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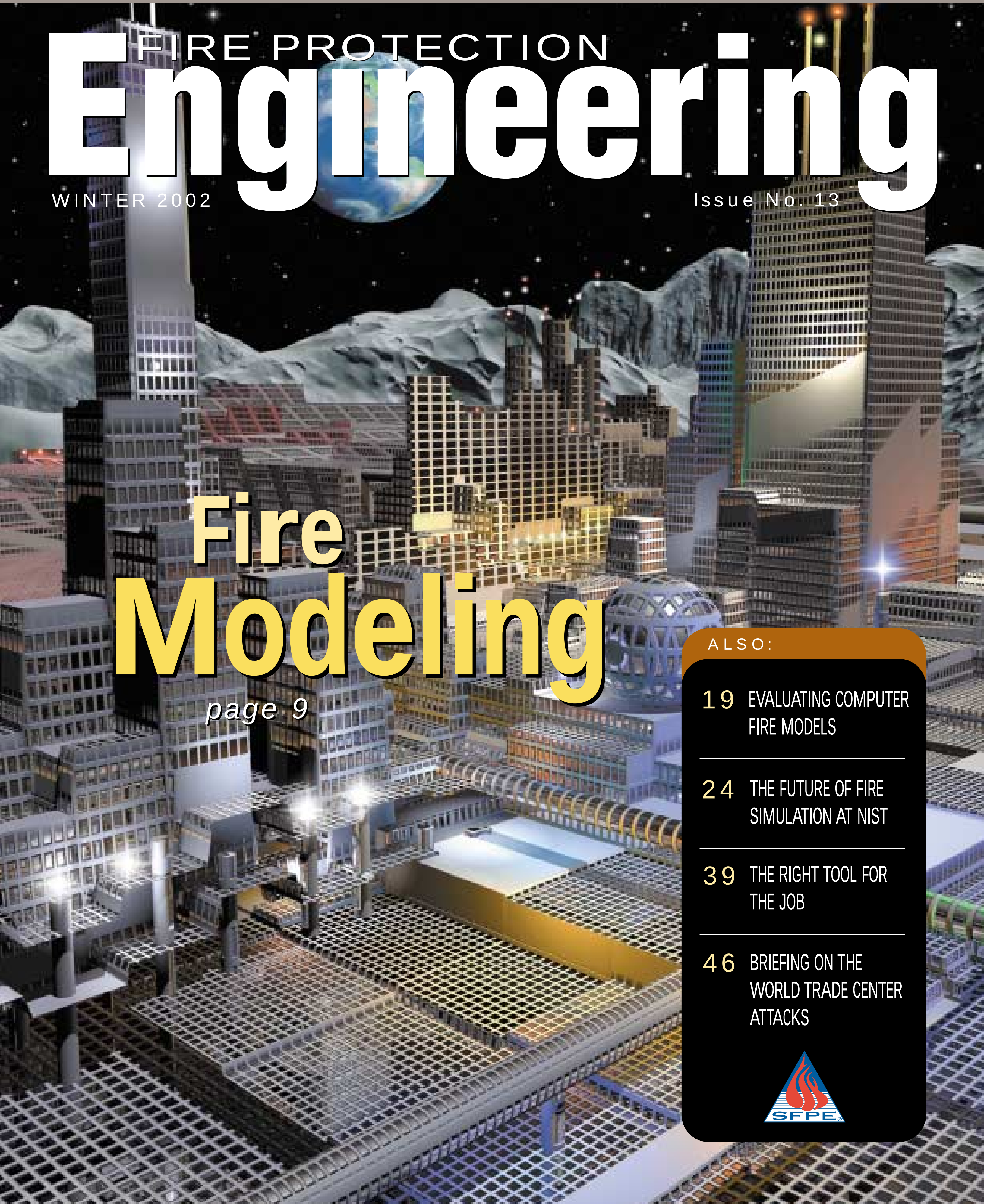

Fire Modeling

page 9

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contents WINTER 2002

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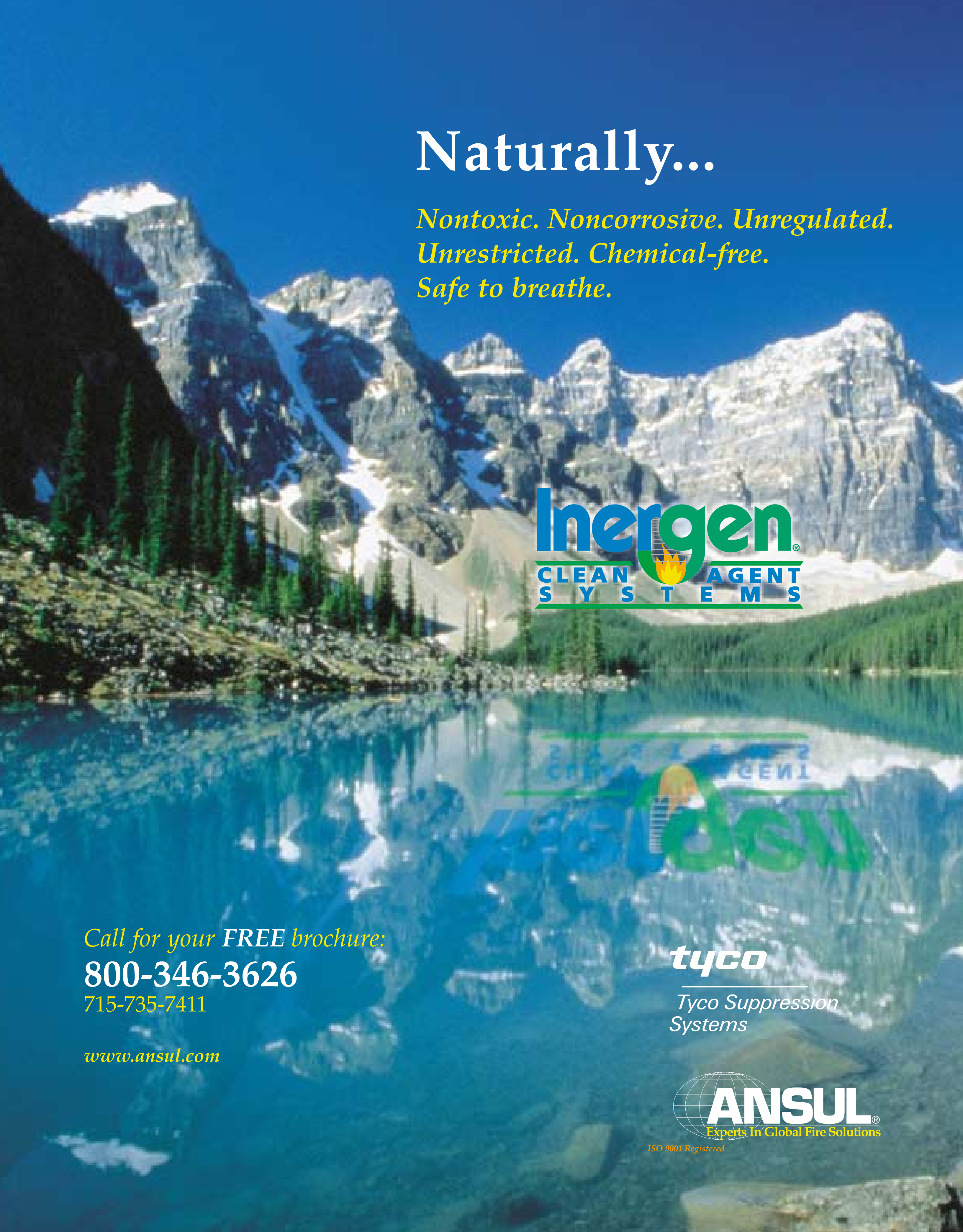
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THE LACK OF PRESCRIPTIVE INPUTS PROBLEM IN PERFORMANCE-BASED DESIGNS

By Joseph M. Fleming

Performance-based designs appear to rely on three sources of information:

1. A Set of Objectives. (This could be a Performance-Based Code.)
2. A Design Guide. (These are general rules on documentation and methodology.)
3. Reference Material. (For example, an engineering handbook.)

The problem with the use of this material is that it allows too much flexibility in the selection of critical "input" items such as performance criteria and assumptions about occupant behavior. A code official trying to use these documents to ensure 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 the affairs but are almost useless as a set of enforceable rules.

These input items could substantially alter the output of computer models and algorithms. How is a code official supposed to ensure that the output of a design process is safe when they have no method to measure the validity of the inputs? This is not a problem with prescriptive codes because the output is "prescribed." With performance-based designs, the output is not "prescribed." To ensure the safety of future occupants in performance-base-designed buildings, I believe that the inputs must be "prescribed." Failure to prescribe the inputs could lead to either unsafe or overly expensive designs.

As Fire Marshal of the City of Boston, I have reviewed many "deterministic" timed egress analyses. A key component of these analyses is the selection of tenability criteria. This selection could increase or decrease the time available for egress by several minutes depending on the fire scenario. Unfortunately, many guidelines, such as the *SFPE Handbook*, provide multiple choices for acceptable tenability criteria or "factors to consider" when deciding what tenability limit to utilize. Even the *SFPE Engineering Guide to Performance-Based Fire Protection Analysis and Design of Buildings* only states, "Visibility through smoke might affect the occupants' ability to safely exit a building. The factors that affect visibility include the amount of particulate in the path of vision and the physiological effect on the eyes. Low light levels might also affect occupants' ability to egress." Utilizing these references would provide the designer has a lot of leeway in this matter. If a code official wants 0.25 OD/m to be used, as the criteria for visibility and a designer wants to use 0.5 OD/m, how do we "referee" the disagreement?

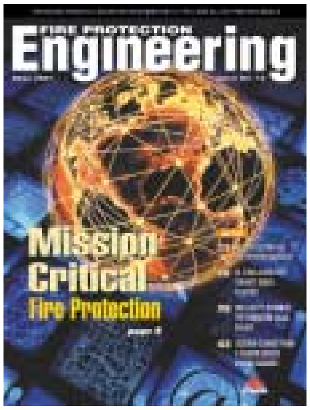
The proper use of safety factors is another area where there seems to be only general guidelines as opposed to rules. It does not appear that any algorithm or model that is currently utilized is 100% accurate. As a consequence, it would seem prudent to utilize safety factors to offset the uncertainty. In actuality, many designs that the Boston Fire Department has seen have not utilized any Safety Factor. Others have used a Safety Factor of 1.5. All of these selections were based on "engineering judgment." In the *SFPE Handbook*, Jake 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.'" Despite this well-documented recommendation, one of the engineers who participated in a design we reviewed stated, "Jake Paul's method (*SFPE Handbook*) 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." Do I have the right as a code official to reject this design based on this comment? The engineer felt that I did not since his "engineering judgment" justified the opinion. But isn't this type of thinking circular reasoning? An engineer's opinion regarding the proper choice of safety factors has to be justified by more than just the engineer's opinion.

SOLUTION

It seems reasonable to give designers the freedom to choose different designs, i.e., different outputs, to achieve the same goal. At the same time, it does not seem reasonable to allow designers the freedom to pick any criteria and make any assumption that they can find a reference for in a technical handbook or peer-reviewed journal. Until a set of prescriptive inputs can be published, it seems prudent to always require the following:

1. The logic justifying the selection of criteria or assumptions should be explicit. Whenever possible it should be more than "engineering judgment."
2. An independent peer review should be provided to the code official.
3. All references used to justify assumptions or criteria should be made available to the code official.

Joseph M. Fleming is with the Boston Fire Department.



In Response to "Lessons Learned from a Carbon Dioxide System Accident," Issue No. 12.

Having been at the INEEL for about two years, talked and worked with personnel involved or familiar with the incident, and toured the area where the tragic event occurred, I have learned a few "lessons" that were not focused on in the article. Here they are:

1. Carbon dioxide (CO_2) at minimum design concentrations required to suppress fires is lethal to humans. Given its inherent hazard, it should not be used in areas subject to occupancy – EXCEPT when the risk of fire is documented to be greater than the risk to personnel AND there are no viable suppression alternatives. When considering the recent advances our industry has made in fire suppression agents (notably water mist and Halon alternatives), no situations which meet the exception condition come to mind.
2. When it is evident that adherence to a national consensus standard is not sufficient to preclude a fatal accident, that standard must be evaluated to determine its adequacy. Immediately following the tragic event, *NFPA 12, Standard on Carbon Dioxide Extinguishing Systems* (2000 edition)[1], was changed to require the addition of an isolation valve to enable the system to be physically isolated. Additionally, the appendix guidance in *NFPA 72* (1999 edition)[2] was modified to suggest the use of devices which detect the flow of agent and initiate alarm notification appliances. Yet the question remains: With the incorporation of these changes, are the standards adequate to permit the use of carbon dioxide in areas subject to occupancy? If they are not, then more evaluation is required with the intention of revising the standard or restricting the use of CO_2 in lethal concentrations to areas not subject to occupancy.
3. The specific mechanism that caused the CO_2 system to discharge without warning has been attributed to a design defect in the manufacturer's fire panel [Lockheed Martin, 1999].[3] When significant defects are identified, many manufacturers issue recall notices to ensure that not only is the consumer made aware of the defect, but also that the defect is "corrected." Standards dealing with fire suppression agent design concentrations, which, if exceeded, could be hazardous to occupants, should include provisions that address product defects. These provisions should require manufacturers to immediately notify users of the defective product and initiate recalls when it is determined that the defect is sufficiently hazardous to endanger human life.
4. Standards dealing with fire suppression agent design concentrations, which, if exceeded, could be hazardous to occupants, should include provisions that address system configurations. System configurations where the failure of a single component could result in hazardous concentrations to occupants should be prohibited (some "approved" gaseous agent reserve manifolds would not meet this provision).

A final thought. As fire protection engineers, we need to be continually scrutinizing our engineering approach to the fire problem. To quote one of my engineers, just because "we can" do something doesn't mean "we should."

Stephen Thorne, P.E.
INEEL Fire Marshal

The opinions expressed above are my own and do not necessarily reflect those of my employer.

References:

1 *NFPA 12, Standard on Carbon Dioxide Extinguishing Systems*, 2000 Edition. National Fire Protection Association, Quincy, MA, 2000.

2 *NFPA 72, National Fire Alarm Code*, 1999 Edition. National Fire Protection Association, Quincy, MA, 1999.

3 Lockheed Martin, 1999. Identification of the Specific Mechanism by which the CO_2 System in Building TRA-648 Accidentally Discharged.

I think the article "Lessons Learned from a Carbon Dioxide System Accident" (Issue No. 12) could have gone even further and stressed the importance of simplicity over complexity and of mechanical over electronic schemes where robustness is of top priority. Designers of water-based extinguishment systems have known the value of indicating valves for over a century, and it is still the most robust way of shutting off a system and having its status be unambiguously indicated. Designers, OSHA, and the NFPA 12 committee should consider the wisdom that a heat-seeking missile may prove not to be more reliable than a fly swatter in swatting flies. Get mechanical indicating valves in there now, and don't accept non-robust "modern" substitutions!

Vytenis Babrauskas, Ph.D.
President,
Fire Science and Technology, Inc.

In the Fall 2001 issue (No. 12) of *Fire Protection Engineering*, the article "UL 2360, A New Test for Wet Bench Plastics"[1] by Jane Lataille contains a number of inaccuracies and omissions that could misinform readers about the state of flammability testing for plastics used in semiconductor clean rooms.

Ms. Lataille notes in the article that Factory Mutual Research introduced fire tests to determine the acceptability of plastics for use in the semiconductor industry. These tests, known as the Factory Mutual Research Test Standard 4910[2] (FM4910), were released in 1997 and included both small-scale tests and an intermediate-scale (parallel panel) test adopted in concept several years later by Underwriters Laboratories (UL 2360)[3] as discussed in the article. However, Ms. Lataille inaccurately characterizes Factory Mutual Research's small-scale test as one which plastics manufacturers are not able to run "because the nonstandard test apparatus is not readily available and the test results were not reproducible." She adds, "In addition, the test is complex and expensive."

As I will explain below, in sharp contrast, FM4910 provides a reproducible, standardized, technically sound, and documented method of selecting nonfire propagating materials for use in semiconductor clean rooms.

The small-scale test apparatus generating the results alleged by Ms. Lataille to be nonreproducible is the apparatus known to many as the FMRC Flammability Apparatus. This apparatus has been used to generate the data in the *SFPE Handbook of Fire Protection Engineering,* Section 3/Chapter 4, "Generation of Heat and Chemical Compounds in Fires."[4] It is fair to say that this is one of the most widely used sources for flammability properties of materials. Moreover, the apparatus is considered of sufficient technical soundness to be recognized as the ASTM E-2058 Fire Propagation Apparatus[5] and recognized in the *NFPA 287, Standard Test Methods for Measurement of Flammability of Materials in Cleanrooms Using a Fire Propagation Apparatus (FPA)*.[6] The apparatus also is available in a commercial version from Fire Testing Technology Ltd. (FTT) and is used by Factory Mutual Research's Approvals division for its certification testing.

Although the article asserts to the contrary, it is also important to point out that test complexity and expense are not an issue compared to UL 2360.[3] The parallel panel test in UL 2360,[3] adapted from the Factory Mutual Research test, is virtually the same as that in FM4910,[2] and the tests conducted with the cone calorimeter used in the UL 2360[1] are similar in many respects to the small-scale ASTM E-2058[5] tests in FM4910.[2] There are, however, important technical differences between the small-scale test methodologies.

The FM4910[2] small-scale test uses a "vertical" sample of plastic material to characterize the heat release rate of a material under conditions in which fire propagation is supported by the heat flux generated by the material's own flame. Forty-percent oxygen is used to simulate the high flame heat fluxes that are developed in large-scale tests.[8] In contrast, in the UL 2360[3] small-scale test, the heat release rate is obtained in a test with a "horizontal" sample of plastic material in normal air with a fixed imposed external heat flux. This fixed heat flux is not necessarily characteristic of the heat flux that would be generated by the material's own flame in a large-scale fire. Thus, the generated heat release rate may not be appropriate.

This may be seen in the data presented by Ms. Lataille. Table 1[1] indicates that clear PVC, using the UL classification scheme of Table 4,[1] is a limited propagating material (i.e., flame propagation in the parallel panel is less than 8 ft.). Indeed, clear PVC just misses by 0.2 ft being classified by the UL parallel panel as a nonpropagating material. However, the UL 2360 small-scale test classifies this material as a propagating material, with the UL index being more than double the requirements to be considered as nonpropagating.

Testing of this material at Factory Mutual Research has indicated that this inconsistency would not occur under FM4910, as both the parallel panel test and the FM4910 small-scale test would classify the material as nonpropagating. Similar results have been observed for other materials and reported by Factory Mutual Research.[9]

Another correction to note in the article is the explanation for the equation for the Thermal Response Parameter (TRP). It is not derived from equations for the flame height and flame propagation rate. Rather the TRP is derived from the temperature response of a material under thermally thick heating conditions. For further details, please refer to reference 4.

Of final clarification, the parallel panel test mentioned frequently in the article, without explanation, was developed by Factory Mutual Research as an intermediate-scale test, which would provide an appropriate simulation of the fire hazard in semiconductor clean rooms. This was demonstrated in full-scale wet bench tests at Factory Mutual Research.[10]

Robert G. Bill, Jr., Ph.D.
Assistant Vice President and Director,
Materials Research
Factory Mutual Research

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1. Lataillle, J., "UL 2360, A New Test for Wet Bench Plastics," *Fire Protection Engineering*, No. 12, 30-33, Fall 2001

2. Test Standard, "FMRC Clean Room Materials Flammability Test Protocol," Class Number FMRC 4910, Factory Mutual Research Corporation, Norwood, MA, 1997.

3. *Standard for Safety*, "Test Methods for Determining the Combustibility of Plastics Used in Semi-Conductor Tool Construction," UL 2360, 1st Edition, Underwriters Laboratories Inc., Northbrook, IL, May 2000.

4. Tewarson, A.,"Generation of Heat and Chemical Compounds in Fire," *SFPE Handbook of Fire Protection Engineering*, Section 3/Chapter 4, 2nd edition, NFPA Publications, Quincy, MA, 1995.

5. *ASTM E2058-00, Standard Methods of Test for Measurement of Synthetic Polymeric Material Flammability Using a Fire Propagation Apparatus (FPA).* The American Soc. For Testing and Materials, West Conshohocken, PA, 2000.

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9. Bill, R., Wu, P., Tewarson, A., and Khan, M., "Characterizing the Vertical Fire Propagation Propensity of Materials Through Small-Scale Flammability Testing," *Proc. Fire & Materials 2001*, 209-219, 7th International Conf., Interscience, London, January 22-24, 2001.

10. Wu, P., "Parallel Panel Fire Tests for Flammability Assessment," Proc. 8th International Fire Science & Engineering Conf., Edinburgh, Scotland, 605-614, Interscience, London, June 29 – July 1, 1999.

Spivak Receives W.T. Cavanaugh Award

W. CONSHOHOCKEN, PA – The 2001 William T. Cavanaugh Memorial Award was recently presented to Dr. Steven M. Spivak, professor emeritus and immediate past-chairperson of the Department of Fire Protection Engineering at the University of Maryland in College Park, MD. Established in 1987 in memory of the late William T. Cavanaugh, ASTM chief executive officer from 1970 until his death in 1985, the award is the highest recognition ASTM gives to a person or persons of widely recognized eminence in the voluntary standards system.

Dr. Spivak has been on the faculty of the University of Maryland since 1970; he has been with the Department of Fire Protection Engineering since 1992. The prior 20 years, he worked in textile fire research, fiber science, and polymer/chemical engineering. He has taken three sabbaticals involving standards work, one at the General Services Administration and two at the National Institute of Standards and Technology.

Free, Revised ESFR Sprinkler Datasheet

JOHNSTON, RI – FM Global, the developer of Early Suppression, Fast-Response (ESFR) sprinkler technology for warehouse fire protection – particularly high rack storage – has released a newly revised, easier-to-understand version of its Property Loss Prevention Data Sheet 2-2 Installation Guidelines for Early Suppression, Fast-Response Sprinklers. FM Global is making this data sheet, written for fire protection system designers and installers, available for free to address all-too-common misunderstandings about ESFR technology and the increased international use of such sprinklers.

The revised and reorganized instructions contain more in-depth explanations and illustrations for proper installation of ESFR sprinklers. The data sheet also emphasizes the challenges that can impact the effectiveness of ESFR sprinklers including roof height, structural members, lighting, HVAC, storage heights, and certain types of commodities.

For a free copy, visit www.fmglobal.com/esfr, or call FM Global Customer Services at 781.255.6681.

New Award for Environmental Awareness in Fire Protection

ASHLAND, MA – Kidde plc, in association with the U.S. Environmental Protection Agency (EPA), has created the annual David Ball Award for Fire and the Environment. The award will recognize the significant contribution made by an individual, team, or organization to furthering the understanding of the impact of fire or developing improved methods of fire control that benefit or protect the environment. The first award will be presented at the Fourth Earth Technologies Forum in Washington, DC, March 25-27, 2002.

The award is named in honor of Dr. David Ball, a 25-year employee of Kidde, who died in July 2001. David was Kidde's research manager and was well known in the global fire protection industry as a passionate advocate of environmental awareness.

More more information, contact Stephen Summerill at 304.728.3489 (Stephen.Summerill@kidde-fenwal.com).


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From PHLOGISTON to COMPUTATIONAL FLUID DYNAMICS

By Harold E. Nelson, P.E.

During the last decade, fire models have had a major influence on applied fire protection engineering. Modern compartment fire models solve fire dynamics equations that have been only very recently seriously investigated. The information developed as a result of these investigations has helped transfer fire dynamics methods from the research realm to field application. Fire protection engineering applications now range from straightforward algebraic equations, such as those for describing fire plumes, to complex computer models that solve complex simultaneous fire dynamics equations iteratively.

Over the past 50 years, fire dynamics information was derived from scientific principles abstracted from other disciplines. The basis for the fire dynamics in compartment fire models lies in the physics relationships inherent in combustion, such as heat balance and conservation equations.

All of combustion science rests at least in part on Lavoisier's discovery in the late 18th century that combustion involves reaction with the element oxygen. This article reviews the steps that brought fire dynamics from there to the models of today.

THE DISCOVERY OF OXYGEN – THE FALL OF THE PHLOGISTON THEORY

In ancient times, fire was considered one of the four elements, the other three being earth, air, and water. From the time of the early Greek philosophers until the late 18th century, it was held that the essence of fire is a substance called phlogiston. The phlogiston theory explained most combustion reactions, at least to the degree of measurement available to the experimenters of that day.

At the time of the French Revolution, Antoine Lavoisier, French philosopher and chemist, demonstrated the phlogiston theory as inaccurate. By careful experiment and measurement, Lavoisier showed for the phlogiston theory to be correct, phlogiston had to have a negative mass, an untenable position. At the same time, the English scientist Joseph Priestly isolated what he called "dephlogisticaded air." Lavoisier demonstrated that Priestly's finding was a substance, which he labeled oxygen. Lavoisier further demonstrated that oxygen was part of a combustion reaction and added weight to the product.

Also in the last decade of the 18th century, another English scientist, Benjamin Thompson, demonstrated by studying experiments that no mass changes are associated with temperature change and that heat is a manifestation of motion. These discoveries constituted the final criticism and destruction of the phlogiston theory.

FARADAY'S CHRISTMAS LECTURES

In the 1840s, the famous scientist Michael Faraday in his Christmas lectures at the Royal Institution of Great Britain presented one of the earliest demonstrations of the interaction of elements in fire dynamics. Faraday used the burning of a candle to demonstrate many of the phenomena involved in combustion. The candle lecture included demonstrations of radiant energy, liquidation of the candle wax, and capillary action.

THE START OF MODERN FIRE DYNAMICS

Early Investigations of Fire Plumes. Modern fire dynamics, however, finds its initiation in and following the World War II period in the early 1940s. One of Britain's leading physicists, Sir Geoffrey Taylor of Cambridge University, used his knowledge of fluid dynamics to develop a system for clearing fog at wartime airfields. Gasoline fire plumes rising out of ditches beside runways were used to entrain and remove fog sufficiently for returning aircraft to find the fields and land.

Critical to quantifying the fire plume is an analytical understanding of the amount of air (or other surrounding gases) entrained into the rising fire plume. The initial work of the definition of fire plumes, including the entrainment coefficient, appears to have been published by W. Schmidt in Germany in 1941. Taylor analyzed Schmidt's work and a description of a thermally driven plume was prepared for the U.S. Government under the title of "Dynamics of a Hot Gas Rising in Air" in 1945. The first major publication of plume theory impacting the analysis of accidental fires, however, was the paper titled "Turbulent Gravitational Convection from Maintained and Instantaneous Sources." by B. R. Morton, Taylor, and J. S. Turner, all of Cambridge University, in 1956. This described the first heat-driven plume equation that included entrainment, plume velocity, and plume temperature.

While most current fire models and calculations do not use the early Morton, Taylor, and Turner equations, all of the current methodologies for calculating plume properties are, at least to some extent, descendants of the Morton, Taylor, and Turner work. The work of Morton, Taylor, and Turner was a turning point that has become the basis for the modern zone model.

A progression of investigators carried the work forward increasing the level of understanding. In 1960, Sizuo Yokoi of the Building Research Institute of Japan examined both flame heights and the hot gas currents of a plume flowing from a window, exposing the floor above.

Bernard McCaffery of the Center for Fire Research, in his 1979 report on experimental results, examined entrainment in the area of the flame as well as the rate of entrainment in the portion of the plume above the flame.

In the mid 1970s, Edward Zukoski, along with his colleague T. Kubota and his doctoral student B. Cetegen at the California Institute of Technology, pursued the entrainment phenomena further and developed one of the earliest plume equations. Their plume equation was formally published in 1981 and has been used in fire models such as ASET, FIRE SIMULATOR, and CCFM.

Gunner Heskestad of Factory Mutual Research Corporation developed the concept of virtual source to account for the fact that most accidental fires are not point source in nature. Heskestad then developed a coordinated set of algebraic equations on fire plumes for engineering use. His work, first published in 1984, is accessible to engineers as the chapter on fire plumes in the *SFPE Handbook*.

Others, including Philip Thomas at the UK Fire Research Station and Kunio Kawagoe at the Building Research Institute of Japan, also examined and improved the fire plume equations. Craig Beyler, then a visiting scientist at the UK Fire Research Station, examined 14 fire plume and ceiling jet equations in 1986.

IMPACT OF RESEARCH INSTITUTIONS

The development of the understanding of the dynamics of fire has strong ties to a number of institutionalized programs. It's worthy to briefly discuss some of the major participants.

The UK Fire Research Station. In the UK, both the fire impact of wartime attacks and the use of alternative materials, some of which were very combustible (such as low-density fiberboard linings), produced fires that exceeded expectations. The British came to realize that there was a wide range of speeds of involvement and extent of fire development, spread of fire between buildings, and other aspects of fire danger permitted by the then-current bylaws and regulations. During the war, the British science community had worked diligently on fire prevention and control, as well as on using fire as a weapon. In 1947, one of the most important modern fire research and development groups was assembled: The Fire Research Station. Also, the Joint Fire Research Organization, created in 1946, enabled funding from both the government and private interests, particularly those in the fire insurance industry.

The British fire research programs have long enjoyed a well-deserved leadership position as developers of fundamental and applied fire science and engineering. Examples include the analysis of radiation between buildings as a function of openings, separations, and fire condition by Margaret Law; the venting of hot gases from large space fires by Peter Hinkley and Thomas; and the study of various heat release and heat transfer means by Richard Chitty and Geoffrey Cox. Fire dynamics developments at the Fire Research Station in recent years have concentrated on the advancement of CFD modeling.

Building Research Institute of Japan – Japanese Fire Research Institute. In Japan, the immediate problem in the first years following the war was the reusability of structures that had been damaged during the air campaign. The program initially addressed structural problems, both with and without earthquake considerations, but soon extended to the question of what fire would do in these buildings, and which buildings would be safe for continued use. The Building Research Institute of Japan created a fire research section, and about the same time, a separate Fire Research Institute was established in The Ministry of Home Affairs.

There are many contributions to fire safety developed in the Japanese fire research programs. In terms of fire dynamics and modeling, examples of important work at the Building Research Institute includes that of Yokoi and Kawagoe.

Yokoi was the first director of fire research at the Building Research Institute. Under his direction in the 1950s, important work was developed on flame height and fire plumes, particularly those projected from buildings. Yokoi's plume research has been used to develop the spandrel panel requirements for high-rise buildings in Japan.

Also in the late 1950s, Kawagoe and his colleagues observed that early in the development of the room fire, a reasonably clean-cut smoke layer – or zone – is established. Kawagoe further established that in the simple situation where there is a compartment with a single opening and no forced air, the available air for combustion is limited to that which can be drawn in the room through the opening to replace the mass expelled through the same opening. The rate of air intake was established to be a function of the area of the opening times the square root of its height. Kawagoe mathematically expressed these phenomena in what is frequently referred to as Kawagoe's equation. Kawagoe's observations and calculations are key elements in zone modeling.

There is an anecdote of Kawagoe visiting Zukoski at Cal Tech and telling him about the layer interface phenomena, which was then contrary to many commonly held beliefs. Prior to Kawagoe's work, many researchers believed that the turbulence in the room would cause a mixing of all the gases into one zone referred to as a well-mixed reactor. According to the anecdote, Zukoski challenged Kawagoe to prove his point and they went to a nearby mechanics laboratory where they initiated the phenomena in a liquid tank. They pumped a light density liquid into a higher density liquid as an analogue to fire and clearly saw the layer development. Understanding these two zone phenomena was critical to the concept of zone models.

RESEARCH ON FIRE DYNAMICS AND MODELING IN THE UNITED STATES

Office of Civil Defense Funds Major Fire Research Program. In the 1950s and 1960s in the United States, the impetus for the OCD fire research program, directed by James Kerr, was the Cold War. The OCD program was primarily focused on civil defense, particularly the potential impact of nuclear attack. The OCD programs involved an expenditure of approximately 1 million dollars annually on fire research, the vast majority of which was directed at large-scale nuclear attack-initiated fires. However, work relative to fire dynamics was part of this effort. Extensive work was done at the Naval Radiological Defense Laboratory on understanding the ignitability of materials from radiant energy sources. Much of this information was published in the book *The Effects of Nuclear Weapons* by Samuel Glasstone. Extensive work on flashover was undertaken by the Armor Research Foundation (now Illinois Institute of Technology Research Institute). The principle investigator was Thomas Waterman. Professor Willis Labes of the IIT Department of Fire Protection Engineering performed investigations of radiant fire spread as part of the OCD effort.

OCD Sponsors National Academy of Science Committee on Fire Research. In the early 1950s, OCD sponsored the establishment of the National Science Foundation Committee on Fire Research. This committee was initially headed by Hoyt Hottel of Massachusetts Institute of Technology and subsequently by Howard Emmons of Harvard. In the early 1970s, the committee sponsored the publication of *Fire Research – Abstracts and Review*, essentially the first U.S. science-based fire journal. The *Fire Research – Abstracts and Review* was published 3 times a year for approximately 12 years from the early 1960s to the 1970s. Robert Fristrom of Johns Hopkins Applied Physics Laboratory was editor. The exchange of information provided by this journal was very important to the spread of knowledge among the various groups interested in fire research.

Woods Hole Conference Appraises Application of Science to Fire Problem. In 1962, the NAS Committee on Fire Research autho-

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rized the Woods Hole Study in Woods Hole, MA, which brought together a representation of a cross-section of sciences that potentially could contribute to solutions for fire safety problems. Leaders in the applied fire protection arena were also included. The conference met for four weeks with the first week's agenda consisting of external speakers on the sciences as they could be applied to fire problems. The major recommendation of the conference was the need to establish a national fire research program within the Federal government. This concept, however, was not widely accepted outside of the science community. Leaders of fire protection and prevention organizations, such as the NFPA and the fire insurance industry, strongly opposed a Federal research program. Their position was that there was no need for new information, rather a need for applying the knowledge we currently had and that the Federal government should not impose itself in this arena. Fire research and safety bills proposed in 1963 and 1964 were never enacted.

The Woods Hole Conference, however, had an important impact in that it generated a consensus in the scientific community that there was a potential to mathematically describe, i.e., model, fire phenomena and the impact of the fire on the environment within a building.

THE RANN PROGRAM TAKES PLACE OF OCD FIRE RESEARCH PROGRAM

In the mid-1960s, the U.S. government established an administrative policy that the military should shed itself of research that did not directly impact military objectives. A research program entitled "Research Applied to National Needs" (RANN) was established in the National Science Foundation, and the fire safety aspects undertaken by the Office of Civil Defense were transferred to the RANN organization. Dr. Ralph Long was placed in charge of the fire aspects. The RANN program was focused on research at academic institutions. In addition to individual efforts by eminent scientists, Long encouraged and eventually sponsored centers of excellence. Four such centers were established at Harvard; University of California, Berkley; Johns Hopkins Applied Physics Laboratory; and the University of Utah. Of these, the work at Harvard most directly applies to fire dynamics and fire modeling.

Harvard Program. The Harvard program, under the direction of Howard Emmons, was undertaken in cooperation with the basic research program at Factory Mutual Research Corporation. This center concentrated on the fire environment in a room and the various phenomena needing examination to accurately predict the room fire conditions. Their project was titled "The Home Fire Project." The Harvard fire model came from this program.

In the late 1970s, the National Fire Foundation transferred the RANN program to NBS. The RANN projects were merged with the established grant program of the Center for Fire Research.

FEDERAL FIRE PREVENTION AND CONTROL ACT OF 1974 SETS UP CENTER FOR FIRE RESEARCH

The National Bureau of Standards (NBS), now known as the National Institute of Standards and Technology (NIST), has had a fire research program since 1914. Prior to the creation of the Center for Fire Research (CFR), the program emphasis was generally not directed at the dynamics of fire in a space. It is currently an international leader in research and development of the understanding of fire dynamics and the creation of fire models and other fire protection tools and systems.

PLASTICS INDUSTRY SUPPORTS FIRE RESEARCH THROUGH PRODUCT RESEARCH COMMITTEE

At approximately the same time as the enactment of the Federal Fire Prevention and Control Act of 1974, the Products Research Committee was formed. This committee administered a trust fund established in the consent order of 1974 between the Federal Trade Commission and 25 responders involved in the manufacture of cellular plastics. The work of the Product Research Committee was undertaken in the form of grants totaling $5,000,000 over a five-year period.

OTHER CONTRIBUTORS

It is impossible to review the contributions by all the other organizations and individual researchers to the understanding, quantification, and engineering modeling of the individual fire phenomena and their interactions that make up fire dynamics. A sampling of these contributors include:

- Factory Mutual Research Corporation
- National Research Council of Canada
- University of Lund, Sweden
- University of Edinburgh, Scotland
- University of Maryland

FIRE MODELS

Impact of Livonia and Jaguar Fires on Modeling. In 1953, there was a major fire at the General Motors hydraulic transmission plant at Livonia, MI. A few years later there was a fire, which got out of control and exceeded the ability of hose streams, at the Jaguar Automobile Production Plant in the UK. In both of these cases, there was an interest in determining if roof venting could have made a difference and provide protection in a manner that would eliminate the need to erect firewalls in these spaces.

Thomas and Hinkley conducted extensive experiments at the UK Fire Research Station simulating conditions in these fires. While conducting these experiments, they noted a large-scale version of the same type of layer reported by Kawagoe. A plume developed feeding smoke into that layer following the general descriptions of Morton, Taylor, and Turner, and Kawagoe. They then devised means of determining roof vent requirements, based on an equilibrium between the mass flow into the upper smoke layer, and the mass flow out the roof vents. As this work was done before the common availability of computers to practicing engineers, Hinkley and Thomas expressed their results in the form of nomographs. The nomographs provided the engineer with a reasonable approximation of the venting requirements under a range of building dimensions and exposure fire size. In a way, Hinkley and Thomas developed the first compartment zone fire model.

While both the US and UK were familiar with and have undertaken projects related to both zone models and Computational Fluid Dynamics (CFD) models, a tendency developed in the US to use zone models while activity in the UK was more concentrated on CFD models. The rest of the world has been similarly divided.

ZONE MODELS

A zone model usually divides each room into two spaces or zones: an upper zone containing the hot gases produced by the fire and a lower zone containing all space beneath the upper zone. The lower zone is a source of air for combustion and is usually the location of the fire source. During the course of the fire, the upper zone can expand to occupy virtually all of the space in the room.

In a zone model, the upper zone is considered a control volume that receives both mass and energy from the fire and loses energy to the surfaces in contact with the upper zone by conduction and radiation, by radiation to the floor, and by convection or mass movement of gases through openings. Some models evaluate conditions in the lower layer, others assume that the lower layer remains at ambient conditions. Mass is conserved, accounting for mass entering or vented from the control volume.

Many zone models superimpose the correlations developed initially by Ronald Alpert at Factory Mutual Research Corporation to describe the hot ceiling jet. In most of these models, the correlation by Alpert had been adjusted using techniques developed by either David Evans of NBS or Leonard Copper, then with NBS, to reflect the impact of the hot upper zone on the hot ceiling jet.

Quintiere's Paper "Growth of Fire in Building Compartments." In 1976, James Quintiere, then at the Center for Fire Research, presented a paper at an ASTM symposium marking the 75th anniversary of the National Bureau of Standards. In this paper, he discusses the possibility of creating a fire model and outlines the variables the model would have to solve and the algorithms needed to be solved. He subsequently generated a simple model, which he called RUNF. That model has never been in common use, but it and Quintiere's paper influenced thinking on the part of other researchers including Ronald Pape at IIT Research Institute and Zukoski at Cal Tech.

First Published Model, the IITRI Model. Pape developed the IITRI Model, the first published compartment fire model. It was a simple single-room compartment fire model based on the approaches proposed by Quintiere which used Zukoski's plume equations. Pape also used correlations of burning rate data from prior work at IITRI for the OCD fire threat program. The IITRI Model was published slightly ahead of the Harvard model. Its importance lies in being the first to demonstrate the potential of a mathematical model as a fire protection engineering design tool.

First (The Harvard Model). One of the main elements of the Home Fire Project at Harvard and Factory Mutual Research Corporation was a detailed study scientifically measuring and analyzing the development of a fire from its early ignition through flashover in a bedroom situation. For three years, the project conducted one well-instrumented and carefully directed test each year. The ensuing year was used to analyze the data, often inviting researchers from other fire research programs to join the analysis. Much attention was directed in establishing the algorithms, equations, and relationships that would define the individual phenomena involved and the interaction between phenomena. In 1976, it reached to the point where Professor Emmons brought in help, particularly Henry Mitler, to write a predictive single-compartment fire model. From this, in 1978, emerged the Harvard Model Mark I. The Mark I model was crude by current standards; however, it demonstrated the potential of zone compartment fire models. With the object of making the Harvard Model as comprehensive as possible, the model was expanded and enlarged through a series of improved versions. The last version developed at Harvard was Mark V issued in 1983, the year of Emmons' retirement. Emmons had hoped that the Harvard Model could become so complete and accurate that it could be used to judge the validity of simpler and special purpose models. This objective was not reached. After Emmons retired, the Harvard Model was turned over to the National Bureau of Standards and renamed FIRST. A small cadre of scientists still use FIRST, but it is not generally used in engineering applications at this time. Jonathan Barnett and his students at WPI have modified FIRST into an extensively expanded model they call the WPI Model.

Ad Hoc Committee on Fire Modeling Passes Information among Modelers. During most of the 1980s, scientists and engineers developing zone fire models met and exchanged modeling knowledge and discussed related algorithms at a series of open meetings called by the Ad Hoc Committee on Fire Modeling. The committee meetings were called and provided with secretarial support by Robert Levine of the Center for Fire Research. This committee had no official standing but met several times a year and circulated minutes with such attachments as the attendees submitted. Unfortunately neither the minutes nor any other permanent record of this committee was ever published. Even so, it was an important factor in the exchange of knowledge and the advancement of fire modeling.

Zukoski's Equations Underpin the Model ASET. Also in the time period of the late 1970s into the 1980s, Zukoski produced a set of equations suitable for modeling impact of fire in a room. These equations were then used by Cooper at the Center for Fire Research to produce the compartment fire model we now know as ASET, which stands for "Available Safe Egress Time." The ASET model originally produced by Cooper was designed for mainframe computer and had, by comparison to the ASETB approach, a tedious input program. An important event in the transfer of modeling technology from the research community to the practicing fire protection engineer was the development by W. D. (Doug) Walton of ASETB. Walton took the basic equations and reduced them to 200 lines of simple BASIC programming that could be run at very high speed on the relatively slow portable computers of that day, improving accessibility to the practicing engineer. ASETB was released to the public in 1985.

DETACT Opens Up the Ability to Predict Sprinkler and Detector Response. Within the same period of the mid-1980s, Evans combined the equations for ceiling jet temperature and velocity developed by Alpert in the late '60s with the response time index and related heat transfer equations from Heskestad's work to develop the DETACT models. These models are used to predict the response of sprinklers and heat detectors.

FPETOOL Is Developed by Nelson. Harold Nelson gathered a series of hand equations to which he added the ASETB Model and the DETACT Model. He assembled this collection in a computer program title FIREFORM, an abbreviation for "fire formulas."

The FIREFORM program was subsequently expanded by Nelson to include the room compartment model FIRE SIMULATOR, which added methods for estimating the burning rate history of exposure fires. This collection was titled FPETOOL. The FPETOOL package was first released to the engineering public in 1990. The FPETOOL collection was eventually expanded to include a model of smoke flow in a corridor, and was later extended to add a model related to smoke filling of a room remote from the room of fire origin as a result of smoke transferred to that room from smoke in the corridor.

The FPETOOL package gained great popularity in the fire protection engineering field. Similar packages followed in other places in the world such as, ASK FRS, published by the UK Fire Research Station, and FIRECAL, published in Australia. A survey in 1997 indicated that 60% of the practicing fire protection engineers used the FPETOOL package as their principal computerized fire dynamics calculator.

FAST, CFAST, CCFM, AND BRI2. In 1983, Takeyoshi Tanaka of the Building Reserch Institute of Japan published his paper "A Model of Multi-Room Fire Spread." He spent the two preceding years as a visiting scientist at the Center for Fire Research expanding on his previous fire modeling work in Japan. After he returned to Japan, work continued on his model in both Japan and the US. His efforts produced the model BRI-2.

A Center for Fire Research team lead by Walter Jones extensively revised and extended Tanaka's initial program to a point of development of a distinct, separate model. The model was titled Fire and Smoke Transfer (FAST) and used the core model of Hazard Mark I. The first version of FAST was released in 1985. Cooper concurrently developed the competing model, Consolidated Compartment Fire Model (CCFM). In a consolidation action, the two models were compared function by function, and the approach judged the best and most suitable was adopted. To a large extent, the physics solutions from FAST and the source codes structure and solver procedures from CCFM were adopted into a single model given the name Consolidated Compartment Fire and Smoke Transport Model (CFAST). First released in 1990, CFAST is a multiroom zone model that includes procedures for predicting fire growth and smoke transport from a compartment of fire origin to connecting compartments. It maintains conservation of energy, mass, momentum, and species. The basic conditions predicted by CFAST include the depth of smoke layer in each compartment, smoke layer temperature, and species concentration (oxygen, carbon dioxide, carbon monoxide) in the smoke layers. CFAST has been enhanced over its life to include additional capabilities such as the impact of forced airflow or venting of smoke and the prediction of other toxic species concentrations such as hydrogen chloride or hydrogen cyanide.

SFPE Computer Committee Spread the Word on Models. For about 10 years starting in 1984, the SFPE had a committee on computers. This committee served as an open exchange, usually meeting at NFPA meetings. The committee chairman was Jack Watts, with major contributions by Walton. This committee holds an important position in the technology transfer of modeling and related fire science to the practicing fire protection engineer. These meetings had the distinct value of presentations by practicing fire protection engineers who were using models relating their experiences, including problems as well as successes, to their colleagues considering their use.

CFD MODELS

Computational Fluid Dynamics (CFD) models divide the space being modeled into many small cells (on the order of hundreds of thousands to millions). The basic laws of mass, momentum, and energy conservation are applied in each cell and balanced with all adjacent cells. The computational modeling is a complex fluid mechanics solution of both turbulent and laminar flow derived from classic fluid dynamics theory. The governing equations are the Navier-Stokes equations. These equations involve a set of three-dimensional, nonlinear partial differential equations expressing conservation of mass, momentum, and energy. Important sub-models related to individual cells address turbulence, radiation, soot, pyrolysis, flame spread, and combustion. Approaches to the modeling differ among the various CFD models.

CFD models can examine the fire environment in much greater detail than zone models. In general, CFD models are significantly more expensive to obtain and use. Important engineering decisions are required in setting up the problem and interpreting the output produced by the model. However, the use of CFD models in fire protection problems is increasing. CFD models are particularly well suited for situations where the space is irregular, turbulence is a critical element, or very fine details are sought. CFD models usually require large-capacity computer workstations or mainframe computers. Advancements in personal computers and the improvement in the solver routines in the CFD models are, however, allowing some cases to be run on high-end personal computers.

The most popular approach for simulation of turbulent flows in most CFD codes has been some variant of the k-epsilon turbulence model. In this approach, additional transport equations are solved for time-averaged turbulence variables (i.e., turbulent kinetic energy, *k*, and its dissipation rate, *epsilon*). Examples of this approach are the Fire Research Station model, JASMINE, and most commercially available CFD codes. While this model is computationally economical, it is only moderately accurate due to some simplifying assumptions.

CFD models are by no means restricted to fire problems. They are widely used in the fluid dynamics and combustion fields. One of the most famous cases involving CFD models was the analysis of the Kings Cross underground station fire in 1989. In this particular case, the model used was the CFD model FLOW 3D developed by the Harwell unit of the British atomic energy authority. The details of the model showed how the fire in the escalators bent over to a point where the flame was virtually parallel with the escalator steps, igniting the wood rails, resulting in a fierce and fast fire spread up the escalators to the ticketing space near street level.

The development of faster computers has made it possible to simulate complex flows using other higher-level turbulence models. An alternative model to the time averaged k- epsilon turbulence model is known as Large Eddy Simulation (LES), which allows for the prediction of the instantaneous values of turbulence as opposed to time-averaged valves. Drs. Howard Baum, Ronald Rehm, and Kevin McGratten have developed and released an LES-based model for use on fire problems. This model, titled "Fire Dynamics Simulator" (FDS), has demonstrated its ability to identify conditions and phenomena not recognized by other types of analysis, for example, how fire overcame three firefighters in a simple row house fire in the District of Columbia.

The fact that FDS is free and available on the NIST Web site while most of the other CFD models have annual fee often in the tens of thousands of dollars will result in widespread use of FDS as a tool in actual fire protection design and analysis problems. Fortunately, it is a good, soundly based model with good support.

CFD MODELING HAS BEEN LONG ESTABLISHED IN THE UK

During the early 1970s Professor D. Bryan Spalding and his team at the Imperial College of Science and Technology in London entered into a close relationship with the Fire Research Station with the object of developing a new generation of mathematical models with the treatment of fires in enclosures.

The model developed, titled PHOENIX, was the first to use computational fluid dynamics as a compartment fire model. As noted above, this approach to modeling divides the space into mass numbers of cells and relates the transportation of fluids and energy between cells. The efforts at the Fire Research Station including the work by Professor Spalding were under the direction of Geoff Cox. A special fire model known as JASMINE was developed based on PHOENIX. JASMINE is now being replaced with an improved version called JOSEPINE.

SUMMARY

The application of fire dynamics to the solution of fire problems is quite recent. Twenty years ago, Nelson gave a lecture at the SFPE Technical Sessions at an NFPA meeting and at several SFPE chapter meetings. The lecture consisted of a series of simple algebraic equations designed to quantify fire dynamics applications. For example one equation was Thomas' equation for determining the size of fire required to flashover a space. At the time, there was virtually no interest in these types of computations by practicing fire protection engineers. In 1985, Randy Lawson and Quintiere published the report "Slide Rule Estimates of Fire Growth." The reaction was about the same as that to Nelson's presentation of equations. Then came the proliferation of the portable computer and the generation of user-friendly fire models. Now fire protection engineering demands the application of fire modeling to the problem. The trend to performance-based design expects the engineer to model a spectrum of fire scenarios. The SFPE has established a committee examining the validity of models. To date, the only model they have been able to appraise is DETACT. They are currently examining ASET, by far the least complex of all compartment fire models. This does not mean that it is inherently improper to use other models; indeed, fire protection engineering practice has progressed to almost common use of either much more sophisticated zone models or CFD models. The using engineer is, however, as always responsible for the quality of his or her product and the appropriateness of the solution means chosen.

Harold Nelson is with Hughes Associates, Inc.

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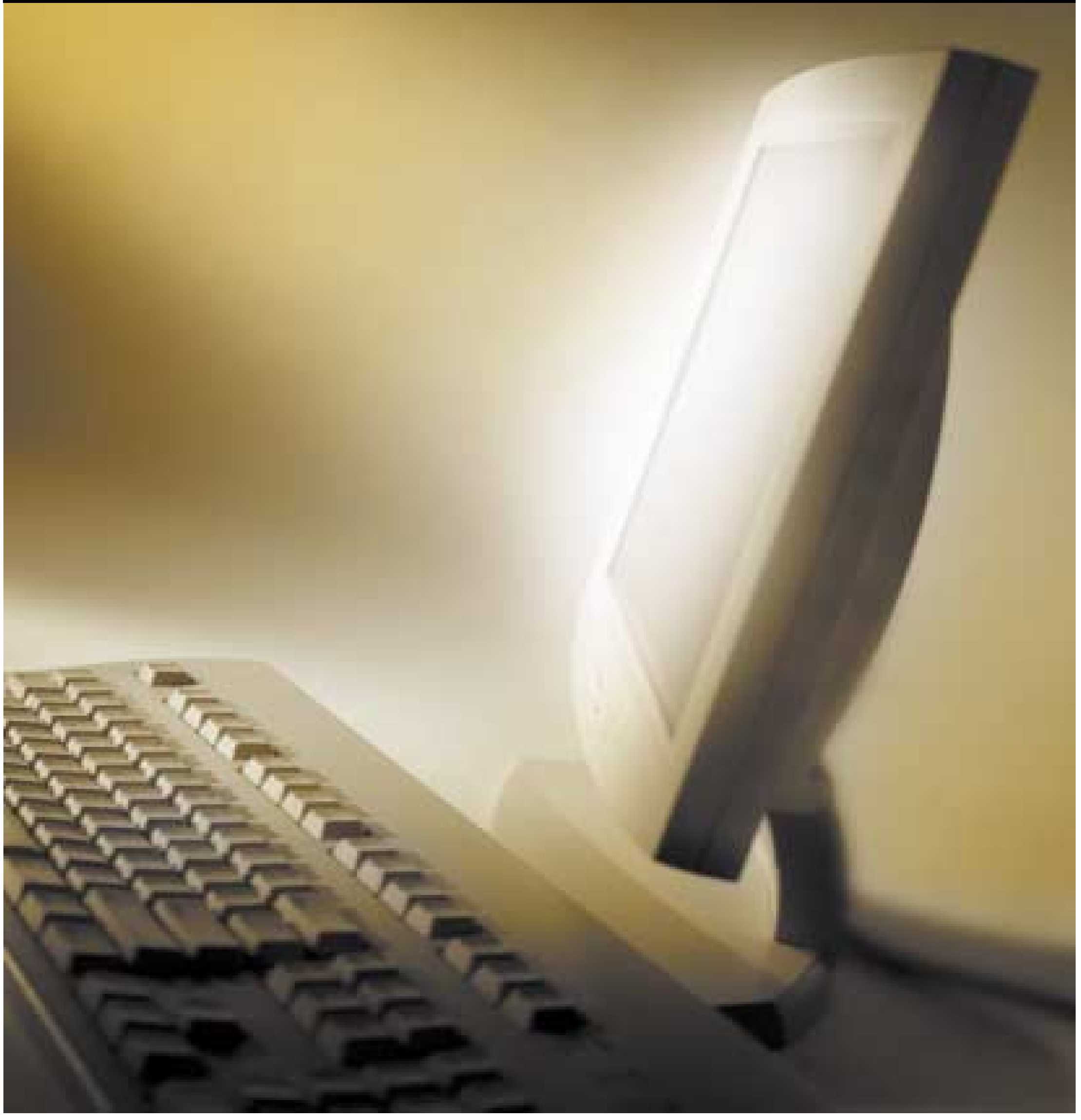
EVALUATING Computer Fire Models



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 complex 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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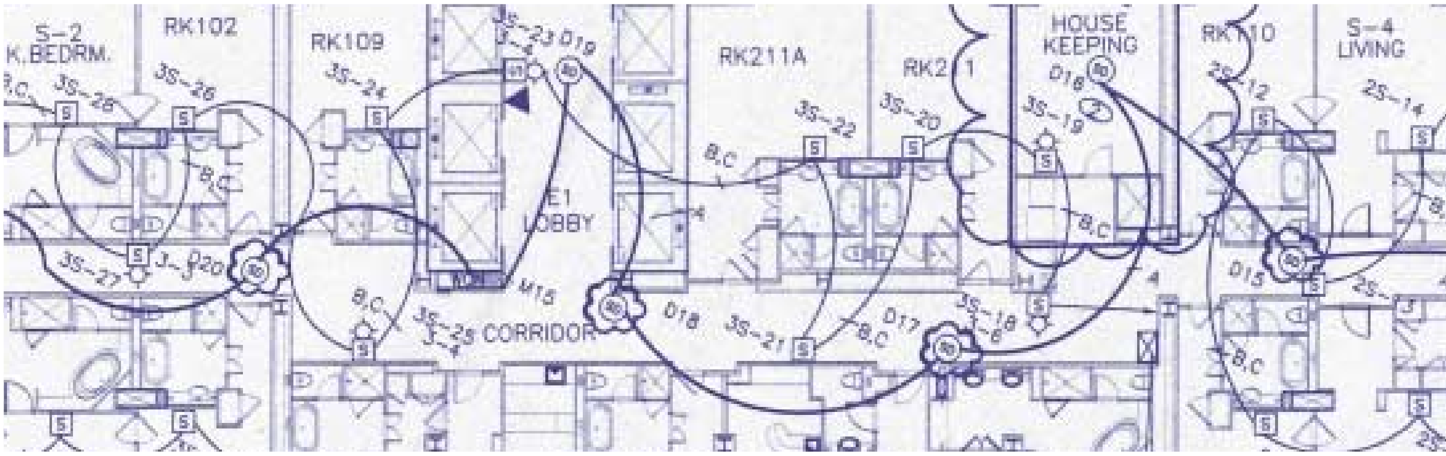

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The Future of Fire Simulation

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-

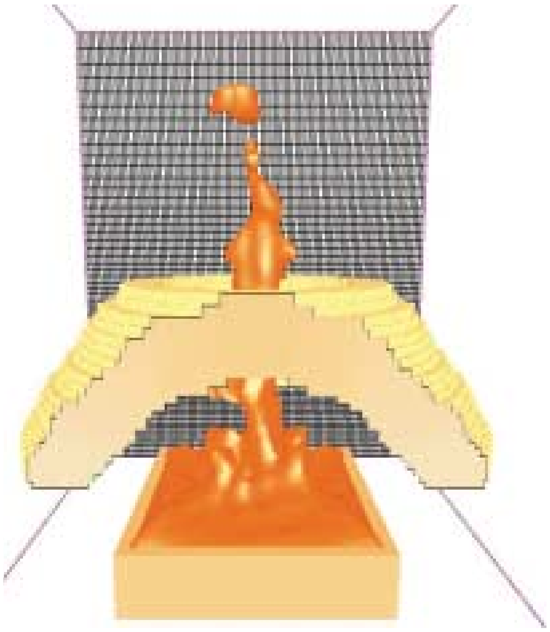

FIGURE 1. Simulation of a sample of wood burning in the cone calorimeter performed with FDS. Courtesy Simo Hostikka, VTT Building and Transport, Finland.

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.

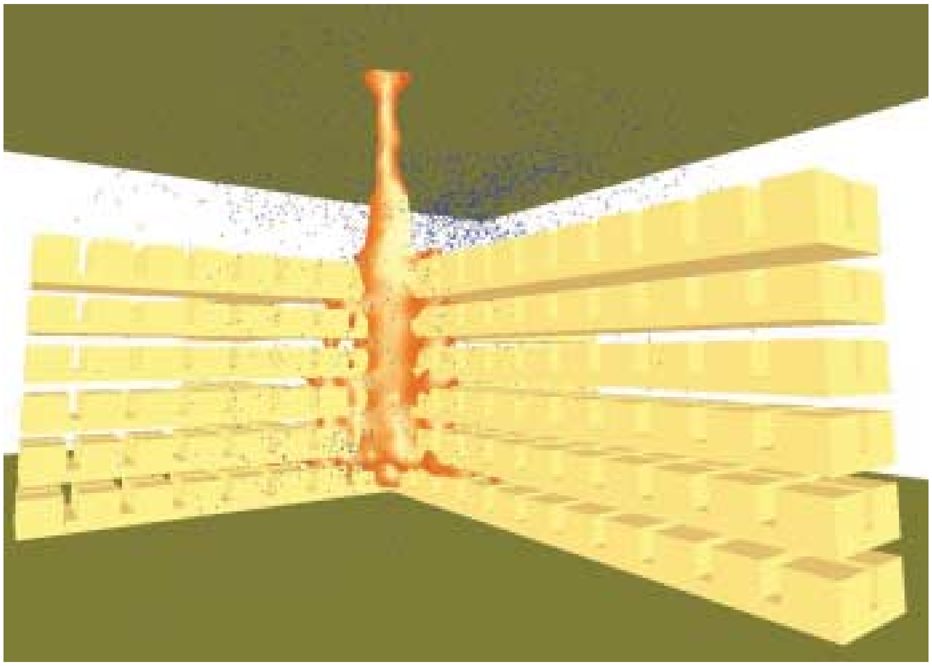

FIGURE 2. Simulation of a rack storage commodity fire. The simulation predicts the growth and suppression of a fire that originates at the floor. These types of simulations are by far the most challenging attempted to date, and it remains to be seen how much the relatively simple solid phase pyrolysis 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

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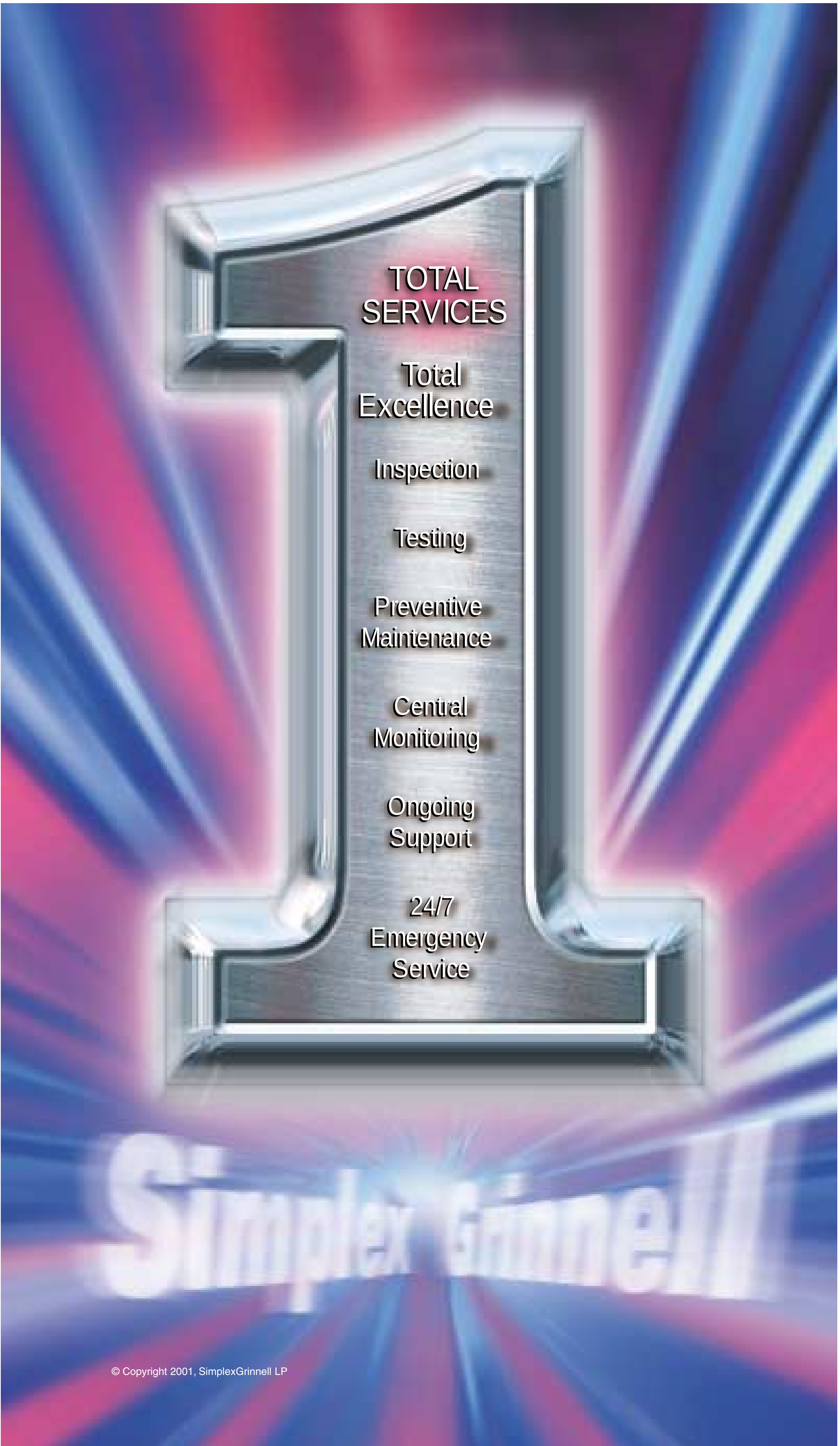

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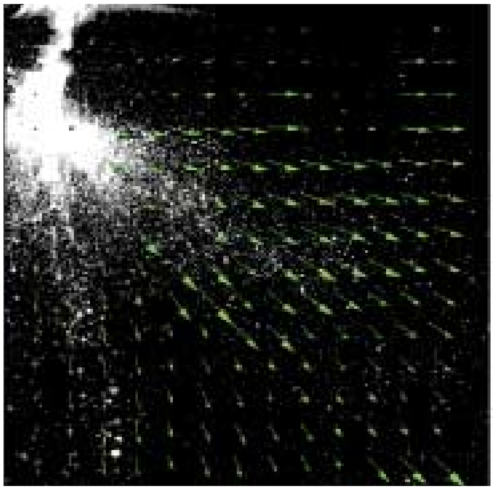

FIGURE 3. Image of a sprinkler spray created with Particle Image Velocimetry (PIV). The green arrows represent the velocity vectors of water droplets leaving the sprinkler orifice. The technique involves taking two photographs of the spray in rapid succession and backing out the velocity from the displacement 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-

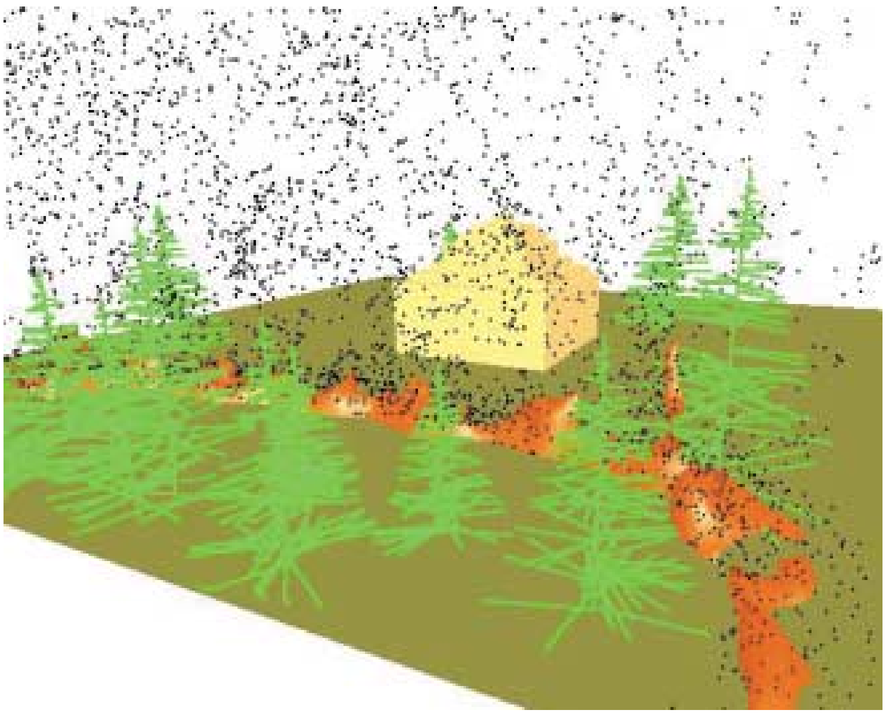

FIGURE 4. Simulation of a brush fire advancing on a house. Preliminary calculations such as these are now being performed to assess the feasibility of simulating community-scale fire spread. Here, the domain is a few hundred meters on a side, the grid cells about 1 m. The trees serve as a drag on the oncoming wind.

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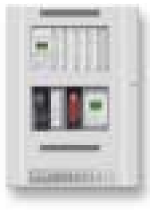

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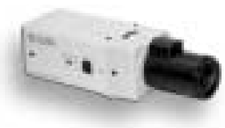

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tions than building fire models. They are closer to zone models in philosophy since they are designed to run faster than real time so that they can be used the day of the actual fire. It would be hard to believe that field models for community-scale 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

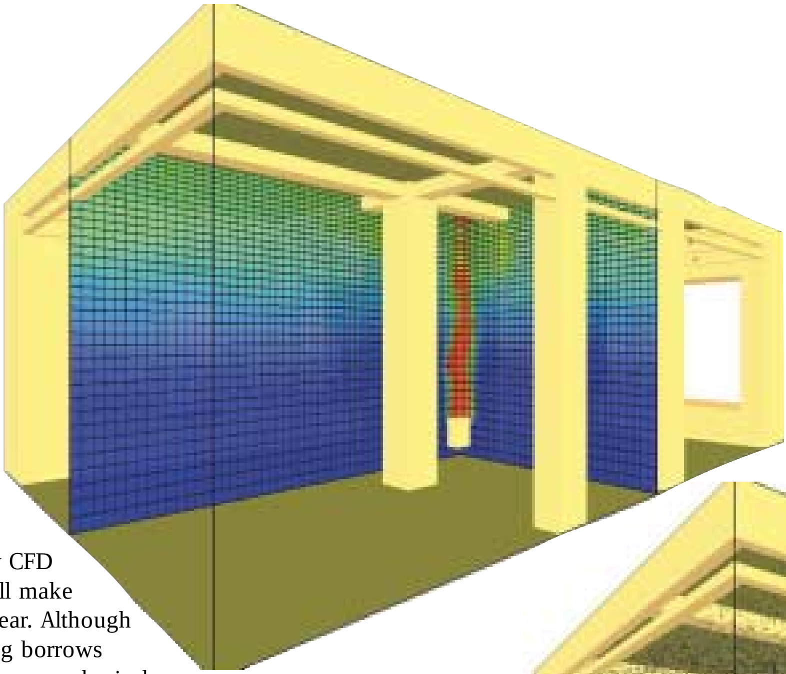
Modelers are looked upon with skepticism by the rest of the fire community because of the perception that they all too often hide behind an eye-catching image or animation without understanding the physics underpinning the model. In fact, some have started to refer to CFD as "colorful fluid dynamics." 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



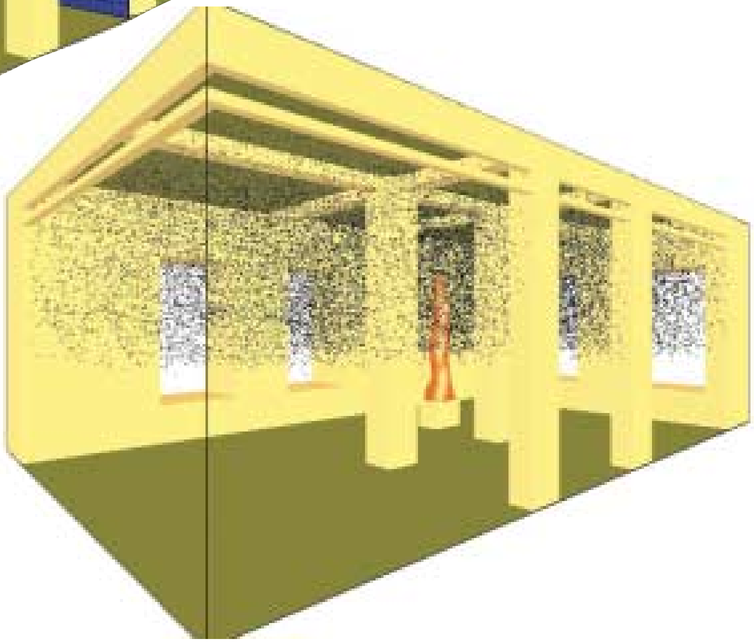


FIGURE 5. Two different ways of visualizing a fire simulation. On the left, contours of gas temperature are shown superimposed on the numerical grid. On the right, the fire and smoke are shown as an orange-colored sheet and black dots.

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-

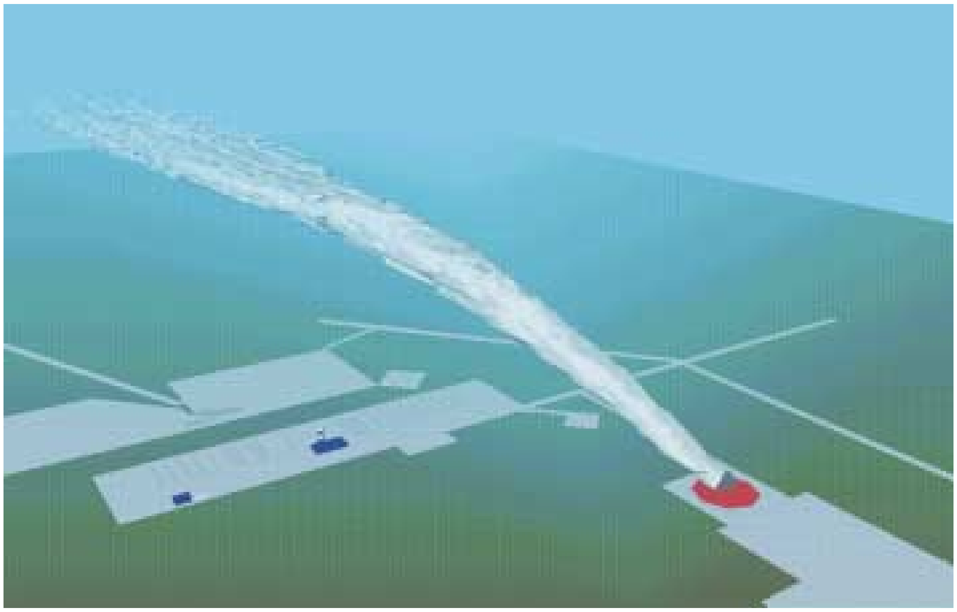


FIGURE 6. This figure is an example of how fog is used to bring more realism into the scene. Shown is a simulated smoke plume made with the ALOFT (A Large Outdoor Fire plume Trajectory) model. The plume is embedded within a fog-shrouded oil field visualized with the commercial software package SGI Performer.

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.

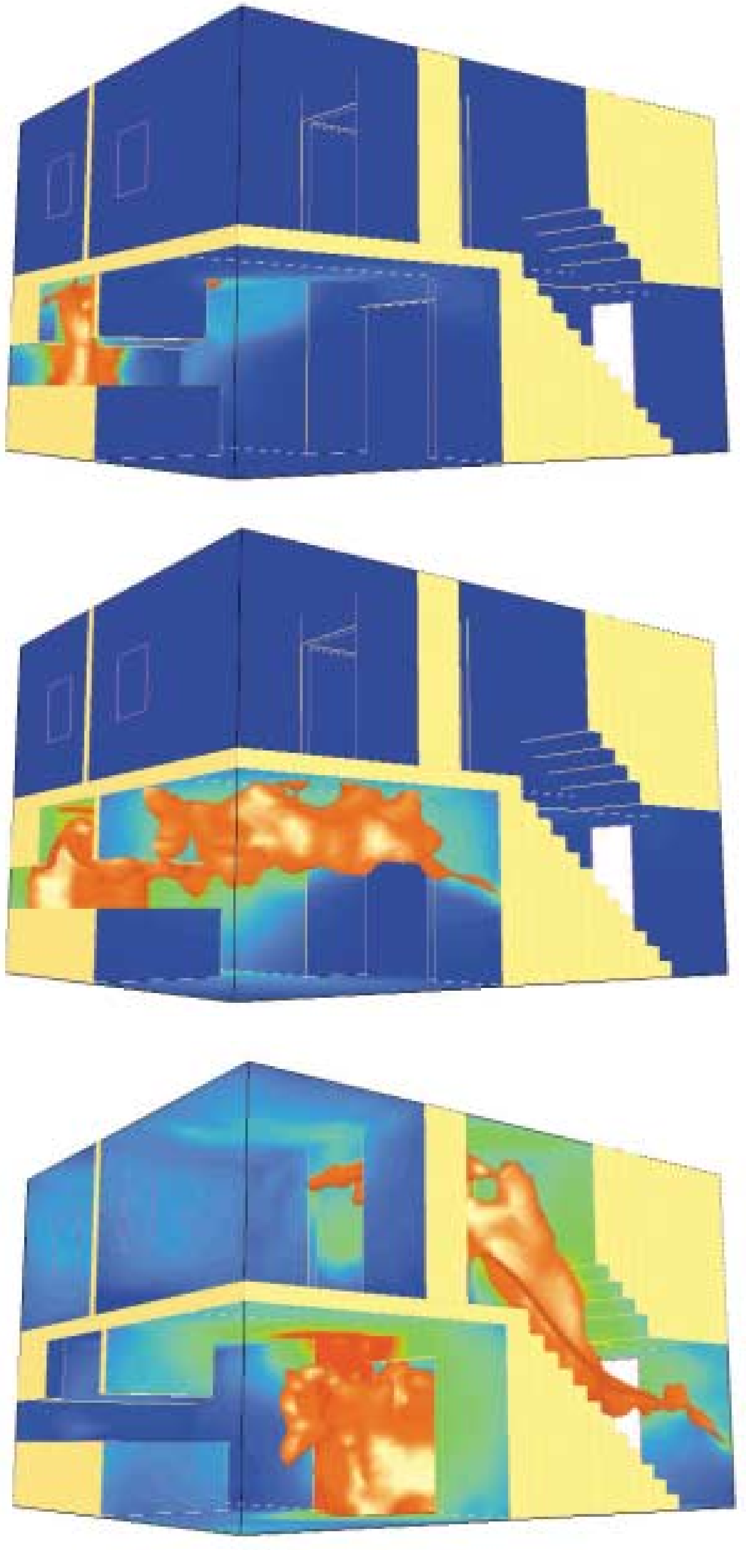


FIGURE 7. Several snapshots of a fire spreading through a townhouse. The fire originates in the kitchen area (lower left), and eventually spreads throughout the house. The front door (right) is assumed to be open, as are the windows on the second level.

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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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.

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

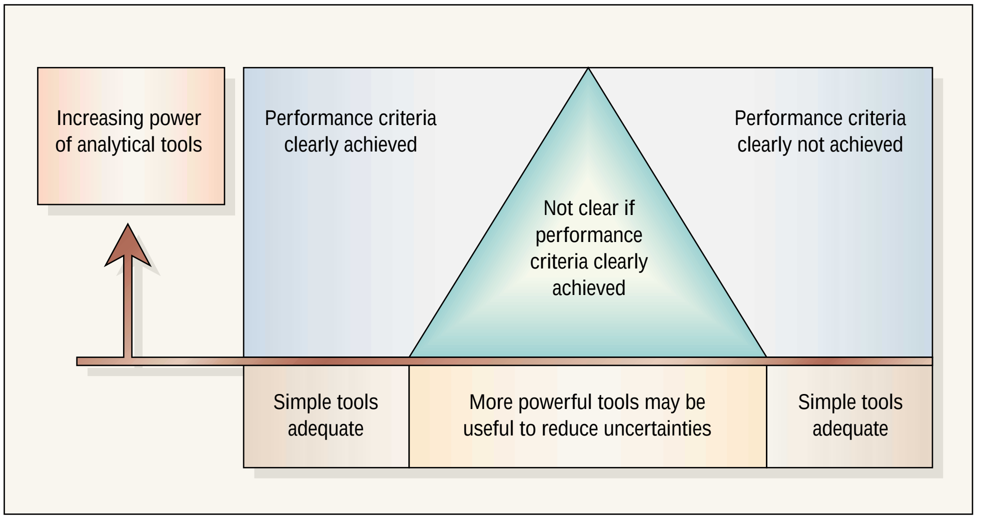

Figure 1. Ideal representation of calculation results as a function of the increasing power of the analytical tools employed.

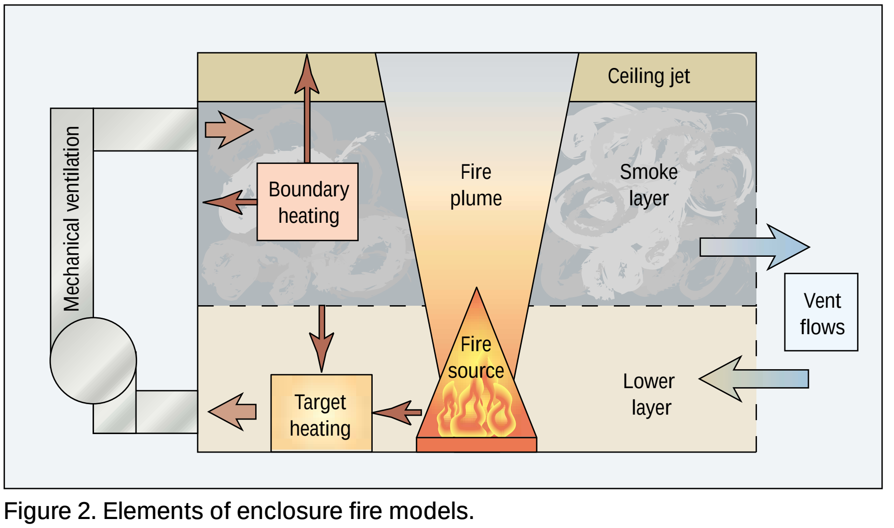

Figure 2. Elements of enclosure fire models.

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.

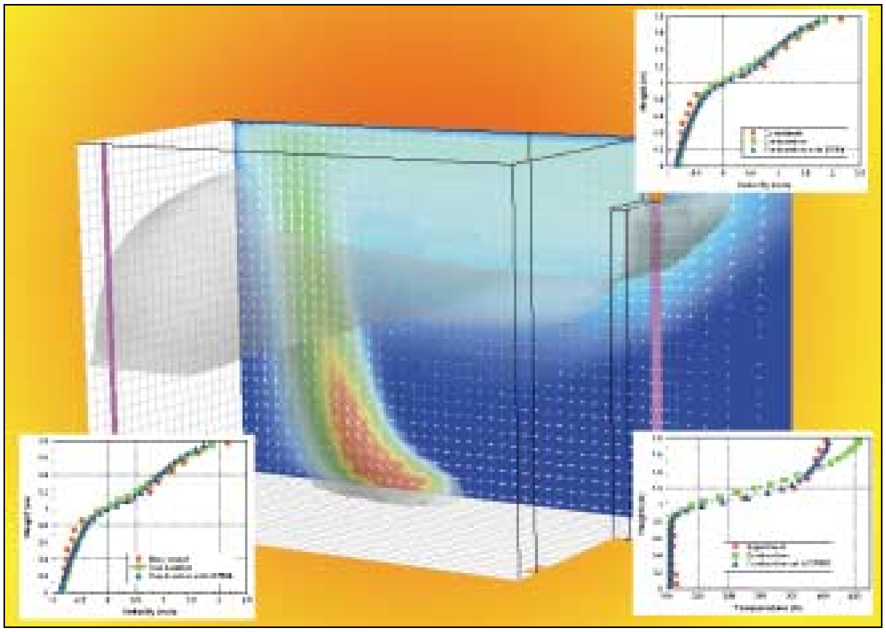

Figure 3. Results of an example SOFIE calculation.

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

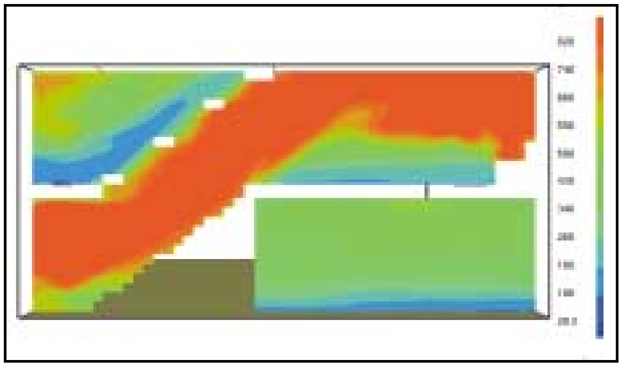

Figure 4. Results of an example FDS calculation.

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-

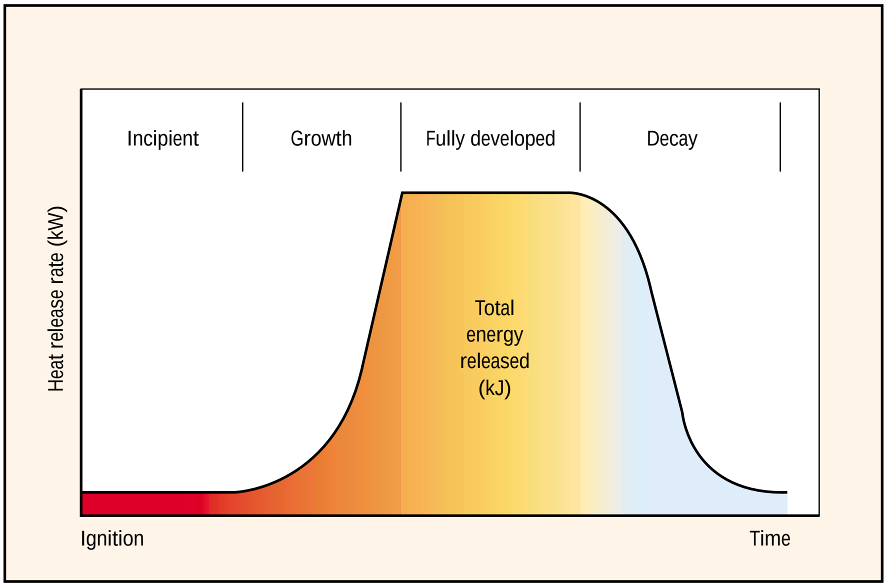

Figure 5. The stages of fire energy release rate.

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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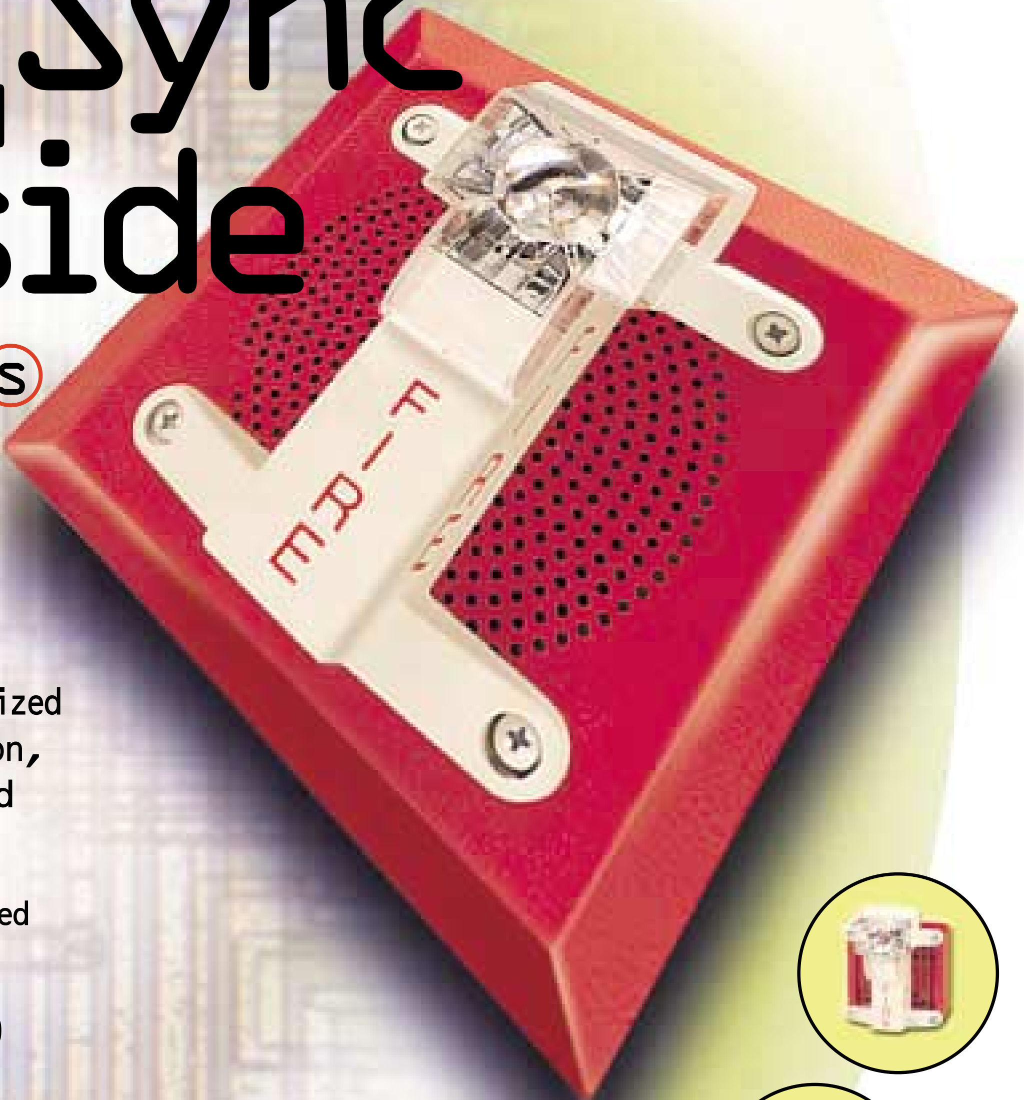

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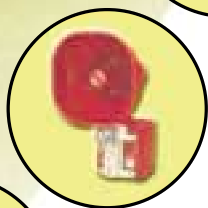

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FOREWARD

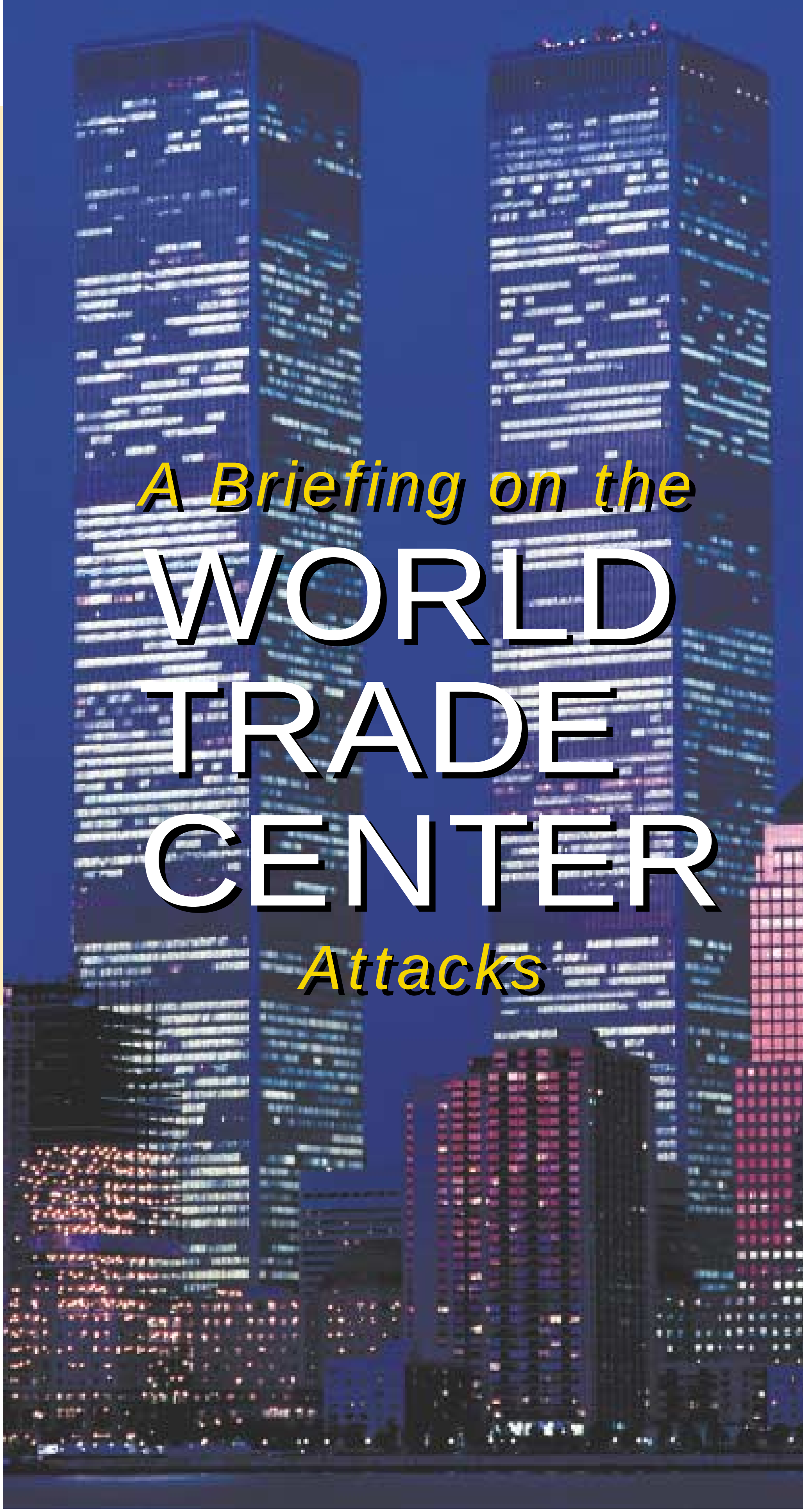
Arup has established an Extreme Events Mitigation Task Force to help understand the events of September 11 in New York and Washington, and their consequences for the buildings industry. Results from this work will be made available to the industry.

The following is based on a "briefing paper" that was prepared two weeks after the World Trade Center disaster by this task force. The briefing paper is posted on the Arup Web site and is being periodically updated as more information becomes known. Members of the task force include:

Tony Fitzpatrick – *Chairman, Arup Americas Board*
Ray Crane – *Team Leader, New York*
Ashok Rajii – *Mechanical, New York*
Bob Cather – *Materials, London*
Brian Meacham – *Risk/Fire, Boston*
Craig Gibbons – *Structures, Hong Kong*
Dick Custer – *Fire and Forensics, Boston*
Faith Wainwright – *Structures, London*
Jim Pinzari – *Risk/Business Continuity, Boston*
Jim Quiter – *Fire, San Francisco*
John MacArthur – *Structures, New York*
Leo Argiris – *Structures, New York*
Michael Willford – *Structures, London*
Richard Hough – *Structures, Sydney*

This brief was prepared for a broad audience inside and outside of Arup. Thus, some material will be familiar to readers of this magazine. However, the brief described many of the factors that need to be considered when evaluating how a building responds to such an extreme event. Accordingly, it forms one part of a broader risk assessment designed to advise clients on individual risk, whether in a new building or an existing one. Prevention measures designed to reduce the probability of a terrorist attack will be taken into account in such an assessment.

A Briefing on the WORLD TRADE CENTER *Attacks*



INTRODUCTION

Towers 1 and 2 of the World Trade Center in New York were both hit by commercial aircraft on Tuesday, September 11, 2001. The aircraft had been hijacked, and the incidents caused both towers to collapse. Neighboring buildings also subsequently collapsed, and there was damage over a wide area.

This was a deliberate act of terrorism, planned to create devastation and destruction. Such events are not anticipated, and current codes and design practice do not address damage on this scale being inflicted on buildings. Nevertheless, looking at the total collapse of both towers and its impact on society, we must see if we can do something in the way we design build-

Pictures courtesy of Paul Doherty and Henry Gifford.

ings to prevent this happening again, and we must explore the options and offer the choices to society. These were manmade structures – society makes choices about how we design buildings and how they should perform, but we are the professionals with the needed expertise to inform the decisions.

The consequences of the September 11 tragedy will be far-reaching, and as governments look at security and international political actions, we need to think how we will respond on our projects. What are the options, and how might they be pursued?

This report sets out some facts, issues, and questions, and suggests how we might begin to address these. It was written shortly after the event and will be further developed and updated by the Extreme Events Mitigation Team Arup has established.

THE EVENT: WHAT HAPPENED?

Events on the morning of September 11, 2001, until the collapse of the WTC Towers 1 and 2

At 8:45 am, American Airlines Flight 11 carrying 92 people was flown by hijackers into the north tower, called One WTC of the World Trade Center complex, hitting the tower on the north face around the 90th floor. At 9:06 am, United Airlines Flight 175 carrying 65 people and also hijacked, hit the south face of Two WTC (the South Tower) at around the 60th floor.

Both aircraft penetrated the buildings and burst into flames. Large and widespread fires were observed following impact, involving both combustion of the fuel from the aircraft as well as combustible materials typically found in office buildings.

At 10:00 am, 54 minutes after the impact, Two WTC collapsed completely. At 10:29 am, one hour, 44 minutes after the impact on One WTC, it, too, collapsed to the ground. Many people escaped in the time that the buildings remained standing, but 2,442 people are currently unaccounted for. More than 550 people have been confirmed dead as of December 20, 2001.

The planes were Boeing 767 200-ERs, which have a cruising speed of 830 km/h (530 mph) at 10 km (35,000') and a fuel capacity of 90,000 l (23,980

US gallons). At this point in time, the impact speed is not known. At an altitude of less than 600 m (2000'), it is likely that the air speed was less than 500 km/h (300 mph).

It is reported that normal occupancy of the buildings would be 40,000 to 50,000 total in the two towers. It is not yet known how many actually were in the buildings; but significantly fewer were likely there at that time in the morning.

On the same morning, the Pentagon was also struck, causing nearly two hundred fatalities. Analysis of this event is outside of the scope of this article.

Neighboring buildings

The twin towers were part of the World Trade Center complex of seven buildings.

In addition to these high-rise buildings, there was a 47-story high-rise building (Seven WTC), a 22-story high-rise building (Marriott hotel), two 9-story buildings, and one 8-story building. Excluding the hotel, most of the occupied space within the buildings was dedicated for office use. All the buildings, except for Seven WTC, were constructed over a plaza area that contained a shopping mall, four underground levels of public parking, and two utility levels.

The entire center contained approximately 1.25 million square meters (13.5 million square feet) of rentable space including .18 million square meters (2 million square feet) in Seven WTC.

The collapse of these neighboring buildings was probably due to the combination of the impact loads from the collapse of One and Two WTC, the tremendous fire that ensued, and foundations being affected by the collapsing towers. Specifics of the collapse mechanism are being analyzed by many parties.

Falling debris also damaged buildings beyond the World Trade Center complex. An assessment of these buildings was undertaken during the week of September 17, by SEAoNY (Structural Engineers Association of NY) and is available on the SEAoNY Web site at www.seaony.org. The assessment was based on an ATC-20 Post-Seismic Building Assessment. The affected perimeter buildings contain approximately 1.5 million square meters (16 million square feet) of space. In all, more than 30% of downtown Manhattan office space has been affected.

Preliminary analysis of what led to the total collapse of One and Two WTC

The initial impact destroyed many columns and more than one floor. How much was damaged may never be known, but the impact itself did not cause the towers to collapse. The buildings remained standing long enough to allow many people to escape.

The initial impact probably removed some columns and significantly weakened many others. Deformed, and probably unbraced over two or more floors, these columns would also have been subjected to additional load from damaged floors and debris. The spreading fire would have continued to weaken the structure, most likely leading to a collapse under vertical load.

The aircraft were heavily laden with jet fuel, having just taken off from Boston en route to Los Angeles. The resulting hydrocarbon-fueled fire would have been much hotter and more rapid than the type of fire against which buildings are normally designed.

THE BUILDINGS – DESCRIPTION OF THE DESIGN

Structure

The Towers were steel framed, 110 stories high, and square on plan. The buildings were designed by Skilling, Helle, Christianson, Robertson, which was the structural engineering firm of record for the World Trade Center complex, and completed in phases starting in 1970. One WTC was 417.0 meters (1368') tall, and Two WTC was 415.1 meters (1362') tall. Each 110-story tower had a floor plate 637 x 637 meters (209' by 209'). The central core in each building was 26.2 x 42.3 meters (86' x 139'), constructed with steel columns and lightweight drywall for infill.

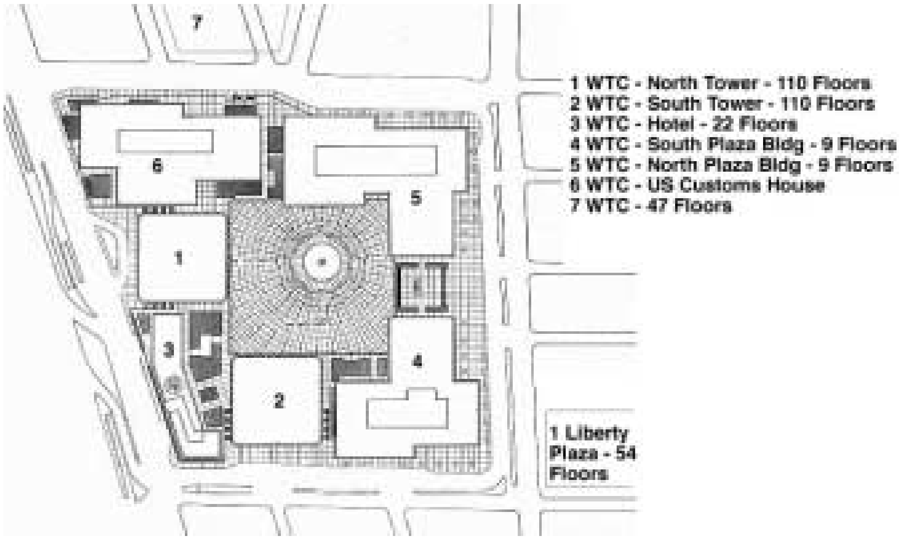
Around the perimeter of the buildings, 356 mm (14") steel box columns were spaced at 1 meter (3'-3") on center, with 1.2 meters (48") deep plate girder spandrels at each floor. At the third level, the columns transitioned in an arch-like formation to a 3.05 meter (10'-0") spacing for the lower story. Floors were supported by steel trusses spanning 18.3 meters (60'-0") from the core to the perimeter wall on each side of the building.

The building perimeter structure was the key element in the performance of the building. In addition to taking vertical gravity loads, it also resisted all horizontal loads by framing action between the close-centered columns and the spandrel beams, such that the perimeter structure acted as a pierced tube in resisting loads.

Vertical structure inside the building supported gravity loads only.

Fire protection

The World Trade Center was developed and constructed by the Port Authority of New York and New Jersey, a self-supporting agency of the two states. Although the Port Authority has not adopted any specific fire safety code, it considers the requirements developed by the National Fire Protection Association (NFPA), New York City, and the Building Officials and Code Administrators International



THE WORLD TRADE CENTER

(BOCA) when developing designs. The steel frame had been clad in fire spray. Asbestos-based spray had been used initially in the building, but later changed to a nonasbestos material. Further specifics, including which structural members were treated and to what level of fire resistance, are still being determined.

Blast resistance

One WTC had already survived an explosion in February 1993 when a rental truck packed with explosives was detonated in basement level B2. That bomb blew out one section of a north tower cross-brace between two of the perimeter columns. The blast ripped out sections of three structural slabs in the basement levels, but did little damage to the columns.

According to one of the original designers, the towers were originally designed to take the impact of a Boeing 707. A member of the original design team has clarified recently that this addressed impact only and not the consequences of a jet-fuel fire.

THE QUESTIONS

How would our current buildings fare under such an attack?

The answer is not simple. Structures are designed to building and fire codes, and these documents reflect our society's tolerance of risk from fire, earthquake, floods, and a host of other hazards, and establish the minimum levels of safety. Historically, building and fire codes have evolved in response to fire and other events that have affected

TYPICAL FLOOR PLATE

buildings, incorporating specific measures intended to address lessons learned. Because building and fire codes do not typically consider deliberate, willful attacks, such as arson or terrorism, these events have not played a significant role in code development.

The current code-based design approach on its own is inadequate for addressing the question "how would buildings perform under such an attack?" However, it is possible to look at any building on a case-by-case basis.

To inform future design, perhaps it may be better to turn the question around – "What are the implications for design if the building were required to remain standing for longer after such an extreme event?" This is addressed below.

Is this a question just for tall buildings?

The World Trade Center's prominence and symbolism must have been factors in why it was chosen as a target. The Pentagon was also a target. As we face the question "will this affect the future of tall buildings?", we have to recognize that tall buildings will always be prominent structures on the cityscape. However, avoiding symbolism and expression in buildings can only lead to a bunker mentality – and even if this were pursued, would we be safe from determined terrorist acts? Wherever large quantities of people gather in one building or complex, be it for work or for play watching some sporting event, then the actions of people determined to kill and themselves to die in the process are a complete new paradigm for design. The focus may be on tall buildings initially, but it is not a question only for tall buildings.

How will this affect the approach to building design?

To answer this, we first have to look at the current approach to design and then consider how we would address the design for safety in such an extreme event.

CURRENT BUILDING DESIGN PRACTICE

Performance required

Current building codes in the United States are predominantly prescriptive in nature. In other words, the code prescribes specific minimum requirements for parameters such as structural loads, fire resistance ratings, and egress requirements. In some other countries, a performance- or functional-based system has been adopted, wherein the overall performance or function of the building and its systems are defined, but the design solutions are not mandated. Frequently these performance codes contain acceptable or deemed-to-satisfy solutions that serve as a prescriptive option to the performance approach.

A performance-based approach is currently being introduced into the United States as well, but for the present time, any engineered or performance-based designs are typically used only under the "alternate methods and materials" clauses found in most US codes. It is not unusual, for example, to undertake egress analyses for large or unusual buildings under the "alternate methods and materials" clauses, taking into consideration such factors as fire resistance ratings, sprinklers, compartmentation, travel distances, and various fire scenarios.

It is worth noting that to operate in a performance-based environment, performance criteria and tools and methods for assessing performance must be available.

Evacuation and refuge

The US does not have a single, nationally enforced building code. Rather, there is a system of model building codes that are adopted by states and local jurisdictions, sometimes with modifications. In some jurisdictions, such as New York City, there are also locally developed codes. As a result, comments about “standard” US procedures are necessarily generalizations.

Having said that, standard practice is to evacuate automatically only those floors in the vicinity of the event (usually floor of origin, floor above, and floor below, although some jurisdictions require more). The responding emergency professionals can then make a decision whether further evacuation is necessary. The voice alarm system, which is much like a specialized public address system, can be used to notify people on a selective or general basis.

There are several reasons to do this:

a. By evacuating only those in the vicinity of the event, it is likely that they can more rapidly enter the stairs, rather than queuing at the entrance while other nonaffected people (from other floors) fill the stairwell.

b. Crowd management is more effective if only those directly at risk are moved.

c. In tall buildings, people can be relocated to alternate floors, rather than out of the building.

This approach allows those directly affected to leave their floors and enter areas of safety, such as pressurized fire-resistive stairs or other floors. People remote from the event are assumed to be safe, at least for some time.

Using this scenario, responding personnel will generally go to the floor below (or some number of floors below) the fire, either via elevator or stair, depending on the Fire Department.

This approach clearly implies that catastrophic failure within a short period of time cannot be allowed to happen.

Sprinklers

Fire protection by automatic sprinklers assumes that there will be water available at a sufficient pressure to deliver a spray of water to the fire area.

Sprinkler systems are not typically designed to support water flow from all sprinklers simultaneously, as the water demand could be enormous and is typically not needed. The intent is that the water supply system provides only enough water for a specific design area, with a certain number of sprinklers at the most hydraulically remote location. The density and water supply volume is determined according to the occupancy type of the building. The sprinklers would not be designed to cope with a widespread aviation fuel fire.

The sprinklers themselves are designed such that each sprinkler head actuates individually. In typical office occupancy, each individual sprinkler has a fusible link, or other reaction device, which, when a defined temperature is reached, allows water to flow. The aim is that a sprinkler will actuate when a fire is relatively small, and the available water will control or suppress the fire.

In the WTC towers, the initial collision and explosion likely damaged a considerable part of the sprinkler system and fire protection water supply system on the floors of initial impact. If so, the sprinkler system would not have been able to operate as intended. For those parts of the system that remained intact, the rapid growth and spread of the fire resulting from the jet fuel would likely have actuated a large number of sprinklers, taxing the available water supply. In addition, if any fire protection water supply risers were taken out on a lower floor, the water supply to floors above may have been impacted.

Progressive collapse

There are no explicit requirements for design to prevent progressive collapse of buildings in the US model building codes. There is an understanding that requirements in the codes develop a limited resistance to progressive collapse although this is not an explicit design requirement. For zones of high seismicity, US model building codes, including the UBC, NBC, SBC, and IBC, all have special detailing provisions that have the goal of increasing ductility and toughness in structures that reduce the possibilities of progressive collapse during seismic events.

The buildings were constructed by the Port Authority of New York and New Jersey, and compliance with the New York City Building Code was voluntary. There was no seismic detailing provision in the code at the time the WTC was designed and constructed.

There are no explicit requirements in the US model building codes or New York City Building Codes for debris loading.

WHAT ARE THE IMPLICATIONS FOR DESIGN?

From a code perspective, the WTC disaster would have to be considered an unexpected event at the time it was designed and constructed. The US has not previously been subjected to such a deliberate act of terrorism of this magnitude, and therefore the building and fire Codes did not have a direct past history to draw upon. In the aftermath, it will be a societal decision whether we want to tolerate the risk of another similar event or whether we want to accept the restraints associated with minimizing this type of event.

How do we begin to consider the basis on which to make such decisions?

Design for robustness under such an extreme event

The challenge here is that an event such as the WTC collision involves impact, explosion, and fire all at once. The "design scenario" cannot be one of a set of loads, but of a level of damage inflicted by whatever cause. One might develop a set of "what ifs?" to try to envisage a "worst possible" or "worst credible" event. Then by posing possible design options, we can ask, "If xxx had been incorporated, would this prevent a collapse?"

For example:

- If the steelwork at Towers 1 and 2 had not succumbed to the fire, the buildings might still be standing. What if we incorporated additional fire resistance into the structure? How much is enough? Would traditional fire resistance have withstood the fire regardless of the rating? Would fire resistance have adhered to the steel given the impact of the aircraft?
- If the floors had not continued unchecked in a progressive collapse to the ground, then the buildings might still be standing. What if we incorporated "collapse" stories every ten floors – a level of structure designed to carry the debris load from the nine collapsing floors above?
- If the towers had had a reinforced concrete core able to continue to provide stability after the loss of the floors and perimeter frame, then a shaft providing a safe refuge might have remained – should we consider dual-stability structures, where one stands after the other has failed?

Phased or total evacuation

Information is slowly being pieced together about escape from the towers, principally from people who escaped. This will ultimately help in the discussion of phased or total evacuation. However, regardless of the intended evacuation approach, some phasing will occur naturally based on people's perception of the threat, the presence of loved ones in the building, and the limitations for the flow of people through exit routes.

Total evacuation is not necessarily always the best answer and needs to be considered at each event assessing who is most at risk, how safe they are without evacuation, and access for firefighters or emergency personnel trying to enter the building. For example, with a moderate fire at low level then total evacuation would bring many people through the danger zone and into the area of the firefighting effort. These are difficult decisions under difficult circumstances requiring accurate information.

Way forward

Design measures to mitigate the effects of this and other extreme events are possible and, therefore, must be researched and evaluated as a matter of urgency. This requires an holistic assessment of all the issues discussed above. The results can then be part of the decision process on the level of robustness to which a building should be constructed.

In the United States, the next generation regulatory approach, a performance-based one, is about to be introduced. This will be an important venue to facilitate the overall discussion of risk tolerance and the related social, technical, and financial impacts. This terrible event emphasized our vulnerability in dramatic fashion, but policymakers should avoid a knee-jerk reaction in seeking to prevent a recurrence. Obviously, it is not just high-rise buildings that are vulnerable to terrorist attack; any change in codes will impact on many other occupancy types.

RESOURCES

- www.sfpe.org
- www.asce.org
- www.seaony.org
- www.ncsea.com
- www.aisc.org
- www.arup.com
- www.m-yamasaki.com
- www.newscientist.com
- www.greatbuildings.com
- www.skyscrapers.com
- www.nytimes.com
- www.usatoday.com
- www.cnn.com
- FEMA – Federal Emergency Management Agency
- SEAoNY – Structural Engineers Association of New York
- NCSEA – National Council of Structural Engineers Associations:
- AISC – American Institute of Steel Construction.

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Products/Literature

Internet-Based Vehicle Management

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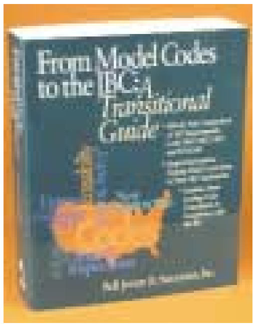
www.manifolddata.com
—Manifold Data Systems

IBC Analysis Guide



Rolf Jensen & Associates, Inc. (RJA) introduces *From Model Codes to the IBC: A Transitional Guide*, a publication aimed at helping architects, engineers, and builders interpret the new International Building Code (IBC). The book, written by RJA consultants and produced and marketed by R.S. Means, presents a convenient way to compare IBC requirements to other model building codes.

www.rjagroup.com
—The RJA Group, Inc.

Loop Hanger Surge Restraint

The CADDY Loop Hanger Surge Restraint (LHSR6) restricts the upward surge movement of activated fire sprinkler systems to meet NFPA 13 and ensure proper spray patterns. One clip fits 1/2 through 2-in. loop hangers. The LHSR6 grips the loop hanger and not the nut, allowing adjustment of the hanger on the threaded rod.

www.erico.com
—ERICO®, Inc.

Halon Replacement Alternative

A new fire extinguishing material – 3M™ Novec™ 1230 Fire Protection Fluid – was developed to be a long-term replacement for halon. It is designed to balance the need for extinguishing performance, human safety, and low environmental impact. Its chemical structure is low in acute toxicity, making it ideal for use in occupied spaces.

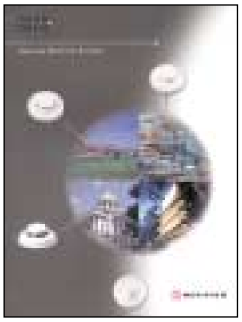
www.3M.com
—3M

Analog Addressable MultiSensor

The latest microprocessor technology in smoke detection is available in the XP95-M Analog Addressable Multisensor, which is optimal for most general applications. The XP95-M includes both photoelectric and thermal sensing elements integrated into a single device, designed to enhance performance, reduce false alarms, and provide quick, accurate response.

www.gamewell.com
—Gamewell™ Worldwide

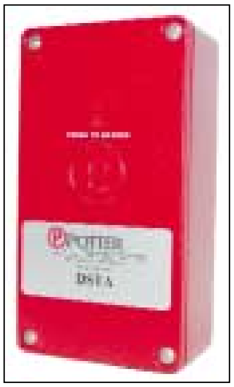
Advanced Detection Systems



NOTIFIER's new, eight-page Advanced Detection brochure provides simple solutions for environments with complex fire detection needs – from sterile cleanrooms to harsh industrial environments. Written for end-users and specifiers, it highlights state-of-the-art detection and control technologies. It also includes application suggestions for the full spectrum of NOTIFIER detection systems.

www.notifier.com
—NOTIFIER®/Honeywell Home and Building Control

Dry System Trouble Alarm



The DSTA (Dry System Trouble Alarm) is a microprocessor-based local supervisory annunciator designed to monitor low/high air pressure and low room temperature of a Dry Pipe Sprinkler System Riser (the pressure and room temperature switch is sold separately). Each unit includes an LED display and an internal buzzer and may be riser- or wall-mounted.

www.pottersignal.com
—Potter Electric Signal Co.

Applications Guide on CD-ROM

System Sensor has released a MAC or Windows-compatible Applications Guides CD-ROM, free to qualified individuals. The CD-ROM includes information on the proper application of various detection products in life safety and property protection environments. It provides comprehensive data on every System Sensor application, navigates easily, and is interactive.

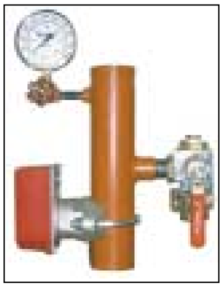
www.systemsensor.com
—System Sensor

Fire-Resistive Cable

Pyrotenax Cables Ltd. manufactures mineral-insulated (MI) cable that has no organic compounds, so nothing burns, releases toxic fumes, or propagates flames. The Pyrotenax System 1850™ two-hour fire-rated power cable is used for fire protection of critical life safety circuits in commercial buildings; it arrives with a UL fire-resistive classification, so conduit or additional fireproofing is not required.

www.pyrotenax.com
—Pyrotenax Cables Ltd.

More Commercial Riser Manifold Options



The EasyPac Commercial Riser Manifold combines a flow switch, drain valve, sight glass, and pressure gauge into a lightweight, compact unit. It is available in five orifice sizes ranging from 3/8 to 5/8 in., in sizes 2-6 in., with a standard take-out dimension of 13 in. There is a choice of end connections, and installation may be horizontal or vertical.

www.vikingsupplynet.com
—Viking SupplyNet

The Security and Access Control Handbook

This handbook outlines practical solutions for security and access control applications. This handbook provides more than 40 different case studies, each including a description, parts list, diagram, and application tips. The Security and Access Control Handbook is a valuable tool for engineers who design or specify security and access control systems. (*Security and Access Control Handbook, A Practical Guide to Application and System Design*, published by EST Press, an imprint of Edwards Systems Technology, Inc.)

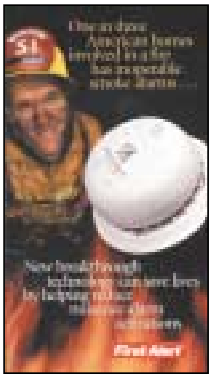
www.est.net
—Edwards Systems Technology (EST)

Fire Protection Reference Guide

Viking has released a new color product brochure entitled, "Your Fire Protection Solutions Partner." A reference guide for fire protection specialists, it contains drawings of sprinkler systems suitable for training. The sprinkler section contains a full range of products, with photographs and technical reference tables. Other areas covered include foam and foam equipment and other related fire protection products.

www.vikingcorp.com
—Viking Corp.

Remote Sensing Fire Alarm



To address the problem of nonworking fire alarms due to dead or missing batteries, First Alert has developed model SA302, which uses "smart sensing" and remote control test/silence technology. The SA302 can be tested or silenced by anyone, using virtually any home remote control device. A "smart-sensing" microchip also helps the alarm distinguish nonthreatening conditions from real emergencies.

www.firstalert.com
—First Alert

Resources

The 4th International Conference on Performance-Based Codes and Fire Safety Design Methods

March, 20-22 2002, at the Melbourne Exhibition & Convention Centre in Melbourne, Australia.

Performance-oriented codes, regulations, and design methods are gaining formal and widespread acceptance in many countries. This three-day conference will again bring together professionals from around the world to discuss the state of the art in performance-based codes and design methods. As in the prior international conferences held in 1996, 1998, and the most recent held in June 2000 in Lund, Sweden, this conference will benchmark the rapidly accelerating codification and implementation of performance-based design.

The first day of the conference will be dedicated to performance codes and will feature updates from Australia, United States, Canada, Japan and the UK on the status of implementation of these codes and the challenges they present. On the second day, the theme of the conference will turn to design in the performance environment, and design aspects such as structural fire performance, smoke management, and reliability assessments will be explored. The third day is a workshop dedicated to an international comparison of a standard building design using performance design methods in regulatory environments from around the world. A mini Trade Fair will be held in conjunction with the Conference.

REGISTRATION: To register, visit www.sfpe.org or contact SFPE at education@sfpe.org

UPCOMING EVENTS

February 5-6, 2002
Flame Retardants 2002
London, England
Info: www.intercomm.dial.pipex.com/fr2002cfp.htm

March 18-19, 2002
Structures in Fire
University of Canterbury,
Christchurch, New Zealand
Info: www.civil.canterbury.ac.nz

March 20-22, 2002
4th International Conference on Performance-Based Codes and Fire Safety Design Methods
Melbourne, Australia
Info: www.sfpe.org

May 19-23, 2002
NFPA World Fire Safety Congress and Exposition
Minneapolis, MN
Info: www.nfpa.org

June 16-21, 2002
The 75th International symposium on Fire Safety Science
Worcester Polytechnic Institute
Worcester, Massachusetts, USA
Info: www.iafss.org

UPCOMING EVENTS

Society of Fire Protection Engineers

An Invitation to Join

What is The Society of Fire Protection Engineers (SFPE)?

SFPE, established in 1950, is a growing association of professionals involved in advancing the science and practice of fire protection engineering and fostering fire protection engineering education.

What are the benefits of SFPE membership?

The Society will provide you with many new opportunities for professional advancement, education, and networking. The specific benefits members receive are:

Free access to SFPE's periodicals

This includes:

- Fire Protection Engineering magazine.
- SFPE Today - Our bimonthly Society newsletter.
- The peer-reviewed Journal of Fire Protection Engineering.

Substantial discounts on continuing education

This includes:

- Technical symposia on current fire protection issues.
- International conferences on state-of-the-art applications of fire protection engineering.
- Short courses and seminars offering hands-on instruction.
- Discounts on fire-related publications.

Other benefits include:

- Recognition of your professional qualifications.
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- Opportunity to network in local chapters.
- Low cost group life, health, and liability insurance.
- Contribute to the profession through technical task groups and committees.
- A periodic profile of the fire protection engineer, including salary information.

Yes!

I'm interested in learning more about joining SFPE. Please send me additional information.

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Fax to 301/718-2242 ▲ Visit the SFPE Web Site: www.sfpe.org

For more information, contact The Society of Fire Protection Engineers:
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Phone: 301/718-2910

BRAINTEASER

Solve the following equation for x:

$$\left(x^2 - 5x + 5\right)^{\left(x^2 - 9x + 20\right)} = 1$$

Thanks to Jane Lataille, P.E., for providing this issue's brainteaser.

Solution to last issue's brainteaser

The difference between any two numbers in the set {2, 3, 4} is equal to their greatest common factor. The same is true of any two numbers in the sets {6, 8, 9, 12} and {8, 9, 10, 12}. Find a set of five numbers for which this is true.

Answer: Two sets of solutions are {900, 912, 915, 918, 920} and {1664, 1665, 1666, 1668, 1680} and the multiples of both sets.

CORPORATE 100

The SFPE Corporate 100 Program was founded in 1976 to strengthen the relationship between industry and the fire protection engineering community. Membership in the program recognizes those who support the objectives of SFPE and have a genuine concern for the safety of life and property from fire.

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Central's K17 ESFR Pendent Sprinkler for warehouse and high-piled storage fire protection. A generation ahead in ESFR technology.

Central's new **K17 ESFR Pendent Sprinklers** usher in a new generation of ESFR fire protection. The K17 ESFR offers an increased level of flexibility for designers, while providing the fast, proven and effective response of ESFR technology for warehouse and high-piled storage fire protection needs. The K17 ESFR utilizes the same flows as traditional 14 K-Factor ESFR sprinklers, but at much lower pressures. The results are significant installation cost savings due to reduced branch line pipe sizing and the potential elimination of fire pumps.

Max. Storage Ht. Ft. (m)	Max. Ceiling Ht. Ft. (m)	K17 ESFR Min. Press. psi (bar)	K14 ESFR Min. Press. psi (bar)
40 (12.2)*	45 (13.7)	63 (4.3)	90 (5.2)
35 (10.7)	40 (12.2)	52 (3.6)	75 (5.2)
25 (7.6)	32 (9.8)	42 (2.9)	60 (4.1)
25 (7.6)	30 (9.1)	35 (2.4)	50 (3.4)

*Indicates One Level Of In-Rack Sprinklers Required.
See Tech Data Sheet 3-1.5 for other ESFR applications.

CENTRAL

tyco Flow Control / Central Sprinkler

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Learning from Tragedy

Morgan J. Hurley, P.E.
Technical Director
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By now, we have all read numerous reports regarding the performance of the Twin Towers and the Pentagon and the occupants of those buildings on September 11, 2001. Some of these reports offer explanations of what went wrong, what went right, and the changes that should be made in the way that buildings are designed in the future. Some of these reports have a sound basis in science and engineering, while others do not.

A fundamental tenet of engineering is learning from past events to prevent or mitigate the effects of similar events in the future. SFPE has developed a three-phase plan for learning as much as we can from the events that occurred on September 11, 2001, at the World Trade Center and the Pentagon.

The first phase is to document available factual information and data. This includes information such as the structural frame of the buildings, installed fire protection, fuel loading, number and distribution of occupants, impact location of the aircraft, etc.

The second phase involves filling in the gaps in the information gleaned during the first phase and developing a better understanding of what actually happened. Such an analysis will involve the development of hypotheses and testing those hypotheses via analytical methods such as modeling.

The third phase is be to develop a listing of the costs and benefits of the types of changes that might be considered in how buildings are designed and constructed in the future. While it is not exclusively up to the engineering community to decide what, if any changes should be made, the engineering community has a responsibility to provide information on the costs and benefits of any changes that might be considered, so that policymakers can make informed decisions.

Also, any changes must be considered in a broad context. Prior to September 11, a scenario involving the collision of a jumbo jet with a building was typically used as an example of the type of high-consequence/low-probability scenario that would typically not be considered in the design of a building. Since September 11, numerous changes have been made in the aviation industry to reduce the likelihood of similar actions in the future. Additionally, we need to be careful to ensure that changes made to mitigate similar events do not have negative consequences for more frequent events.

Designing to mitigate the effects of the types of events that occurred on September 11 in the future could bring with them significant costs – costs that could dissuade developers from building structures of national significance in the future. Therefore, it is important for the engineering community to inform decision-makers as they consider whether any changes in the design and construction of buildings are warranted.

While there is only preliminary information available at this time, it appears that the structures of both of the twin towers were damaged by collisions on September 11. The resulting fires further reduced the load-carrying capability of the structures, which led to the subsequent progressive collapses. If these preliminary findings are correct, it shows that the structural behavior and fire behavior were closely coupled.

It is too early to consider what, if any, changes should be made to the design and construction of buildings as a result of the lessons learned from this tragedy. However, one lesson that can be learned is the importance of taking a comprehensive, multihazard approach when designing buildings in the future.