful egress is defined as the ability of occupants to travel to an exit without being subjected to conditions hazardous to life at any time during their travel.

The relationship between time necessary for occupants to egress, and the time to hazard is best described by a simple mathematical relationship. It is as follows[15]:

$$t_{lt} >= (t_d+t_a+t_o+t_i+2*t_t) = t_{ev}$$

where: t_{lt} = time from ignition to conditions hazardous to life.
t_{ev} = evacuation time.
t_d = fire detector response time
t_a = time from detection to occupant notification. A value of 0.1 minutes is used in the analysis.
t_o = time from notification to occupant response. A value of 0.5 minutes is used in the analysis.
t_i = time for occupants to investigate fire, collect belongings, and fight fire. A value of 0.5 minutes is used in the analysis.
t_t = occupant travel time to a place of safety.

In the previous equation, the factor of 2 associated with the occupant travel time is a factor derived from field studies used to match the calculated occupant travel time to that predicted by egress models. It is used to correct the calculated travel time for egress model uncertainties, and the possibility of blocked exits.

The occupant travel time is modeled with EVACNET4. This is a Windows 95® compatible version of the original EVACNET+ software developed by Professor Thomas Kisko at the University of Florida. The EVACNET4 evacuation model is set up similar to a hydraulic calculation computer program. The evacuation network consists of nodes that represent places where occupants are present and can make choices as to their path of travel. Nodes consist of a capacity that may be present at one time and an initial occupant load. The nodes are connected with arcs, which represent the paths people may take while in motion.

Arcs consist of a travel time, which is the time it would take one person to travel the complete distance without obstruction, and a dynamic capacity. The dynamic capacity represents the upper bound of the flow rate per time step through an arc. This upper bound is usually represented by the most restrictive passage width or door. The nodes and arcs connect occupant locations and exits. The movements of groups of people are calculated at discrete time steps of 10 seconds.

The output of the EVACNET4 program allows the designer to see how efficiently the egress design is utilized. The output consists of tables of data that list the numbers of people utilizing specific paths, doors, stairs, etc. over time. It also lists the numbers of people queuing at various locations at each time step during the evacuation. The information is useful in determining how egress layouts can be modified to increase efficiency and/or reduce egress time.

In order to calculate the travel time for occupants of the facility, the travel speeds of the occupants must be estimated. The travel speeds of occupants moving over level paths will differ according to the occupant density. A travel speed of 1.02 m/s is used for mall areas and 0.76 m/s used for tenant areas based on studies of people movement.[16]

In order to model the movement of people with the EVACNET4 model, the general travel speeds are further refined to account for evacuation path width, stairs, and doors.[17] For walkways, it is assumed that people flow at a maximum rate of 15 people per foot of width per minute (PFM). For movement through stairs, it is assumed that people flow at a maximum rate of 10 PFM. The horizontal travel speed through stairs is taken to be 0.51 m/s.

In evacuation models, occupant flow through doors is typically addressed by examining the number of door leafs available.[18] For exit and stairway doors, the maximum flow rate of people is assumed to be 60 people per minute per leaf. A summary of travel speeds and flow rates is contained in Table 2.

Table 2: Travel Speeds and Flow Rates

Location	Travel Speed (m/s)	Flow Rate Per Width
Mall	102	15 PFM
Tenant Spaces	0.76	15 PFM
Stairs	0.51 (horizontal distance)	10 PFM
Doors	N/A	60 people per minute per leaf

Detector and Sprinkler Activation--DETACT

The fire detector and sprinkler response times are calculated using a heat transfer model. DETACT will be used to simulate the activation of area detectors and sprinkler fusible link elements. For smoke detectors, a Response Time Index (RTI) of 1 is used and the detector is assumed to activate with a temperature change of 11.1°C.[19] Sprinklers are assumed to have a temperature rating of 73.9°C and an RTI of 65. DETACT inputs consist of basic geometry definitions as well as ambient temperature, sprinkler spacing and characteristics, and fire characteristics. DETACT assumes a homogenous upper layer interacting with a smooth ceiling where there are no heat losses to the ceiling.

Fire Effects Evaluation--Fire Dynamics Simulator

To assist the design team in its efforts to quantify the effects of the design fires via fluid flow modeling, a Computational Fluid Dynamics (CFD) program developed by the National Institute of Standards and Technology (NIST) is utilized. The FDS model is used to characterize low speed hot gas flows represented by the Navier-Stokes equations. Additional subroutines are used to ascertain the production and behavior of smoke as well as certain aspects of sprinkler actuation during typical fire events. The OpenGL graphics program, *Smokeview*, is used to visualize the numeric output of the CFD model. Primarily steady state conditions are modeled using FDS. Appropriate documentation of the modeling software and its mathematical components can be obtained from NIST.[20]

Each case examined in FDS originates from an input data file, which contains all of the necessary information to describe the scenario. Included in the input file are descriptions of the following:

- **Physical Size of the Domain.** The domain modeled by FDS assumes a variable rectilinear grid where portions of the grid can be blocked to better simulate geometric configurations that may exist in the modeling domain. The computational domains include the areas immediately adjacent to the fire, above the fire, and outside above the smoke vents. The grid is extended above the vent to allow the design team to accurately model the flow through the vent. The grid domain is limited to save computational time.

- **Description of the Energy Source**. The energy sources modeled by FDS are typically steady state, as the design team is concerned about the long-term effect of cooling on smoke distribution as well as arriving at a conservative estimate of smoke production. Because of time constraints, steady state modeling presents a more attractive solution for large grid sizes such as those employed in the modeling of the mall space. Additionally, because of the grid sizes involved, the fire is represented by a solid obstruction of a finite height, with the top of the obstruction being designated as a burner. The area of the "burner" corresponds with the equivalent area of the design fire. Please note that approximately 65% of the energy is assumed to be convective and the balance is radiative.

- **Description of Solid Surface Boundary Conditions.** Other limiting boundary conditions must be prescribed in order to provide a closure mechanism for solving the equations. Solid surfaces are not designated as absorbing media for the radiation associated with the energy (fire) source. The default condition specified for walls is that of an adiabatic, inert surface.

  Though not necessarily presented in the final output, the effects of varying the thermal and velocity boundary conditions are considered. In addition to the default adiabatic condition specified in FDS, it is possible to model constant temperature, thermally thick or thermally thin boundaries.

- **Description of Species Boundary Conditions**. A simple no-flux condition and a species yield condition describing the amount of species N produced as a fraction of the fuel mass loss rate are considered. Species concentrations (ppm) will be predicted.

  In addition to the basic input information described conceptually above, the analysis in question takes advantage of FDS to predict the impact of sprinkler actuation on the fire as it relates to heat release rate and smoke production via cooling of the hot fire gases. A sprinkler definition from the database provided with FDS is used in conjunction with the sprinkler-cooling algorithm. Suppression of the fire due to sprinklers is **not** considered as it is assumed that the sprinklers in the mall are not designed for that purpose.

  The output of FDS contains the listing of the input parameters as well as the numerical solution for the Navier-Stokes equations. Minimally, five channels of output are collected, including temperature, the three velocity components, and the heat release rate. Also of particular interest in the modeling are smoke production and species yield. In addition to the basic three-dimensional output, thermocouple data, sprinkler data, heat release rate, specified slice files, boundary data, and particle data files are also saved. Through the use of these files, results may be viewed in a static or animated form.

- **Validation.** The FDS model has been validated in a number of case studies published by NIST. Four case studies are published in the User's Manual:

- Isolated Fire Plume--Examines validity of LES model and fire specification. This study was completed, in part, to calibrate the plume specifications with previous studies of plume zones conducted by Baum and McCaffrey.[21] Additionally, it was of interest to determine average temperatures and velocities above the fire.

- Sprinkler Study--Examines validity of sprinkler modeling (cooling effects only) for medium-sized space. Twenty-two large-scale fire experiments in a controlled environment were used as the basis of comparison.

- Large Outdoor Fire--Examines validity of large fire using large grids. Also, near field hazard associated with flame radiation was studied.

- Rack Storage Fire--Suppression validation for complicated fuel array in a controlled environment. Nineteen experiments were used as the basis of comparison for this modeling study.

These case studies were useful in validating the pieces of the model, though none can be stated as validating all of the elements of the model as a whole. The simulations performed for the case study analysis were relatively simple, incorporating elements from the Isolated Fire Plume Study, Sprinkler Study, and Large Outdoor Fire. The rack storage fire was not used as a basis of comparison in any fashion for the modeling efforts.

While the design team is aware of other studies that have been performed using FDS, the results of these studies are not readily accessible, and have not necessarily been published in peer reviewed documents. It is also useful to note that the general methodologies and algorithms outlined in the FDS Technical Reference Guide[22] are generally consistent with those used in other Computational Fluids Dynamics models. The general theories associated with heat, mass, and momentum are well developed, as are the algorithms associated with turbulence modeling and similar sub-models. It is believed that the model, as a whole, as well as the sub-models have been used within the boundaries established by the theory as well as those implied by the case studies that have been published.

RESULTS

The engineering analysis was undertaken to determine the performance of the trial designs; natural ventilation, reduction in stairs, and reduction in structural fire resistance relative to the design scenarios and performance criteria. This analysis consisted of evacuation modeling, fire effects modeling, and heat transfer modeling. The data produced by the models was reviewed and deterministically compared to the performance criteria for pass/fail decisions.

Table 3 summarizes the trial/scenario results of the engineering analysis as a function of the performance objectives. This indicated acceptance of all of the trial designs. This optimistic conclusion must be tempered by the fact that the FDS output was limited to 400 seconds for the atrium fire scenario and 720 seconds for the remote mall scenario. The data was not evaluated for toxicity, and the data was not evaluated for radiant exposure to occupants. However, the data

suggests that steady-state conditions would prevail during the time required to evacuate the building. This is consistent with the expected results of a sprinkler-controlled fire. Additional work is necessary to confirm this assumption.

Table 3: Trial/Scenario

Objective	Natural Vent		Δ Stair		FR	
	$T_1(1)$	$T_1(2)$	$T_2(1)$	$T_2(2)$	$T_3(1)$	$T_3(2)$
A1	✓	✓	✓	✓	✓	✓
A2	✓	✓	✓	✓	✓	✓
A3	✓	✓	✓	✓	✓	✓
B1	✓	✓	✓	✓	✓	✓
B2	✓	✓	✓	✓	✓	✓
B3	✓	✓	✓	✓	✓	✓
C1	✓	✓	✓	✓	✓	✓
C2	✓	✓	✓	✓	✓	✓
D1	✓	✓	✓	✓	✓	✓
D2	✓	✓	✓	✓	✓	✓
D3	✓	✓	✓	✓	✓	✓
E1	N/A	N/A	✓	✓	N/A	N/A
E2	N/A	N/A	✓	✓	N/A	N/A
E3	N/A	N/A	✓	✓	N/A	N/A

T_N = Trial Design
(1) = Floor 1 Atrium Fire Scenario
(2) = Floor 2 Remote Mall Fire Scenario
✓ = Passed
X = Failed

The following sections describe the results of the engineering evaluations. References are made to the details of the analyses which are included in the Appendices.

EGRESS EVALUATION

The egress evaluation consisted of two design scenarios; the first was the prescriptive design scenario, and the second was the trial design scenario which deleted two stairwells serving the two mixed-use retail levels and the top parking level.

The prescriptive exiting design is in conformance with the UBC, including number of exits, exit width, travel distance, and distribution of exits. The total occupant load evacuated from the upper levels was 8,431 people. This population was assumed to be evenly distributed throughout the building.

The paths of egress had to be described and input in the EVACNET4 evacuation model. These paths of travel are graphically represented as arcs and nodes in the drawings found in Appendix B. The time for the smoke detector activation (t_d) was calculated with DETACT, which is documented in Appendix C.

The model results of the first scenario analysis indicated that all occupants would be able to flow through the exits and outside the building on grade in a travel time of 11 minutes 50 seconds. When input into the evacuation time equation (see Page 13), the total time for evacuation was predicted to be 26 minutes.

The second scenario included the removal of two stairs, as shown in Figure 5. Otherwise, the size and distribution of other exits and the number of occupants were identical to the first scenario noted above. The results of the model indicated that the time to flow all of the occupants out of the building on grade was 16 minutes 40 seconds. When this travel time was input into the total evacuation time equation, the result was 35 minutes 40 seconds. The calculations for this scenario are included in Appendix B.

The total time to evacuate in each scenario appears reasonable. There are no known references to mall evacuation studies which could be used to verify the results.

Those occupants intimate with the fire were assumed to move away from the fire within 30 seconds after ignition. Their travel speed was assumed to be 0.76 meters per second. At that time, these occupants would be integrated into the total occupant flow moving through the building's exiting system.

These evacuation times are compared to the time for the onset of hazard (temperature and obscuration) predicated by FDS. The natural ventilation system trial design passes since the onset of hazard does not occur prior to the evacuation from the areas of hazard. The prescriptive design solution of the mechanical exhaust system is deemed to comply. Further discussion of these findings is presented below.

FIRE EFFECTS EVALUATION

The data produced by the FDS Model was studied to determine the times predicted when the temperature and smoke obscuration performance criteria had been met or exceeded. The data was taken along points, located 1.8 m above the walking surfaces established throughout the mall. These data points, referred to as "thermocouples," actually track temperature (°C), heat release rate per volume (kW/m^3), smoke density ($\mu g/m^3$), and species (kg/kg). The "thermocouple" identification numbers and locations are shown in Appendix D.

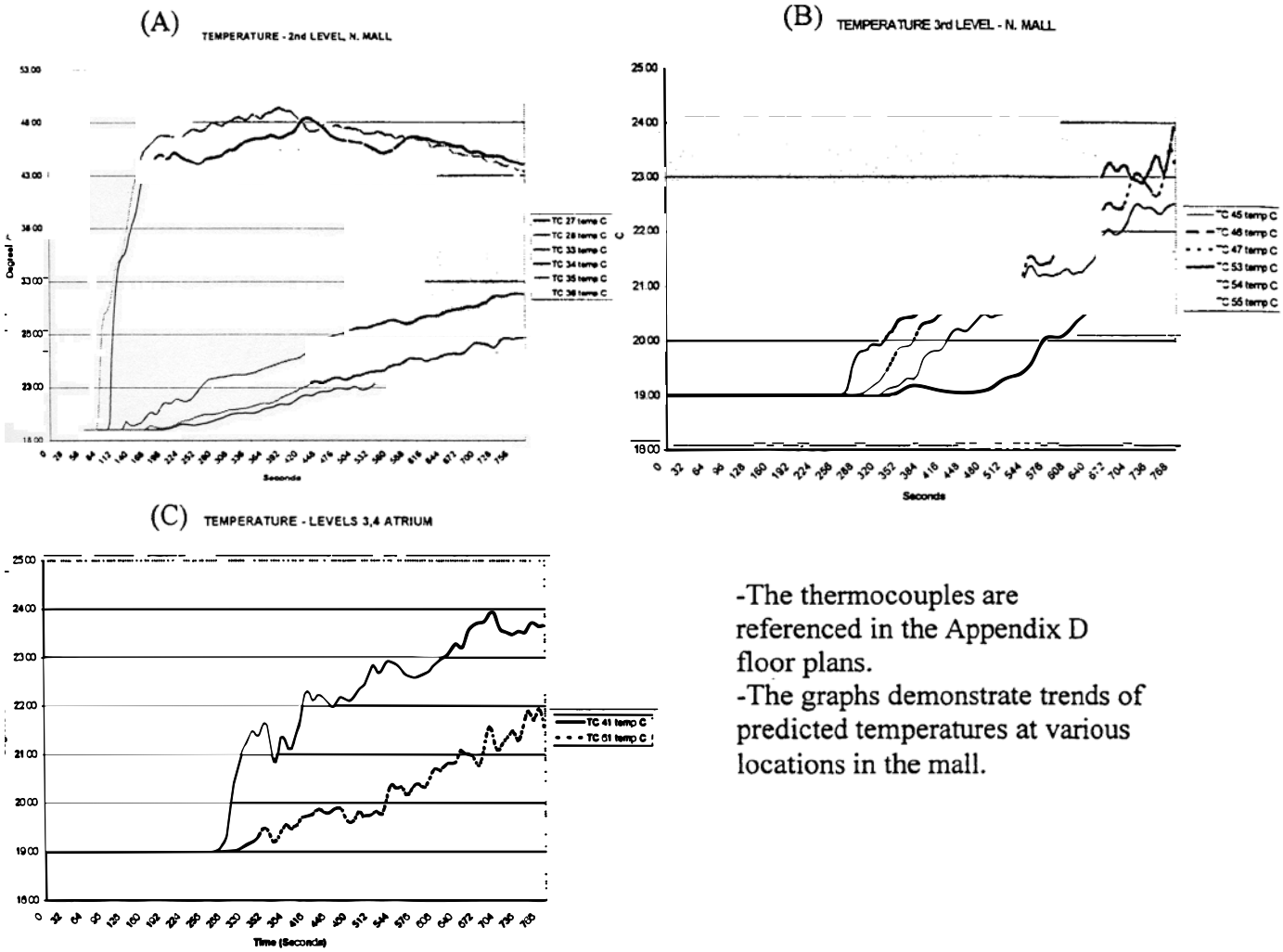
The two design fire scenarios that were evaluated, Floor 1 Atrium Fire Under the Balcony, and Floor 2 Mall Fire Remote from the Atrium, were naturally vented at the top of the atrium. The impact of thermal effects and visibility on occupants, and thermal effects on property, was evaluated. Analysis of other criteria (toxicity, thermal radiation) and other scenarios (mechanical smoke exhaust, fire in a tenant space) was not undertaken due to time limitations. An in-depth compilation of the input data files, assumptions, output files, and references are also included in Appendix D.

Thermal Effects

The data from FDS was downloaded into an Excel file, which could be graphed as a function of time. Temperature profiles, which reflect a series of thermocouples grouped by areas in the mall,

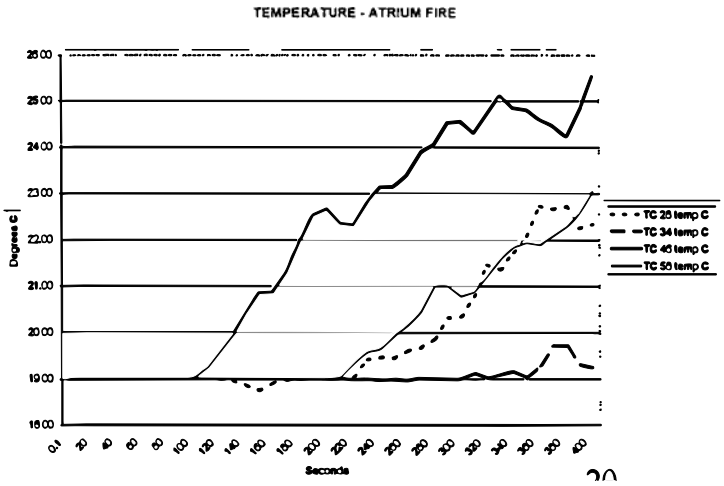
were created to observe areas where the temperature criteria may have been exceeded. The following graphs present some of the critical temperature data that was evaluated.

Figure 7: Remove Mall Fire



-The thermocouples are referenced in the Appendix D floor plans.
-The graphs demonstrate trends of predicted temperatures at various locations in the mall.

Figure 8: Atrium Fire Under Balcony



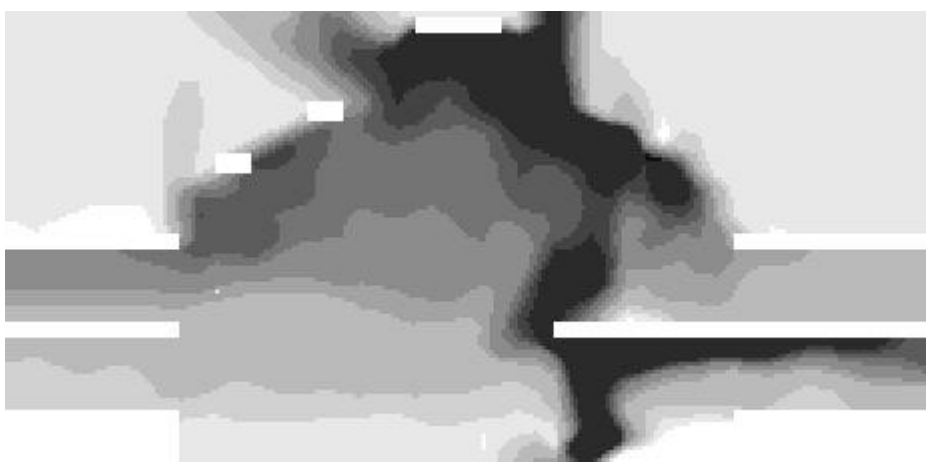
-These thermocouples represent the predicted temperatures at the balconies around the atrium and above the fire. Their exact locations are referenced in the Appendix D floor plans.

The minimum temperature criteria for the onset of hazardous conditions for the occupants is 100°C. This temperature is not seen beyond the centerline of the fire in each of the two fire scenarios tested. Figures 7 and 8 show temperatures <50°C. The temperatures near the fire, Figure 7(A), approach steady-state. The remote locations, Figure 7(B&C) and Figure 8, have lower temperatures that are increasing. However, steady-state temperatures of <50°C are predicated to be observed at these locations as the calculations progress. Therefore, the occupants are not impacted, due to heat, from evacuating safely during the duration of each fire scenario.

The minimum temperature criteria for property damage is 325°C (flame spread) beyond the fire floor, and 39°C, Δ20°C over ambient (smoke spread), beyond the fire floor and the floor above. These temperatures are not evidenced in the model data beyond the floor limits established in Objectives C-1 and C-2. Therefore the property damage objectives have been met.

The model data was also studied qualitatively with the use of the Smokeview graphics package. The color-coded slice files graphically present the isotherms and distribution of other particles as a function of time. The slices, which can be captured in any dimension, provide a powerful tool in analyzing the data quickly (see Figure 9). Unfortunately, the color coding of the graphics package does not easily lend itself to presentation in black and white text such as this. The FDS User's Manual[23] does recommend other graphic tools that are able to capture the data for assessment and presentations.

Figure 9: Thermal Distribution at Atrium Section



Visibility

The two criteria that were established for visibility include the optical density (OD/m) for tenant spaces of 0.5 m^{-1} and for mall areas of 0.08 m^{-1}. These optical densities correspond approximately to a visibility of 2 meters and 10 meters, respectively.

The data set for smoke density is used to determine if and where the performance criterion of OD = 0.8 m^{-1} is exceeded in the mall space. The output from FDS is presented in the form of mass concentration, *m*, with units of $\mu g/m^3$. Therefore, to convert this into optical density, we first determine the corresponding extinction coefficient.

$$K = mK_m$$ [24]

where, K_m= specific extinction coef, 7.6 m^2/g for flaming combustion.

We then calculate optical density per meter,

$$OD = K / 2.3$$ [25]

Generally speaking, the output from FDS shows a lot of scatter. These data would ultimately require further analysis, including sensitivity analysis, by modifying input parameters and data analysis techniques that might help to "smooth" the output into a more readily useable form. As is, the data indicate sporadic "failures" of the mall space optical density criterion.

Other factors may also affect the validity of the model output. Considering that the smoke "measurements" in the model are taken 1.8 meters above the floor, we do not know exactly where the hot gas (smoke) layer interface is relative to the floor. Something to consider for future model runs is to place smoke measurement "thermocouples" at locations nearer the ceiling in order to more accurately determine the level of the hot gas layer. One would expect the model to produce more consistent smoke density predictions within the hot gas layer near the ceiling. Also, smoke optical density measurements in practice are taken over a known path length for light attenuation. Since the model output represents a point measurement, there is question as to the accuracy of the output compared to a real fire situation where, for example, visibility can be measured across a corridor.

For all of these reasons, the data is used here simply as input to help make a qualitative engineering judgment about the spread of smoke through the mall and how occupant egress may be affected, rather than as a strict pass/fail criteria.

Tables 4 and 5 list the time of first "failure" of the criteria for key locations in the second and third floors of the mall for the Atrium Fire and the Remote Fire scenarios, respectively. Discussion of each failure with regard to occupant egress is included. The analysis of smoke density data from FDS is an area for further study, including sensitivity of the model to smoke yield output. More work is needed, especially regarding the placement of "thermocouples" for measuring smoke in the model. Further study should include resolving discrepancies associated with point measurement or prediction of smoke in the model versus dynamic measurement of light attenuation along a known path length.

Table 4: Location and Time to Failure of Mall OD Criteria (OD = 0.08 m^{-1}), Fire in Atrium, Below Balcony

Thermocouple #	Location	Time to exceed OD = 0.08 m^{-1}	Discuss Relative to Egress
TC 110	Third floor atrium walkway, North	190 s	Atrium top and third floor naturally fill with smoke early on in this scenario, natural smoke vents at atrium roof are open during this simulation. Egress paths are still clear.
TC 122	Third floor corridor near small Shop #19, South	370 s	Smoke is beginning to spread into the corridor toward horseshoe section of the third floor. Egress paths are still relatively clear, but starting to see smoke in the horseshoe.
TC 92	Second floor atrium walkway, North	320 s	Smoke is filling at second floor, especially where fire plume hits bottom of balcony.
TC 98	Second floor corridor near small Shop #2, North	370 s	Second floor corridor starting to fill with smoke. Occupants in the horseshoe still have clear access to exit passageways.

Table 5: Location and Time to Failure of Mall OD Criteria (OD = 0.08 m^{-1}), Second Floor Fire in Remote Mall

Thermocouple #	Location	Time to exceed OD = 0.08 m^{-1}	Discussion Relative to Egress
TC 107	Second floor North corner corridor, near medium Shop #3	48 s / 184 s	This location is very near the initial fire (within 30 m), but blocks an exit. Two times are reported because of inconsis-tencies between readings of smoke at this point; readings are more consistent after 184 s.
TC 98	Second floor corridor near small Shop #2, North	116 s / 228 s	Located approximately 50 m down the north corridor, blocking access to the exit stair between medium Shops #2 & 3. Significant gap between the two reported times where no smoke is observed.
TC 92	Second floor atrium walkway, North	460 s	Smoke progression into the atrium area. At this point, occupants still have access to the back of house passageways and three separate stair enclosures.
TC 110	Third floor atrium walkway, North	304 s	This affects primarily the exits near large Shop #3 on third floor. Occupants have access to exits via corridors leading to the horseshoe area of the mall.

Thermocouple #	Location	Time to exceed OD = 0.08 m^{-1}	Discussion Relative to Egress
TC 121	Third floor corridor, near small Shop #20, South	620 s	Smoke is finally beginning to spread into the horseshoe section of the third floor. At this point, occupants have had more than 10 minutes to make their way into an exit corridor, which provides a smoke-tight enclosure protecting them to the exit.

Verification

The design team has not verified any of the data produced from the simulations, except from the standpoint of practical experience. The data will likely need further verification as possible, though to acquire such data is inherently challenging. It is worth noting that the results appear to be consistent with known fire effects behavior with respect to entrainment, average temperatures, yields, and smoke movement.

STRUCTURAL EVALUATION

Firefighter safety is the focus of Goal B. Objectives B-2 and B-3 have been met in the base design with a complete fire alarm system, including detection and annunciation, and a wet standpipe system installed throughout the mall. However, Objective B-1 requires analysis of the building's structural performance during a fire. Since one of the trial designs reduces the fireproofing on the steel structure, this is considered in the performance design analysis. A heat transfer analysis was conducted for the protected structural steel columns and beams to determine the impact of the fire on the structural steel having one-hour protection with a standard specified mineral fireproofing application. The methodology was based upon the numerical method presented by Milke.[26]

Analysis

Milke[27] presents the following equation to estimate the steel temperature of a column protected by an insulating material and exposed by a temperature (T_f),

$$\Delta T_s = \frac{K_i}{C_{sh} \, W/D} \left(T_f - T_s\right) \Delta t$$

Where,

ΔT_s	=	temperature rise in the steel (C),
D	=	heated perimeter (m),
W	=	steel weight per linear foot (kg/m),
c_s	=	steel specific heat (J/kg-c),
T_f	=	exposing temperature (C),
K_i	=	insulation material thermal conductivity (W/m-C), and
h	=	insulation thickness (m).
t	=	time (s)
T_s	=	steel temperature (C)

Solving this equation involves determining the severe-case heated-perimeter-to-steel-weight-per-lineal-foot-ratio, based upon the structural design. Given the lack of an overall structural design, W14X109 members were assumed to pose the most severe exposure. Next, the steel specific heat, insulation material conductivity, and thickness were determined. Finally, the exposure temperature was estimated. The analysis separated the exposure temperature into two regimes: direct flame impingement and exposure due to a plume impingement.

- **Direct Flame Impingement.** The direct flame impingement was estimated to consist of heated gases at temperatures between 1,500°C and 2,000°C. This range is representative of hydrocarbon/air adiabatic flame temperatures and should be a reasonable estimation of expected flame temperatures. However, it is suggested that additional flame temperature studies be performed in the FDS model with a more refined grid within the flame region.

- **Plume Exposure.** The plume temperature was estimated above the flame height. The flame height, virtual origin, and plume centerline temperature were calculated from equations reported by Heskestad.[28] This calculation provides an upper-bound estimate of the maximum plume temperature.

  These parameters were input into a mathematical solver to iterate the steel temperature equation over time. Details of the steel temperature calculations are contained within Appendix E.

Assumptions

This analysis has a number of inherent associated assumptions. Specifically, the following is assumed:

1. Sprinklers will not cool the steel insulation surface nor will sprinklers cool the heated gases exposing the structural steel (conservative, given that the design scenarios assume sprinkler operation).

2. Monokote Type Z-146, produced by W.R. Grace Company, will be used to achieve a one-hour, fire-rated assembly for the structural beams/columns. The thermal conductivity as a function of temperature of Z-146 was obtained from W.R. Grace Company. The specific heat and density were assumed to be similar to those reported by Milke.

3. Specific heat of steel was assumed to be 450 J/kg-°C as reported in Table B-6 of SFPE Handbook, Appendix A.[29]

4. Steel failure was assumed to occur at a temperature of 538°C as referenced in ASTM E-119, "Standard Test Methods for Fire Tests of Building Construction and Materials."

5. The severe-case exposing member was assumed to be a W14X109 steel member. Properties of this member were obtained from the Manual of Steel Construction, Volume I.[30]

6. The flame temperature impinging upon the structural element was assumed to be within a range of 1,500°C – 2,000°C. This is representative of typical flame temperatures.

7. Milke reports that the referenced equation is valid if the thermal capacity of the insulating materials is neglected. The thermal capacity of the materials can be neglected if the following inequality is satisfied.

$$c_s W / D > 2 c_i \rho_i h$$

Note in Appendix E that this inequality is indeed true, therefore, the referenced equation is appropriate.

Results

The outlined methodology was used to estimate the steel failure time. Based upon a flame temperature impingement ranging between 1,500°C – 2,000°C and a steel failure temperature of 538°C, the steel is estimated to fail within 40 and 57 minutes. The centerline temperature above the fire is estimated to be 470°C. Since this is less than the steel failure temperature, a plume impingement should not cause a column or beam to fail.

The maximum Fire Department response time was given as 6 minutes. An additional 10 minutes to locate the fire and to move hose lines and equipment is assumed. Manual suppression will occur within another 15 minutes. This timeline results in a total firefighter exposure time of 31 minutes. If the timeline for firefighting is considered "reasonable," then the hazard to firefighters from structural collapse is not evidenced in this trial design.

RISK EVALUATION

The life safety and property risks of the alternate trial designs were evaluated in relation to the expected performance of the prescriptive design solution. A fault tree analysis method is used to

assess critical events such as safe evacuation, fire/smoke spread, and structural failure. In addition, the failure of critical systems, such as smoke control equipment and fire sprinklers, is considered. Stakeholders decide on the relative risk acceptability through probabilities and consequences that are rationalized by the classical risk assessment matrix.

ASSUMPTIONS

1. Mall structure and its systems have a life cycle of 20 years.
2. Mall occupants (employees and patrons) occupy the mall 12 hours per day.
3. The mall is open all year long.
4. Firefighters have the potential of being "exposed" to the mall any time there is an emergency.
5. Fire and life safety systems are properly maintained.

RATIONALIZATION OF THE RISK MATRIX

One should recognize that the severity of losses depends, largely, upon the type of building occupancy. Severity of losses is also driven by the perception of society of what an acceptable loss is.

Although it is not often discussed, the acceptance of risk by American society is reflected in the statistics on automobile fatality rates. It is widely accepted that during an exposure of 1,000,000 hours of driving, one fatality is an acceptable risk. This yardstick will serve as the baseline for societal risk acceptance in the approach of alternate building designs. In other words, during an exposure time of 1,000,000 hours, at least one affected occupant, by the fire, is an acceptable risk. A matrix is developed for each category; occupants, firefighters, and property. These are provided in Tables 6 through 8.

Table 6: Risk Matrix for Mall Occupants/Employees

	PROBABILITIES					
Severity	**Impossible (F) 10^{-9}**	**Improbable (E) 10^{-8}**	**Remote (D) 10^{-7}**	**Occasional (C) 10^{-6}**	**Probable (B) 10^{-5}**	**Frequent (A) 10^{-4}**
Catastrophic (1,000 affected)	10^{-6}	10^{-5}	10^{-4}	10^{-3}	10^{-2}	10^{-1}
Critical (100 affected)	10^{-7}	10^{-6}	10^{-5}	10^{-4}	10^{-3}	10^{-2}
Marginal (10 affected)	10^{-8}	10^{-7}	10^{-6}	10^{-5}	10^{-4}	10^{-3}
Negligible (1 affected)	10^{-9}	10^{-8}	10^{-7}	10^{-6}	10^{-5}	10^{-4}

This value means that there is one in a million "chance" for having a "critical" severity of 100 mall occupants "affected" by an occurrence.

Table 7: Risk Matrix for Fire Impact on Firefighters

Severity	PROBABILITIES Impossible (F) 10^{-8}	Improbable E) 10^{-7}	Remote (D) 10^{-6}	Occasional (C) 10^{-5}	Probable B) 10^{-4}	Frequent (A) 10^{-3}
Catastrophic (1,000 affected)	10^{-5}	10^{-4}	10^{-3}	10^{-2}	10^{-1}	1
Critical (100 affected)	10^{-6}	10^{-5}	10^{-4}	10^{-3}	10^{-2}	10^{-1}
Marginal (10 affected)	10^{-7}	10^{-6}	10^{-5}	10^{-4}	10^{-3}	10^{-2}
Negligible (1 affected)	10^{-8}	10^{-7}	10^{-6}	10^{-5}	10^{-4}	10^{-3}

Table 8: Risk Matrix for Fire Impact on Mall Structures

Severity	PROBABILITIES Impossible (F) 10^{-8}	Improbable (E) 10^{-7}	Remote (D) 10^{-6}	Occasional (C) 10^{-5}	Probable (B) 10^{-4}	Frequent (A) 10^{-3}
Catastrophic ($100 M loss)	10^{-6}	10^{-5}	10^{-4}	10^{-3}	10^{-2}	10
Critical ($10 M loss)	10^{-7}	10^{-6}	10^{-5}	10^{-4}	10^{-3}	10^{-2}
Marginal ($1 M loss)	10^{-8}	10^{-7}	10^{-6}	10^{-5}	10^{-4}	10^{-3}
Negligible $.01 M loss)	10^{-9}	10^{-8}	10^{-7}	10^{-6}	10^{-3}	10^{-4}

The risk assessment matrix shows three areas. The area on the right-hand side of the table reflects the riskiest combinations of severity and corresponding probability. The area on the left-hand side of the table reflects the least risky combination. And finally, the area in between the high and low risk is simply the reflection of "perhaps" reality.

The risk assessment matrix becomes a tool to appreciate the acceptability of risk in given situations. The matrix is expected to be created by the stakeholders. The stakeholders include mall ownership, mall real estate management, Authorities Having Jurisdiction, and insurance providers.

EXPOSURE TIME AND SEVERITY

The level of risk in any activity depends upon the length of time of exposure. Usually, the longer the exposure time, the riskier the activity becomes. In the mall example, exposure time is assessed for mall occupants and employees, for firefighters, and for the mall structure.

The second component of risk is severity. It is the degree of loss or negative impact on a mission. More specifically, the severity for two selected targets is human casualties (occupants/employees, and firefighters). The term selected, in this study, is the number of "affected" people. The nature of severity of an affected person could range from a minor injury (necessitating medical attention) to death. The reason for this broad definition is due to the inherent difficulty in accurately predicting the degree of harm emanating from a fire.

RISK TARGETS

Three targets for risk assessment will be considered. These are:

1. Occupants of mall and employees of mall;

2. Firefighters; and

3. Mall structure.

OCCUPANTS OF MALL AND EMPLOYEES OF MALL

Mall patrons and employees are expected to be in the mall structure on average 12 to 14 hours. That amount of time corresponds to approximately 100,000 hours of exposure during the life cycle of the mall.

FIREFIGHTERS

Firefighters are expected to be exposed anytime there is an emergency condition in the mall. That exposure time is potentially 175,200 hours (365 days/year x 24 hours/day x 20 years).

POPULATION OF EXPOSED

1. Occupants of the Mall: It has been calculated that patrons can add up to 8,500 occupants, and 500 assumed mall employees.

2. Firefighters: It has been assumed that a multi-alarm would total approximately 100 firefighters.

The total number exposed is important because as the number of exposed increases, so does the risk level.

PROBABILITY OF LOSS DUE TO FIRE DURING THE MALL LIFE CYCLE

Fault tree analysis has been chosen as the technique for evaluating the probability of reaching a hazardous condition and having at least one affected chosen target. Appendix F, Figures 1 through 9 illustrate the different fault trees for different scenarios.

Based upon the fault tree top event, for example, the probability of having a fire with such attributes as the formation of a smoke layer of at least 6 feet above the highest level of walking surface coupled with the affected presence of at least one occupant or employee in the mall, is 10^{-4} (with functional fire alarm, automatic sprinklers, and smoke control systems). This means that out of 10,000 fires, during the life cycle of the mall of 20 years, one fire would produce a severity of at least one person being affected, given the reliability of the fire and life safety systems provided.

Values in Tables 9, 10, and 11 represent the average yearly probability of mishap. Note that the calculated probabilities are smaller as fire and life safety systems are eliminated. The reader should also note that the impact from the elimination of fire and life safety systems is not reflected in these tables.

Over 20 years of exposure, these probabilities become:

Table 9: Summary of Probabilities as a Function of Building Protection From Figures 1, 2, and 3

Fire and Life Safety Systems Provided	Probability that smoke layer is formed from a given fire, 6 feet from the highest level of walking surface while at least 1 occupant or employee is present and is affected by smoke criteria (over mall life cycle)
• Fire alarm system • Automatic sprinkler system • Smoke control system	1.3×10^{-4}
• Fire alarm system • Automatic sprinkler system	8×10^{-5}
• Fire alarm system	8.4×10^{-7}

Again the probability values in the Table above are simply values taking into account the assumed life cycle of the Mall and its systems.

Table 10: Summary of Probabilities as a Function of Building Protection From Figures 4, 5, and 6

Fire and Life Safety Systems Provided	Probability that temperature is reached from a given fire, 550°C from the highest level of walking surface while at least 1 firefighter is present and is affected by temperature criteria (over mall life cycle)
• Fire alarm system • Automatic sprinkler system • Smoke control system	3×10^{-3}
• Fire alarm system • Automatic sprinkler system	2×10^{-3}
• Fire alarm system	2×10^{-5}

Table 11: Summary of Probabilities as a Function of Building Protection From Figures 7, 8, and 9

Fire and Life Safety Systems Provided	Probability that temperature is reached from a given fire, 550°C from the highest level of walking surface while at least 1 structural member is present and is affected by temperature criteria (over mall life cycle)
• Fire alarm system • Automatic sprinkler system • Smoke control system	3×10^{-4}
• Fire alarm system • Automatic sprinkler system	2×10^{-5}
• Fire alarm system	2×10^{-7}

One may notice from either Figures 1 through 9 in Appendix F, or Tables 9, 10, and 11, that as the building becomes deprived of some fire and life safety features, the probability for the top event gets smaller. What the reader should realize is that hazardous conditions become present sooner in the building when the building lacks sufficient protection. Hence, the top event probability is inversely proportional to the onset to hazard.

INDUCED UNCERTAINTIES IN THE OUTCOME

A number of key decisions are made by the designers and/or parties with Authority. For example, these decisions are concerning the type of the simulated fire, its location, the geometry of the structure, and simulation duration.

Each decision the designer makes has a varying degree of impact on the simulation outcome. Some input has more impact on the magnitude of the output. For example, the height of a space has more impact on the outcome that the length or the width the space would have. Hence, it is important to be as accurate as possible when attempting to quantify critical input information.

Each probability value that is either assigned, deduced, or derived, has its associated uncertainties. Often, uncertainties are addressed using means of known probability values. Those means are geometrical means instead of arithmetical means. Geometrical means are more representative of reality than arithmetical means.

Uncertainties can be reduced but not eliminated. The reduction of uncertainties can be achieved using more extensive data, or a rationalized one based upon enhanced knowledge of fire data and known fire behavior. One important uncertainty is whether there would be a fire in this mall. In this treatise, it is assumed that a fire is imminent, yet no probability value has been explicitly assigned to it. In this paper, it is assumed that an undesirable fire will start. It is not the goal of this presentation to discuss the likelihood of an ignition but rather assume that a fire has started. The focus is, instead, to investigate how fire and life safety systems are performing when confronting the assumed fire.

One way to address uncertainties is by determining ranges of probable values and applying geometrical means calculations using the range of values. That estimation of probabilities is obtained by calculating the geometrical average (located midway between the limits of estimates). This is also known as the log average method.[31]

CONCLUSION

The final step in the risk analysis is to obtain data from the FDS Model coupled with the results from the timed-egress analysis. The simultaneous use of criteria of onset of hazard (smoke layer/height and temperatures) and timed-egress of occupants/employees results in a count of "affected" people or structural members. That count of affected entities is the severity of that fire scenario.

Once the fault tree is qualified, the top event is further quantified into a measure of risk. That risk value is then compared to the contours of the risk matrix. Stakeholders, who created the risk matrices, also make that final exercise in comparing risk values. The goal of stakeholders is to make the ultimate decision as to which design carries the most acceptable risk.

Given that evacuation of mall occupants and employees occurred before the onset of hazardous conditions, they were not "affected" and, therefore, the severity does not change in comparison to the prescriptive design. It was also concluded that because of sprinkler protection, fire conditions would not threaten firefighters or the mall structure, again resulting in no change in severity and risk.

Economic Evaluation

Initial and life cycle costs and increased leasing revenue are estimated for inclusion in a cost/benefit analysis to compare the prescriptive design solution with the performance trial design alternatives. The actual hours of engineering and architectural time related specifically to this case study has been tracked to establish an estimate of design costs. This "design cost" is included as a deduct from the savings estimated for each of the alternate designs.

The prescriptive building has a construction cost estimate of $56,000,000 US. This includes:

- Floor 1 Parking ($7,000,000)
- Floor 2 Retail--Shell and Core ($23,800,000)
- Floor 3 Retail--Shell and Core ($23,800,000)
- Rooftop Parking ($14,000,000)

This analysis considered three trial designs; natural smoke control, removal of stairs, and reduction in structural fire resistance. Each of these is expected to create initial savings in construction costs as well as additional savings in life cycle costs. In the case of removing the two stairs, the area is recaptured and becomes leasable. This adds additional revenue during the lifetime of the building.

The first trial design replaces the mechanical smoke control system with a natural ventilation system. This results in the savings on initial costs for exhaust fans, supply fans, generator capacity, and controls. This system is replaced with a set of four automatic dampers located at the top of the atrium. The initial cost savings from the natural exhaust design is $1,000,000 US initial costs. The life cycle costs are negligible.

For the second trial design, the initial cost savings of removing the two stairs is estimated at $40,000 US. The savings in floor area, 150 m^2, generates additional revenue during the lifetime of the building. This additional revenue is estimated at $155,000 US per year. Life cycle costs are negligible.

The third trial design suggests the reduction of the overall fire resistance of the building. This includes removal of fireproofing on the structural steel elements to reduce their fire resistance from 3 hours to 1 hour and removal of fireproofing from steel supporting the roof and floor structures, reducing the fire resistance from 2 hours to 1 hour. This results in an initial cost savings of $900,000 US. Life cycle costs are negligible. These costs are compared in Table 12 below.

Table 12: Net Present Cost of Trial Designs

Cost	Trial Design #1	Trial Design #2	Trial Design #3
Building Cost	($56,000,000 US)	($56,000,000 US)	($56,000,000 US)
Natural Exhaust Substation	+$1,000,000 US	-	-
Stairs Removal	-	$40,000+ US $155,000 US/year*	-
Fireproofing Reduction	-	-	$900,000 US
Net Cost	($55,000,000 US)	($54,640,000 US)	($55,100,000 US)

*The annuity amount is changed to its equivalency of present value at an effective interest rate per year of 10% over 20 years or $1,319,600.

The engineering and architectural time required to complete this analysis has an approximate value of $85,000 US. It is estimated that another $65,000 US would be required to complete the fire modeling, include this work into the construction drawings and specifications, and complete final negotiations with the Authority Having Jurisdiction.

Given that the three trial designs are acceptable, the savings, based upon the substitution of the mechanical smoke control system by the natural exhaust, the reduction of stairs, and fireproofing, are approximately $3,260,000 US over the mall life cycle. This compares favorably to the performance design cost estimate of $150,000 US.

Operations And Maintenance Manual

The purpose of the Operations and Maintenance Manual (OMM) is to outline the means by which the performance design components of the mall are to properly function, whether on an

individual or interfaced basis. A description of the system components and associated testing schedules are presented in the OMM, along with compensatory measures to be taken, should any part of the performance design need to be repaired or removed.

DESIGN COMPONENTS

Mall performance design components are as follows:

- Fire Alarm System
- Mechanical Smoke Control System/Exhaust and Supply
- Natural Smoke Control System/Ventilation
- Automatic Sprinkler System/Tamper Switches
- Standpipe System/Tamper Switches
- Emergency Power Generator
- Smoke Detection System
- Central Station Monitoring Service
- Public Address System
- Municipal Water Supply Connection(s)

Mall performance design components and respective interactions are presented in Table 13.

Table 13: System Matrix

Component	Interaction Description
• Automatic Sprinkler System • Smoke Detection System • Standpipe System • Mechanical Smoke Control System	Trouble and alarm signals activate fire alarm system
• Automatic Sprinkler System • Smoke Control System • Standpipe System	Signals routed to Central Monitoring Station
• Smoke Control System • Fire Alarm System • Public Address System	Connected to Emergency Power System

MAINTENANCE

The primary focus of the maintenance program for the above-noted components is proper training of all mall personnel, including the engineering staff, the security staff, and the tenants.

Engineering Staff

Annual seminars on the proper status and maintenance of the systems below are to be provided annually to all engineering staff and to all new engineering staff hires. This would include mandatory training with PKC videos on related subjects.

- Fire Alarm System
- Automatic Sprinkler System
- Standpipe System
- Municipal Water Supply Connection(s)
- Mechanical Smoke Control System
- Natural Smoke Control System
- Interaction of fire alarm system with smoke control, automatic sprinkler, and standpipe systems
- Proper fire rating of all construction

In addition, the security staff is to be updated annually on the proper compensatory actions in response to the repair or removal of any performance design component. Compensatory actions for the security staff include fire watches during the repair or removal of any design component.

Tenants

A Tenant Manual is to be provided by the mall operator to all new tenants. The manual is to be updated annually and is to provide full documentation of any fire protection features that could impact tenant design and construction. In particular, the manual is to clearly define all fire-rated construction and proper placement of sprinklers and detectors within each tenant space so that tenant design and construction do not compromise any fire protection systems.

In addition, all tenants are to be updated annually on the proper compensatory actions in response to the repair or removal of any performance design component. Compensatory actions for tenants include fire watches during the repair or removal of any design component.

INSPECTION AND TESTING

The performance design components are to be inspected and tested as shown in Table 14. All testing reports and procedures are to be kept on the mall site.

Table 14: Inspection and Testing Schedule

	Fire Department	Mall Engineering Staff	Mall Security Staff	Third Party
Emergency Generator	Annually	Annually	None	None
Smoke Control System	Annually	Annually	None	None
Municipal Water Connections	Monthly	Monthly	None	None
Fire Alarm System	Biannually	Biannually	Biannually	Biannually
Smoke Detection System	Biannually	Biannually	Biannually	Biannually
Heat Detection System	Biannually	Biannually	None	Biannually

In addition, any change in tenant occupancy must be accompanied by the following tests and inspections, to be performed by the fire Department and the mall engineering staff.

- Proper function of automatic sprinkler system within tenant space/no blockage of sprinklers
- Proper function of smoke detection system/no blockage of detectors
- Maintenance of fire-rated construction

Conclusion

This performance-based case study was undertaken with specific goals in mind. We were interested in demonstrating the application of the new "SFPE Engineering Guide to Performance-Based Fire Protection Analysis and Design of Buildings" to this example. It also provided an opportunity to use the new PC-based FDS Model from NIST. Finally, we wanted to include other "stakeholders" into the performance-based design process. We accomplished these goals.

It is important to look beyond these goals to the results of the actual performance analysis to develop specific conclusions. As with any project of this magnitude, there were many observations, questions, and, sometimes, answers. The following is a synopsis:

> The fire effects analysis needs to be completed in order to support or contradict the conclusion that all the performance objectives have been met. Additional results and complete data files, along with an electronic copy of this report, will be posted on the website at www.rjagroup.com.

The three trial designs have resulted in a substantial net savings, which deserves further consideration. In the future, it would be useful to conduct an assessment of scenarios which would drive the trial designs to failure (i.e. sprinkler failure, arson fire, etc.) and then compare the cost benefit to the quantitative change in risk.

The overall process for this type of design approach is time-intensive. In particular, the run times for FDS (>5 days per scenario on a 500MHz PC) have to be factored into the design schedule. Efficiencies are expected to occur in the future as a result of lessons learned.

The deterministic modeling tools have to be validated for the specific applications. A repository of data is needed in order to verify the results of the numerical analyses. Likewise, the statistical data is needed to improve the precision of the risk analysis component.

It is important to carefully choose and manage the performance criteria. The stakeholders need to be educated about the importance given to this criteria as pass/fail points in the analysis. Likewise, the engineer needs to be clear that the engineering methods available must be capable of producing valid results in a form that matches the specific criteria.

The SFPE GUIDE provides a good framework to follow in developing an analysis of this magnitude. However, it is not always clear where the deterministic solution fits with the risk solution. We believe they need to be complimentary to one another. As a result of this exercise, we realized that the use of risk analysis methods would have been a better approach in defining the design fire scenarios.

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APPENDIX D

Society of Fire Protection Engineers

GUIDELINES FOR PEER REVIEW IN THE FIRE PROTECTION DESIGN PROCESS

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GUIDELINES FOR PEER REVIEW IN THE FIRE PROTECTION DESIGN PROCESS

October 8, 2002

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1.0 GENERAL

These guidelines address the initiation, scope, conduct, and report of a peer review of a fire protection engineering design. In these guidelines, peer review is defined as the evaluation of the conceptual and technical soundness of a design by individuals qualified by their education, training and experience in the same discipline, or a closely related field of science, to judge the worthiness of a design or to assess a design for its likelihood of achieving the intended objectives and the anticipated outcomes. A peer review could be conducted on any or all components of a design, such as the fire protection engineering design brief, conceptual approaches or recommendations, application or interpretation of code requirements or supporting analyses and calculations.

1.1 Purpose

These guidelines provide guidance to members of the Society of Fire Protection Engineers and others in the fire protection engineering community concerning the peer review process of fire protection engineering designs.

1.2 Introduction

These guidelines address issues such as when to use a peer reviewer, the choice of reviewer, the scope of the review, the agreements needed, the documentation of the peer review, and other related details. These guidelines describe the decisions that a stakeholder should make in establishing and conducting a peer review. As defined in the *SFPE Engineering Guide to*

Performance-Based Fire Protection Analysis and Design of Buildings,[1] a stakeholder is an individual or a representative interested in the successful completion of a project.

As performance-based design and other forms of design requiring greater engineering rigor increase, the use of peer review will likely become more prevalent. Peer review is a tool that can be used to help a stakeholder make decisions regarding the suitability of a design. Typically a peer review is sought by a reviewing authority to provide a second opinion regarding the design's likelihood of achieving the stated objectives. However, other situations may also necessitate a peer review.

Given that the use of a peer review may add time to the critical path of the design process, a stakeholder who wishes the advice of a peer reviewer should begin the process of identifying and contracting for the peer review as early as possible, but no later than at the design review and approval stage. That stage typically involves numerous stakeholders.

2.0 SCOPE OF A PEER REVIEW

2.1 Overview

The scope of the peer review might be a complete review of the entire documentation, including compliance with applicable codes and standards and the appropriateness of the assumptions, engineering methods and input data used to support the design. Alternatively, the scope of the peer review might be limited to specific aspects of the design documentation, such as specific models or methods and their associated input data and conclusions drawn from the output data.

Agreement on the scope of the peer review should be achieved between the contracting stakeholder and the peer reviewer. The scope should be explicitly identified at the time of execution of the agreement to undertake the peer review. Any changes to the scope must be agreed to by both the contracting stakeholder and the peer reviewer.

The peer review should be limited to only the technical aspects of the design documentation. The peer review should not evaluate the education, experience or other personal aspects of the person or company that prepared the design.

The peer review should examine both the internal and external appropriateness of the design. External appropriateness considers whether the correct problems are being solved. Internal appropriateness considers whether the problems are solved correctly.

2.2 Third Party Inspection vs. Third Party Review

Some stakeholders may also utilize third parties to undertake inspections of completed installations. As the scope of these inspections is typically related to compliance of the completed installation with the previously-reviewed design documents, such inspections are outside the scope of a peer review as covered by these guidelines.

2.3 Details of a Peer Review

Whether the scope of the peer review is the complete documentation of a project or some specific aspect of it, the peer reviewer should consider the following details, as appropriate to the design being reviewed:

- Applicable codes, standards and guides
- Design objectives
- Assumptions made by the designer (e.g., performance criteria, design fire scenarios, material properties used in correlations or models.)
- Technical approach used by the designer
- Models and methods used to solve the design problem (see Appendix F of the *SFPE Engineering Guide to Fire Protection Analysis and Design of Buildings*)
- Input data to the design problem and to the models and methods used
- Appropriateness of recommendations or conclusions with respect to the results of design calculations
- Correctness of the execution of the design approach (e.g., no mathematical errors or errors in interpretation of input or output data)

3.0 INITIATION OF A PEER REVIEW

3.1 Overview

The decision to initiate a peer review is typically made by a project stakeholder, whose interest might be safety, financial, environmental or cultural. A peer review is often commissioned by an enforcement official; however, other stakeholders may also commission such a review. This decision usually follows the design development of a project and is occasionally a prescribed part of the design review and approval. A determination to initiate a peer review might be made by a stakeholder during a preliminary project meeting, when presented with a project design brief, or when presented with a complete set of design documents.

3.2 When to Conduct a Peer Review

The decision as to whether or not to conduct a peer review is up to individual stakeholders. The motivation might be a desire to have a better understanding of the quality, completeness or the scientific bases of the design. The decision to conduct a peer review might also be made by a stakeholder who has resource limitations and wishes to bring in outside assistance to evaluate the fire safety features of the design. Another possible reason to initiate a peer review might be to provide additional quality assurance for the design.

3.3 Choice of a Peer Reviewer

The importance of a peer reviewer's independence and technical expertise cannot be overemphasized. The peer reviewer should be objective and have no conflict of interest in the project. Any candidate being considered as a peer reviewer should disclose to the contracting stakeholder any conflict of interest or technical bias.

A peer reviewer should have the necessary knowledge and fire protection engineering or fire science expertise to understand and evaluate the design that is being evaluated. For example, a peer reviewer should at least have the necessary knowledge and fire protection engineering experience to prepare an acceptable design that is similar in scope to the design being reviewed. Section 1.2.1 of the *SFPE Engineering Guide to Fire Protection Analysis and Design of Buildings* identifies one means to assess the abilities of engineers who are qualified to practice fire protection engineering and prepare acceptable designs. Peer reviewers should be able to demonstrate, through documented education and experience, that they are competent to perform the requested peer review.

3.4 Identification of Agreement to Perform a Peer Review

Prior to commencing a review, the peer reviewer should execute an appropriate agreement with the contracting stakeholder. Once this agreement has been formalized, the contracting stakeholder should notify the design engineer of record, and other appropriate parties, of the initiation of a peer review as required by applicable ordinances, engineering practice acts, canons of ethics, etc. A sample agreement of this type is published by the American Consulting Engineers Council[2] and is available at www.nspe.org. That sample agreement identifies who takes responsibility for design, records retention, confidentiality, dispute resolution and other related topics.

4.0 CONDUCT OF A PEER REVIEW

4.1 Standard of Care for a Peer Review

Peer reviews should be conducted in accordance with the SFPE Canons of Ethics. Within the agreed-to scope, a peer review should be performed to the same standard of care that would be expected of a responsible designer during the evaluation of trial designs. Section 2.3 of these guidelines identifies the attributes of a performance-based design that should be evaluated during a peer review. However, if a peer-reviewer discovers deficiencies that fall outside of the scope of the review, those deficiencies should be brought to the attention of the contracting stakeholder.

A peer review is often intended to ensure that the public's safety goals or the fire protection goals of other stakeholders are met. Generally, improvement of the design or value engineering

is not the purpose of a peer review. The design team will typically accomplish improvement of the design.

4.2 Communications between peer-reviewer and designer

Communication between the peer reviewer and the designer can facilitate the peer review. The methods of communication should be understood by all parties.

4.3 Standard of Reasonableness

Peer reviewers should not be influenced by matters of their own design preference, since there will frequently be more than one acceptable solution to a design problem. Technical issues that would not be expected to have a significant effect on the performance of the design should be identified as observations or findings rather than as deficiencies.

4.4 Tools Required for Review

Peer reviewers should have sufficient documentation of the validity of the tools and data that were used in the development of the design. A full evaluation of a design might require that the designer provide the peer reviewer with access to the tools used to develop the design. In such cases, the peer reviewer should respect any confidentiality issues associated with the tools, and should use the tools only for conducting the specified peer review. In some peer reviews, it might be necessary to use additional tools and data to perform checks on the results that were obtained during the development of the original design.

Some design and analysis may be carried out using commercial software that is licensed to an individual or company and copies of the software may not be available to the reviewer (e.g.

FLUENT, StarCD or ANSYS). There may also be situations where the reviewer is not familiar with or qualified to use the software. Should this occur, it may be necessary to seek persons with appropriate skills and access to the software to assist in determination of the appropriate use of the software and the accuracy of the input and results. Approval for such arrangements may be needed from the commissioning stakeholder.

4.5 Confidentiality

Normally, the results of a peer review should be communicated only to the contracting stakeholder. At the discretion of the contracting stakeholder, the results may be communicated to the design engineer of record. In some instances, when dictated by professional ethics, communication of the results to the appropriate enforcement officials may be necessary.

4.6 Intellectual Property Rights

During the peer review process, the peer reviewer should treat the information and materials as confidential and with privilege, and should not extract, copy, or reproduce through mechanical, electronic, or other means any or all of the concepts or approaches developed by the design engineer.

5.0 REPORT OF A PEER REVIEW

5.1 Documentation

At the conclusion of a review, the peer reviewer should prepare a written record that identifies the scope of the review and the findings. The report should identify whether, in the peer

reviewer's opinion, the design meets the design objectives. The items shown in Section 2.3 of these guidelines should be addressed in the report. Peer reviewers should substantiate any comments on appropriateness by references to published technical documentation.

5.2 Supplemental Information

Resolution of differences in the conclusions between the design team and the peer reviewer may require supplemental technical documentation to resolve the differences. It is important for the designer and the peer reviewer to realize that peer review is only a tool to make an informed decision.

6.0 ADDITIONAL INFORMATION

More information on Fire Protection Engineering, Performance-based fire protection design and peer review in the fire protection design process can be found on the Society of Fire Protection Engineers web page - www.spfe.org.

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[1] *SFPE Engineering Guide to Performance-Based Fire Protection Analysis and Design of Buildings*, National Fire Protection Association, Quincy, MA: 2000.
[2] "Standard Form of Agreement between Owner, Designer, and Peer Reviewers for Professional Services for Independent Peer Review." American Consulting Engineers Council, Washington, 1999.

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APPENDIX E

FINAL ACTIVITY

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FINAL ACTIVITY

BOARD OF APPEALS MOCK HEARING
SMOKEY HOLLOW MARINA
CONSIDERATION OF PERFORMANCE BASED DESIGN

Background

A developer has submitted a proposal for a performance-based design of a new marina facility based upon the provisions of NFPA 5000 *Building Construction and Safety Code* as used by the local jurisdiction. This submittal was received by the local building and fire marshal officials without any prior involvement of the code officials in the process.

Because of their concerns, the local building and fire marshal's office has issued a letter to the proponents denying approval and advising that that their decision can be appealed to the appeals board.

The proponents have chosen to appeal the code officials' decision and an appeals board hearing is set for this coming Friday at 1:00 PM in the classroom.

The proposed facility will be located on Fire Lake which has over 1900 miles of shoreline with a capacity of over 23 million acre feet of water. It is a deep, clear lake with plenty of feeder streams, winding bays, and sloughs. Steep bluffs cradle much of the lake, with water depths dropping as deep or 60 or 70 feet just a few yards offshore.

The local area has an excellent year-round climate. Winters are short and mild with summers that are long and warm. Most rainfall occurs in the winter and early spring, but afternoon thundershowers are common in summer. Snow sometimes falls in the winter. The mean annual temperature is around 60 degrees F with a January mean of 34 degrees and a July mean of 77 degrees.

Role Assignments

You will assign members of the class fill several roles in this activity. Any class members not assigned specific roles may be asked by other students to assist them in their research and preparation for the hearing.

Building and Fire Officials

A very generic disapproval letter already has been issued jointly. Students must review the proposed design in depth and provide the proponents a letter detailing their concerns by no later

then Wednesday at 8:00 a.m. The code officials should review the provisions of NFPA 5000 *Building Construction and Safety Code* as they pertain to performance based design requirements.

Students must also be prepared to defend their positions and respond to the presentation of the developers at the board of appeals hearing on Friday at 1:00 p.m. in the classroom. They will have a maximum of 30 minutes to present their case during the hearing and respond to the developers' presentation.

Smokey Hollow Marina Developers

Role players must review the proposal--that has been submitted already--as well as the denial letters from the local building and fire officials.

Students must be prepared to defend their original proposal at the board of appeals hearing on Friday at 1:00 p.m. They will have a maximum of 30 minutes to present their case during the hearing. The developer should review the provisions of NFPA 5000 *Building Construction and Safety Code* as they pertain to performance based design requirements.

Since the building and fire officials already will have detailed their concerns and objections prior to the hearing, the role players must present their side of the matter first at the hearing.

Board of Appeals

Students have until the end of class on Tuesday to provide to all involved parties any rules of procedure or other information that they feel is necessary to conduct a professional hearing on Friday at 1:00 p.m. in the classroom. The members of the board should review the provisions of NFPA 5000 *Building Construction and Safety Code* on the duties and responsibilities of the board.

Students should also elect, as soon as possible, a chairperson for the board. The chairperson will be responsible for conducting the hearing. Once a chairperson has been selected, the board should adopt any rules and procedures they feel are appropriate for conducting the hearing. They should also publish an agenda for the meeting no later than Wednesday morning.

The total time for testimony for both sides is a maximum of 60 minutes. At the end of the hearing, the board must make a decision to either uphold or overturn the code officials' original decision to deny approval. The board must provide specific reasons for their decision.

Available Resources

Students may use any materials that they deem pertinent. This includes any materials contained in the classroom and class manual. They also are encouraged to use the Learning Resource Center (LRC) on the campus. Copies of NFPA 5000 *Building Construction and Safety Code* are available in the LRC for use during the activity.

ASSIGNED ROLES

Smokey County Building and Fire Marshal's Office

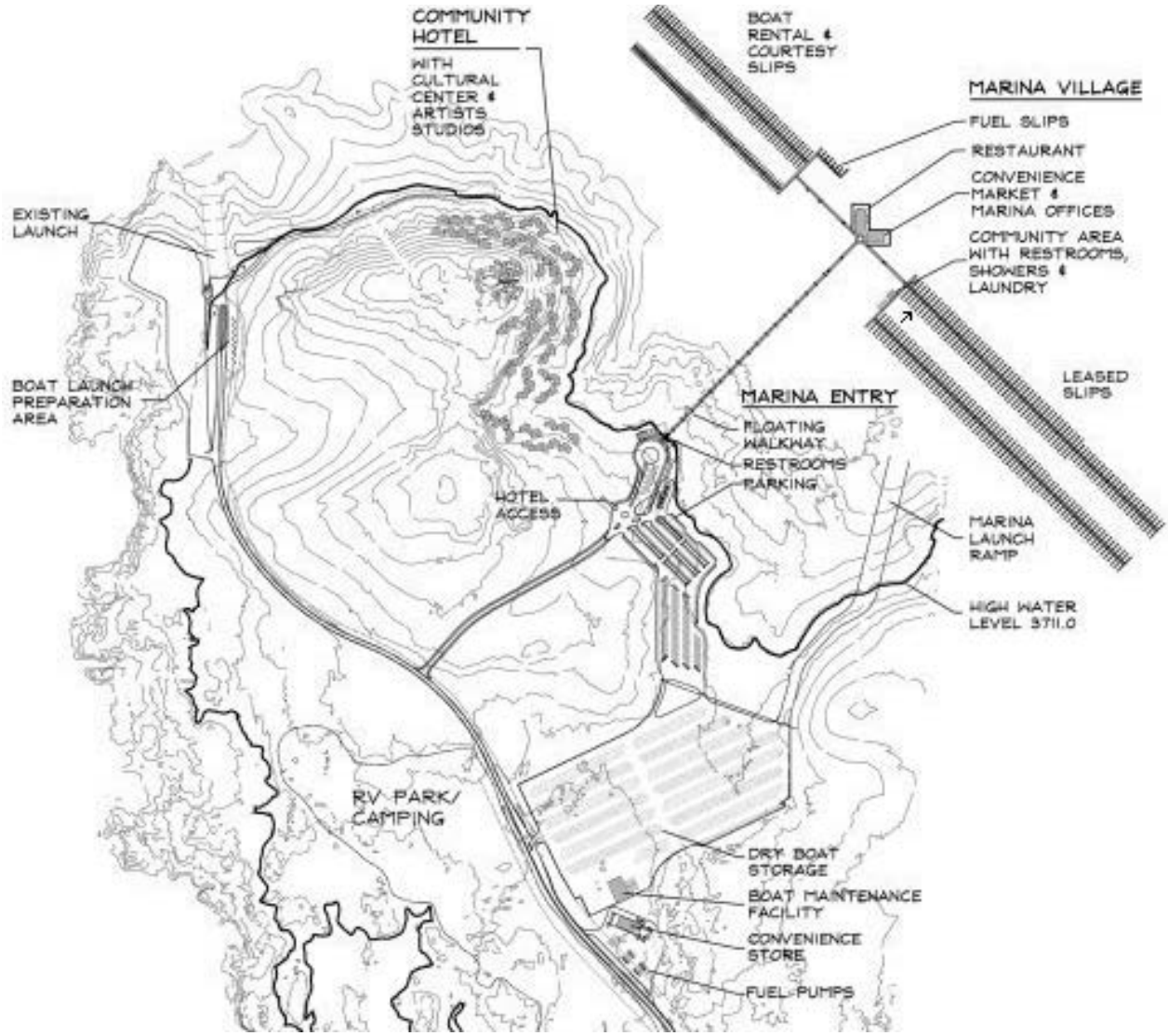
County Fire Marshal:
County Building Official:
Director of Planning and Development:
Fire Protection Engineer:
Building Inspector:
Fire Inspector:
County Attorney:

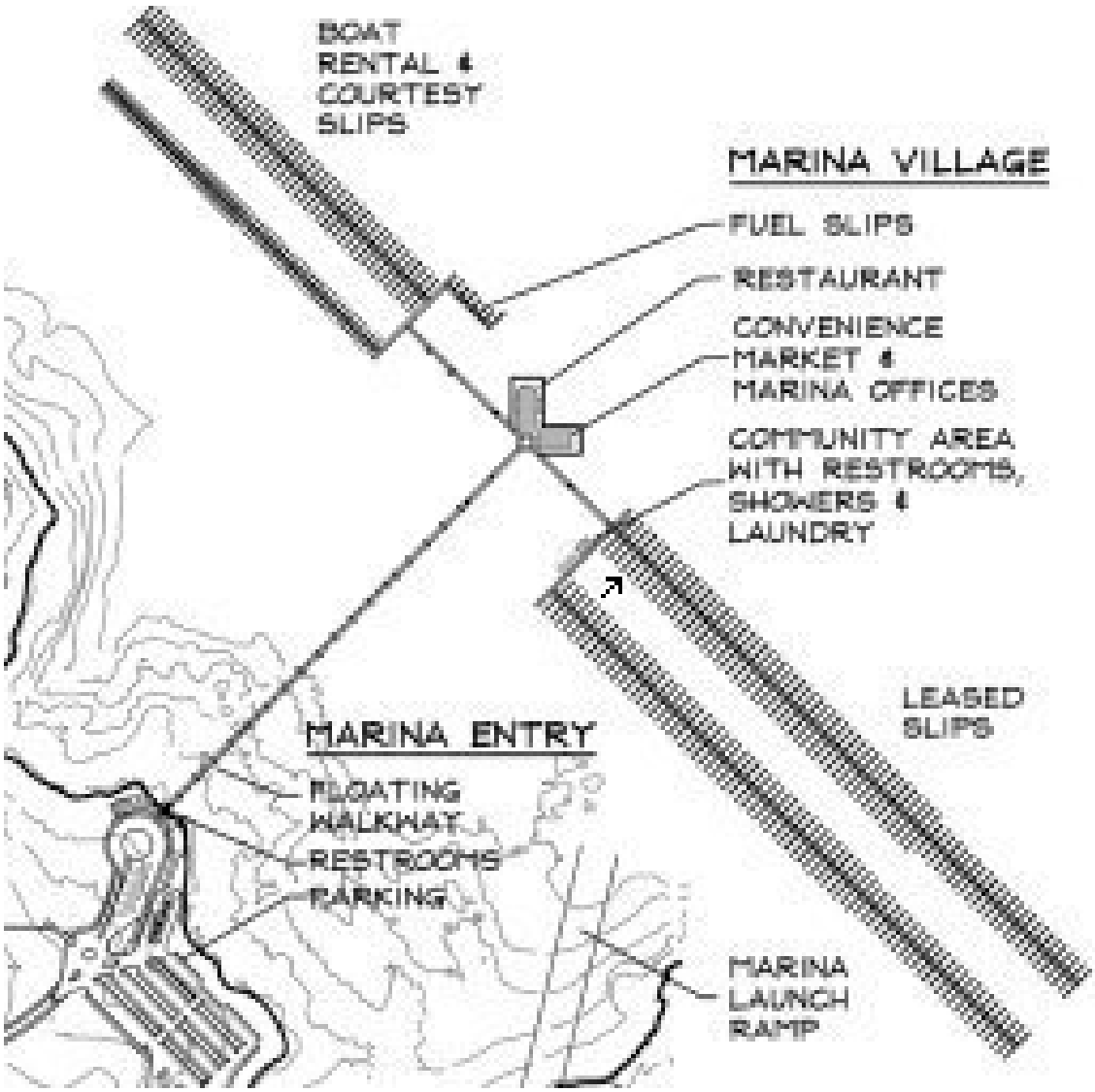
Smokey Hollow Marina Development

Project Architect:
Development Corporation President:
Marina Manager:
Fire Protection Engineer:
Staff Architect:
Attorney representing the developer:
Investment banker:

Smokey County Building and Fire Codes Board of Appeals

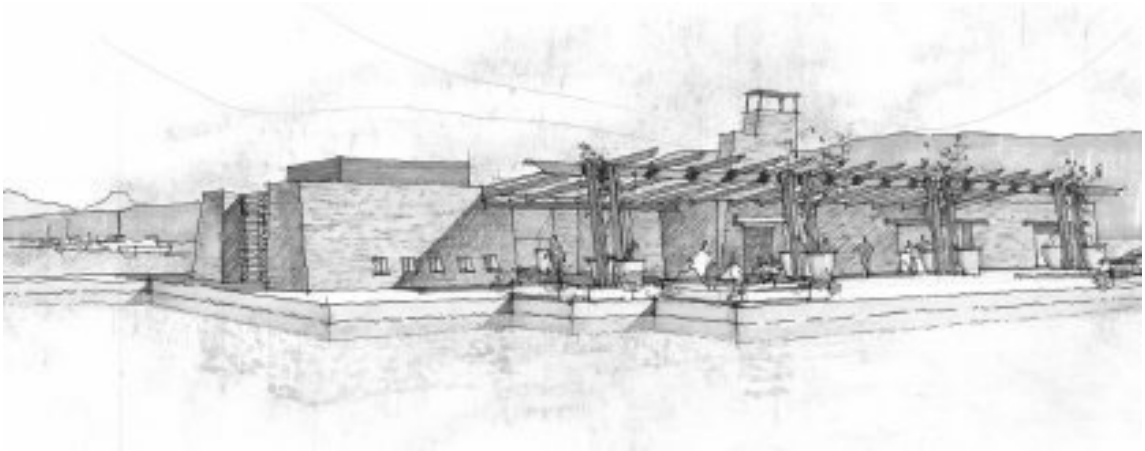
Board Member #1 (architect):
Board Member #2 (general contractor):
Board Member #3 (area marina owner on same lake):
Board Member #4 (electrical contractor):
Board Member #5 (plumbing contractor):
Board Member #6 (citizen at large):
Board Member #7 (chamber of commerce president):
Board Member #8 (engineer):
Board Member #9 (real estate developer):
Board Member #10 (environmentalist):


COMMUNITY HOTEL
WITH CULTURAL CENTER & ARTISTS STUDIOS
BOAT RENTAL & COURTESY SLIPS
MARINA VILLAGE
FUEL SLIPS
RESTAURANT
CONVENIENCE MARKET & MARINA OFFICES
COMMUNITY AREA WITH RESTROOMS, SHOWERS & LAUNDRY
EXISTING LAUNCH
BOAT LAUNCH PREPARATION AREA
LEASED SLIPS
MARINA ENTRY
FLOATING WALKWAY
RESTROOMS
PARKING
HOTEL ACCESS
MARINA LAUNCH RAMP
HIGH WATER LEVEL 3711.0
RV PARK/ CAMPING
DRY BOAT STORAGE
BOAT MAINTENANCE FACILITY
CONVENIENCE STORE
FUEL PUMPS



Example of fireboat at nearby marina

Renderings of Marina Buildings



SMOKEY HOLLOW MARINA
DEVELOPMENT CORPORATION
321 SafetyAvenue
Nofire, USA

Dear County Building Official and Fire Marshal:

It is our understanding that your county has adopted the latest edition of NFPA 5000 *Building Construction and Safety Code* as the primary code document for facilities within your jurisdiction.

The NFPA 5000 recognizes the use of Performance-Based options in Chapter 5 of the Code. We would like to use the Performance-Based option to analyze the fire protection provisions for the Smokey Hollow Marina project.

Attached to this letter is a code analysis, developed by our fire protection engineering consultants, using the provisions of Chapter 5 of the NFPA 5000 as well as some of the prescriptive requirements from the NFPA 5000. Please consider this report as a request to use alternate fire suppression methodologies that are suitable to the environment of the proposed pier structure at Smokey Hollow Marina using the Performance-Based option of the NFPA 5000 as the format for analyzing the suppression system.

We ask that upon review of this material that you issue a letter of approval of our design concepts. We look forward to your timely response.

SMOKEY COUNTY
BUILDING AND FIRE MARSHAL'S OFFICE
911 Fire Prevention Lane
Safety, USA

Re: Performance Based Design Proposal
Smokey Hollow Marina

Dear Sirs:

This is to confirm our office's receipt of your performance based design proposal for the Smokey Hollow Marina and our careful review of the same.

Our jurisdiction has adopted the provisions of NFPA 5000 *Building Construction and Safety Code* and relied upon this document along with the SFPE *Engineering Guide to Performance Based Fire Protection* in our review and evaluation. Based upon our review our office is, at this time, denying approval of your proposal due to numerous concerns including, but not limited to, your failure to contact this office for its input prior to submitting your proposal and your apparent heavy reliance on human intervention in the event of a fire event.

You will be receiving a full detailed report of our findings not later than Wednesday morning. This report will address all of our concerns with your proposal.

Under the provisions of NFPA 5000 *Building Construction and Safety Code* you have the right to appeal this decision. The Smokey County Building and Fire Codes Board of Appeals is set to meet this Friday at 1:00 p.m.

Sincerely

Code Analysis and Performance-Based Analysis Utilizing the NFPA 5000 *Building Construction and Safety Code* 2003 Edition

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EXECUTIVE SUMMARY

Because of the unique construction of the floating pier and a remote location, a code compliant fire protection system presents a number of installation and operational problems. This report requests the use of an alternative analysis using the NFPA 5000 Chapter 5 performance-based analysis to address the fire protection challenges of this project. Typical installation problems include long pipe runs, freezing temperatures, limited pier access for piping, a floating pier, wave action on pipe joints, maintenance, and a water surrounded environment.

Using the performance-based analysis process of the NFPA 5000, alternative fire protection techniques are suggested in this report that would be equal to or better than a code system. The code would accept a standpipe system for the pier without hoses or nozzles (the assumption is that responding fire companies would supply the hose). The nearest fire company is 45 minutes away. The use of two fire boats with pump, hose and foam capability would be provided in lieu of the fire standpipe system to provide insitu fire fighting for the 800 plus boats docked at the pier.

The fire boats would then contain the portable fire pump to charge the fixed manual sprinkler system provided for the buildings located in the center of the boat slip pier. The dry, manual sprinkler system charged by the fire boats will provide fire protection for the buildings with smoke and heat detectors providing early warning.

This alternative approach is unique to this type of environment and has been successful for a similar facility on Jones Lake operated by the same concessionaire.

INTRODUCTION--DESCRIPTION OF PROJECT

An 800 plus boat docking pier is proposed for Smokey Hollow Marina, on Fire Lake on the west side of the lake. The pier will consist of a floating pier structure. The boat slips will be located approximately 1700 feet from shore with a 1700 feet connecting walkway between the slips and land. The boat slips will consist of two (2) sets of parallel slips perpendicular to the shore-walkway with a single walkway connector from the terminus of the shore walkway to the slips. The east side slips contain leased spaces and the west side slips will be rental and courtesy slips. The leased side pier structure will also have a utility building containing an electrical room, sewer grinder room and toilet/shower facilities. At the terminus of the shore walkway, it is proposed that a restaurant building and a store/office/storage building, be placed on a "V" shaped pier structure. The rental boat slips are also proposed for future installation. The final piece of the pier facility includes fuel slips and a fuel cell for fuel dispensing.

The project will be phased as follows:

First Phase:

Installation of shore walkway

Installation of utility pier and buildings

Installation of leased slips

Second Phase

Installation of restaurant and store pier and buildings

Installation of fuel cell

Installation of rental slips

INTRODUCTION--APPLICABLE CODES AND FIRE SUPPRESSION REQUIREMENTS

The local building and fire department has adopted the 2003 Edition of the NFPA 5000 Building Construction and Safety Code as the applicable building code for facilities located within their jurisdiction. Other referenced or applicable codes or standards include the following:

NFPA 303	Fire Protection Standard for Marinas and Boatyards
NFPA 30A	Code for Motor Fuel Dispensing Facilities & Repair Garages
NFPA 220	Standard on Types of Building Construction - 1999 Edition

SPRINKLER REQUIREMENTS

Section 6.4.2.40 of the Building Code (NFPA 5000) includes a reference to NFPA 303, Fire Protection Standard for Marinas and Boatyards as a requirement for pier structures.

NFPA 303, Section 4.3.1 indicates:

"Buildings in excess of 500 ft^2 that are constructed on piers shall be protected by an approved automatic extinguishing system.

Exception No. 1: Buildings of Type I or Type II construction without combustible contents in accordance with NFPA 220, Standard on Types of Building Construction."

Based on the referenced codes and standards, an automatic extinguishing system would be required for each building on the pier structure with an area greater than 500 square feet unless that building is constructed of Type I or II construction and has non-combustible contents, as defined by NFPA Standard 220. Non-combustible material is defined as follows:

"A material that, in the form in which it is used and under the conditions anticipated, will not ignite, burn, support combustion, or release flammable vapors when subjected to fire or heat."

Three buildings are proposed for the pier, a utility building, which will meet exception No. 1, and two other buildings, a store/office and restaurant building.

FIRE STANDPIPE REQUIREMENTS

Section 4.4.1 of NFPA 303 indicates that:

"Class I standpipe systems shall be provided for piers, bulkheads, and buildings where the hose lay distance from the fire apparatus exceeds 150 feet. Supply piping for standpipes on piers and bulkheads shall be sized for the minimum flow rate for Class II systems.

Exception: hose racks, hoses and standpipe cabinets shall not be required on piers and bulkheads."

Therefore, a standpipe system with the components of the pipe, valves, and hose connections are the only requirements for the pier structure. The assumption for this type of system is that the responding fire crews will bring a hose and nozzle for connection to the standpipe for fire fighting purposes.

CODE SUMMARY

In summary, the NFPA 5000 is the applicable building code with reference to NFPA 303 for the fire protection criteria. NFPA 303 requires the installation of an automatic fire sprinkler system for buildings over 500 square feet and a standpipe system with hose connections installed throughout the pier structure.

LOGISTICAL PROBLEMS FOR MEETING FIRE PROTECTION REQUIREMENTS

Because of the size, location and unique configuration of the Smokey Hollow project, there are several logistical problems in meeting the fire suppression requirements of the code and referenced standards.

The project is located approximately 30 miles from the nearest fire department resulting in a fire response time of approximately 45 minutes. Therefore, additional fire fighting strategies as recognized by the referenced codes and standards are not available. Therefore, to reduce response times, an on-site type fire response is suggested.

Also, because the pier structure is located 1700 feet from the shore, and is surrounded by water on all sides, a fire fighting effort conducive to a water environment is suggested. As well, with over 500 boat slips, the predominant fire danger is from a boat fire and not from a fire on the

non-combustible pier structure. The second greatest fire exposure is from the fuel cell; this will be addressed separately later in this report.

A third issue is the size of the pier structure. As can be seen on the attached plans, the pier is over 3500 feet in width from the leased pier to the rental pier and 1700 feet from shore. The size of the structure presents some logistical problems in responding manually to a fire utilizing the pier as access to a fire. As indicated above, boat fires are the most common type of fires associated with this type of facility. In fact, the most common emergency response is not a fire but rather a medical emergency. In a typical pier environment (based on a facility operated by this concessionaire at Jones Lake), medical emergencies out number fire incidences by a 50 to 1 ratio. Therefore, emergency response to medical emergencies should be considered in the solution to the extinguishing criteria because of the use of the same personnel.

Another size constraint limiting the size of sprinkler and standpipe installation is the space in the truss system for the floating pier. The utility space drawings indicate that a 6 1/4" diameter pipe is the maximum size. This limitation creates a number of installation problems for the sprinkler and standpipes. For the long pipe runs needed for the standpipe system, pipe sizes would exceed the available space in the pier structure. Therefore, some other means of providing on-site standpipe protection should be considered, such as the fire boat system described in the performance based analysis section.

The sprinkler installation creates some of these similar problems associated with the standpipe installation. The water supply for the sprinkler system could originate from four sources: an onshore source; a single fire pump source located on the pier; multiple fire pumps located near the area served; or a fire boat. The first three water supply options are prohibitive for a number of reasons. An on-shore water supply has limitations because of the following items:

1. Well size and available water supply is limited for the on shore water supply.

2. The pipe size needed for an onshore source would exceed the available space in the pier structure.

3. The pier is a floating pier subject to wave action, which would create an excessive maintenance to insure that the pipe is in working order. Piping materials for the domestic water piping will be more flexible and not subject to the pressures associated with a fire suppression system.

4. With the higher maintenance required for sprinkler or standpipe piping in this environment, the system might not perform when required.

5. The long runs for the pier would be prohibited and cause an imbalance in the pier. As well as freezing temperatures would require a dry pipe system.

A single fire pump located on the pier structure has limitations because of the following limitations:

1. Long runs of sprinkler and standpipe piping would create a situation where the pipe size would exceed the available space for the pipe in the pier structure.

2. Because of the wave action, flexible connections would be required at every pipe joint and pier section. This would create an extreme maintenance condition that if left undone may cause the system to be ineffective when required to be used. The maintenance may be so overwhelming that eventually it won't be done.

3. The pier is subject to freezing temperature, thereby, requiring a dry pipe system, including an air supply, thus adding to the maintenance problems.

4. The fire pump requires, weekly, monthly and annual testing and because of the remote location of this site, it may be difficult to obtain or conduct the required testing resulting in a decrease in the reliability of the equipment.

Multiple fire pump locations creates the following limitations:

1. Although the pipe runs could be reduced resulting in a pipe size that may fit into the pier structure, yet item #3 and #4 from the single fire pump scenario are still a problem for the multiple fire pump installation. In fact the maintenance triples if three fire pumps are used.

PERFORMANCE-BASED ANALYSIS

Because of the limitations of a pier installed piping system as a result of physical limitations on pipe sizing and the creation of an extreme maintenance condition, a performance-based option is required. Most of the prescriptive requirements of the Building Code (NFPA 5000) and the Fire Protection Standard (NFPA 303) are based on the response of a municipal fire department to continue the fire fighting process. However, with a probable 45-minute response time from the nearest fire department, the effectiveness of the effort is questionable. As a result of the fire response time, a natural progression is that reliance on on-site fire suppression utilizing sprinklers in the building over 500 square feet in area would be in order. However, as indicated above, an automatic sprinkler installation utilizing a single or multiple fire pump installations has installation and maintenance problems that would render a "code acceptable" system useless in very short order. Also, a fixed extinguishing system does not address the preponderance of fires from boat fires, therefore, just "meeting code" will not address the entire fire response effort needed for this unique environment. In addition, none of the "code acceptable" fire extinguishing systems addresses the need for emergency medical response, which far out numbers the fire response.

Therefore, using Chapter 5 of the NFPA 5000, a performance-based analysis is in order to address the unique needs for fire fighting and emergency medical response for this small water-based city. Section 5.5.2 of the NFPA 5000 identifies 8 Fire Design Scenarios (FDS) that should be considered when conducting a performance-based analysis. However, most of these scenarios are dealing with land-based environments. The NFPA 5000 scenarios are as follows:

Fire Design Scenario No. 1	Occupancy based criteria
Fire Design Scenario No. 2	Ultra fast fire in means of egress
Fire Design Scenario No. 3	Fire in unoccupied room
Fire Design Scenario No. 4	Fire in concealed space
Fire Design Scenario No. 5	Slow developing fire shielded from fire protection
Fire Design Scenario No. 6	Severe fire from target fuel load
Fire Design Scenario No. 7	Fire from an outside exposure
Fire Design Scenario No. 8	Ordinary fire with ineffective active or passive systems rendered ineffective

Because of the unique water-based environment, two additional scenarios should be added to this list as follows:

Fire Design Scenario No. 9	Boat fire not associated with any building
Fire Design Scenario No. 10	Medical response on pier, on a boat tied to pier, or on a boat floating near pier

(Although this item is not a fire scenario per se, response to this item requires personnel devoted to the fire fighting effort)

A response to each fire scenario is as follows:

<u>FDS No. 1 Occupancy Based Criteria</u>

Three buildings are proposed for the pier and will be developed in phases. The first building is an utility/shower/bathroom building. It will be constructed out of non-combustible materials and essentially have non-combustible contents. Therefore, per exception No. 1 from Section 4.3.1, this building would not have to be sprinklered. The building will meet Type II (000) construction without combustible contents.

The second building will be a store/office storage facility of approximately 7500 square feet. This building would require a sprinkler system according to Section 4.3.1 from NFPA 303.

The third building will be a restaurant/kitchen/restroom facility with open-air dining and separated kitchen. This building would require a sprinkler system according to Section 4.3.1 from NFPA 303.

No other buildings or structures are planned at this time that would require sprinkler protection.

Because of the piping installation problem expressed earlier in this report, an alternate extinguishing system is definitely indicated for the new buildings. The following alternative is requested for the sprinkler system for the two buildings:

1. Sprinkler Piping Installation:

   Both buildings will have the sprinkler piping and heads installed in the building with connection to a short run of pipe connected to a fire department connection. Multiple fire department connections could be added for flexibility. The sprinkler system will be a dry, manual pipe system connected to the fire department connection (FDC) with the water supply provided by a portable fire pump outfitted on a fire boat(s).

2. Fire Boats:

   Two fire boats will be provided on opposite sides of the pier to decrease response time by the concessionaire with FDC connection capability to connect to the sprinkler system. Personnel operating the fire boats will be available at all times and will be trained in the operation of the fire boat and be familiar with the Standard Operating Manual for Fire Fighting. This manual will be developed by Fire Safety Engineering for the concessionaire.

3. Standard Operating Manual (SOM):

   The SOM will identify the various fire fighting and emergency medical procedures. In addition, training, maintenance and testing procedures will be included in the manual.

4. Boat Fires:

   The SOM will also include procedures for fighting a boat fire tied to the pier or free of the pier.

5. Early Detection:

   To offset the provisions of an automatic sprinkler system, early detection and alarm notice to fire boat personnel is needed. Each building will be equipped with a combination smoke/heat detection system connected to an alarm system capable of paging the staff. Both fire boats will respond to an alarm with one connecting to the FDC charging the sprinkler system and the other capable of charging a second connection or providing hard line extinguishing capability.

6. Emergency Medical Response/Boat Fire Response:

   Pull station alarms will be located throughout the pier slip area with direct notification to fire boat personnel. The alarm system will be zoned to assist in rapid response. This system will be used for notification of boat fires as well as medical emergencies. Secured alarm devices will be used to reduce false alarms. The alarm locations will be located every 200-400 feet along the pier area. The SOM will include procedures for responding to the fires as well as medical emergencies.

FDS No. 2 Ultra Fast Fire in Means of Egress

Assuming the use of the fire boat with fixed in place FDC charged sprinkler system, the remaining FDS will be addressed.

To address this FDS, all buildings will have access to one or more exits direct from the room or space served. With the early detection system, quick detection to any fire situation will be given. The restaurant will also be an open area environment with direct access to the pier from several locations. The kitchen will be provided with 2 exits and a localized automatic extinguishing system for any grease producing equipment.

Therefore, due to the open air environment, early detection by smoke and heat detectors, fire boat response, manual sprinkler system and direct exits, this fire scenario is addressed.

FDS No. 3: Fire in Unoccupied Room

This fire scenario would primarily affect the restaurant building. By providing early detection via smoke and heat detectors and by providing a fire barrier between all unoccupied rooms and the restaurant area, this scenario is addressed.

FDS No. 4: Fire in Concealed Space

With the utilization of in-pier utility wiring and localized air handling equipment, fire spread via a concealed space or ceiling space is non existent.

FDS No. 5: Slow Developing Fire Shielded From Fire Protection

With the utilization of smoke and heat detectors for all rooms, early detection will be provided for all areas.

FDS No. 6: Severe Fire From Target Fuel Load

The most severe fire scenario for the pier structure is a fuel spill and subsequent fire on the refueling cell. The following response is recommended for the refueling area.

1. All equipment and processes shall be installed, tested and maintained according to NFPA 30A.

2. A foam piping extinguishing system will be provided for the fuel cell with charging from the fire boats. Two FDC connections will be provided to allow the application of foam to the effected area.

3. Concessionaire personnel will be on site when fuel is being dispensed or when the tanks are being filled from shore.

4. An alarm system will be installed to provide for early identification and response of the fire boats.

5. The SOM will include a section devoted to emergency response and action for the fuel cell.

6. The fuel cell will be limited in size according to NFPA 30A for the minimum fire exposure hazard.

FDS No. 7: Fire From an Outside Exposure

The primary outside fire exposure is a boat fire next to one of the buildings. This hazard is reduced by limiting boat parking to designated areas on the pier and not near the buildings. Signs, buoys and patrolling will limit this fire exposure.

Another outside fire exposure is that associated with a boat fire when a boat is parked in one of the slips. By providing an alarm system throughout the pier structure the fire boat can be notified. Upon answering a fire, the SOM will identify that the boat will be cut from its moorings and pushed away from the pier. The fire boat will extinguish the fire with the hazard removed from adjacent boats. With this action, the fire boats take the place of a fixed pipe standpipe system and the response time will be much quicker than a "code acceptable" standpipe system. The code requires a fixed standpipe on the basis that a municipal fire department will respond to a pier fire. Standpipes are required, however, hoses and nozzles are not required. It is assumed that the responding fire department will provide them. With a response time exceeding 45 minutes plus the time to negotiate the pier, over an hour would pass by providing a "code acceptable" standpipe system. The fire boat response time will be less than 5 minutes.

The alarm system will also provide emergency medical response capabilities. This alarm system will reduce the liability of the concessionaire by providing medical response in excess of minimum requirements. The manual alarm system will supplement a quick notice usually provided by cell phones, which may be inoperable in this area.

FDS No. 8: Ordinary Fire With Ineffective Active or Passive Systems Rendered Ineffective

With two fire boats, one connecting to a standpipe charging the sprinklers and the other available for fire fighting, an acceptable level of backup is provided in case the primary fire fighting system (sprinklers is not effective).

FDS No. 9: Boat Fire Not Associated With Any Building

The fire boats will provide an effective means to fight a boat fire for boats tied to the pier or for boats approaching the pier. Standpipes will not provide an effective means of fighting the fire as indicated elsewhere in this report.

FDS No. 10: Medical Response On Pier or Boat Tied to Pier or Boat Floating Near Pier

In a concessionaire operated environment, users of the facility will expect response to medical emergencies. A variety of medical responses can be expected from this environment. By providing the emergency pull stations at various locations in the boat shop area, the alarm system

can be used to provide EMS response also. Fire boat personnel will receive EMT training to provide the medical response. Helicopter evacuation to the nearest medical facility can be provided by the County Sheriff or through private service. The first response and stabilization can be provided by concessionaire personnel utilizing the alarm system located on the piers.

Based on the 10 fire scenarios and the unique site conditions, a fire extinguishing and emergency medical response as outlined below is requested as a performance-based analysis for the Smokey Hollow facility.

1. Sprinkler Piping Installation:

   Both buildings will have the sprinkler piping and heads installed in the building with connection to a short run of pipe connected to multiple fire department connections. The sprinkler system will be a dry, manual pipe system connected to the fire department connections with the water supply provided by a portable fire pump outfitted in a fire boat(s).

2. Fire Boats:

   Two fire boats will be provided by the concessionaire with FDC connection capability to connect to the standpipe charging the sprinkler system. Personnel operating the fire boats will be available at all times and will be trained in the operation of the fire boat and be familiar with the Standard Operating Manual for Fire Fighting. This manual will be developed by Fire Safety Engineering for the concessionaire.

3. Standard Operating Manual (SOM):

   The SOM will identify the various fire fighting and emergency medical procedures. In addition, training, maintenance and testing procedures will be included in the manual.

4. Boat Fires:

   The SOM will also include procedures for fighting a boat fire tied to the pier or free of the pier.

5. Early Detection:

   To offset the provisions of an automatic sprinkler system, early detection and alarm notice to fire boat personnel is needed. Each building will be equipped with a combination smoke/heat detection system connected to an alarm system capable of paging the staff. Both fire boats will respond to an alarm with one connecting to the FDC charging the sprinkler system and the other capable of charging a second connection or providing hard line extinguishing capability.

6. Emergency Medical Response/Boat Fire Response:

Pull station alarms will be located throughout the pier slip area with direct notification to fire boat personnel. The alarm system will be zoned to assist in rapid response. This system will be used for notification of boat fires as well as medical emergencies. Secured alarm devices will be used to reduce false alarms. The alarm locations will be located every 200-400 feet along the pier area. The SOM will include procedures for responding to the fires as well as medical emergencies.

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