The application of performance-based design concepts has been permitted by various codes and standards through equivalency or alternative means of protection provisions. Initially, the overall concept was to allow for the use of alternative approaches or technologies in meeting the intent of the code. As such, equivalency concepts were pursued where the code did not specifically address a given situation, or where priority was given to a design concept that called for a building arrangement or feature that was not in strict compliance with the prescriptive provisions of the code. While the equivalency approach has been implemented for decades, no guidance or established approach existed that would aid the designer or the enforcing authority in making appropriate decisions about the equivalent means of protection.

Over the past several years, a more formalized approach to the equivalency concept has been developed. This approach is often referred to as performance-based design. Both the Society of Fire Protection Engineers (SFPE) and NFPA have developed guidance documents in this regard. As noted in Chapters 4 and 5 of the Life Safety Code, performance-based design is now specifically addressed and permitted by NFPA 101 as well as NFPA 5000®. The application of performance-based design for fire safety should include a risk analysis to identify the types of fires to be considered. This is an important step, as the threat to occupants by fire needs to be identified and quantified if an appropriate fire safety solution is to be developed. Traditional building regulations do not identify the fire hazard against
which the standard protects. In most cases, building regulations prescribe a solution to some unidentified or vague fire situation.

Performance-based design provides a more flexible approach, allowing greater design freedom while specifically addressing fire and life safety concerns of a specific building project. When properly applied, it provides a more informed approach so that life safety risks can be more carefully addressed. Performance-based design also typically involves the use of computer fire models or other fire engineering calculation methodologies, such as timed egress studies, to help assess if the proposed fire safety solutions meet the fire safety goals under the conditions specified.

Although performance-based design can be applied to any building project, it is most effective for complex and unusual structures, particularly those that do not fit well within the guidelines of prescriptive building regulations. Examples include convention centers, shopping malls, airport terminals, transportation centers, and buildings with unenclosed vertical openings, all of which pose challenges with regard to egress, spread of fire and smoke, and detection and suppression. Museums and historic structures also benefit from performance-based design because the designers of these buildings must balance aesthetics and historic preservation with fire safety concerns, and building regulations do not usually address property protection or historic preservation. For similar reasons, industrial facilities with hazardous or sensitive processes and contents also benefit from performance-based design.

EGRESS FROM AN OBSERVATION TOWER

In developing the fire and life safety program for a building such as an observation tower with a large population and amusement rides, numerous issues need to be addressed. The tower rises over 900 ft (274 m) above grade, with eight occupied levels and two amusement rides in the "pod" or upper portion of the tower. At the base of the tower is a casino building. Occupied floors of the pod include two levels of observation deck, a restaurant, a meeting room level, wedding chapels, and a bar level. The top level functions as an amusement level, containing a roller coaster and "space shot" ride. Exhibit S7.1 illustrates level 6 of the pod, which functions primarily as a restaurant. Exhibit S7.2 illustrates level 8 of the pod, which functions as the lower observation level. Exhibit S7.3 illustrates level 1 of the pod, which serves as one of two refuge areas.

The most obvious concern is providing for emergency egress, considering that the lowest occupied floor is 795 ft (242 m) above grade. In accordance with applicable regulations, some floors of the structure could include an occupant load in excess of 500 people. Strict adherence to the Life Safety Code requires three remote exit stairs leading from the top of the tower to the base of the building. The physical area of the supporting structure is not large enough to provide remotely located stairs in accordance with the Code, and the height of the building makes the use of stairs as a means of egress somewhat impractical. An alternative approach based on performance-based design concepts was necessary to develop a workable egress strategy.

Exit Program

The primary evacuation method for this building is the use of typical exit stairs for the occupied floors, discharging to areas of refuge on the lowest two floors of the pod. In other words, from floors 3 through 10 of the pod, three sets of exit stairs are provided, each enclosed in 2-hour fire-resistant construction, just as would be found in most other buildings. However, these stairs discharge to an area of refuge at the lowest two levels of the pod, which is still 750 ft (230 m) above grade. These two areas of refuge are used for no other purpose, and consist entirely of non-combustible construction. Rather than rely on mechanical systems to maintain the areas of refuge free of smoke in the event of a fire, the two floors are open to the surrounding exterior environment so that natural ventilation occurs. Since the two areas are below the occupied levels, it is unlikely that a fire in an occupied level would spread to the areas of refuge. Additionally, all the floors including the areas of refuge are provided with sprinkler, standpipe, and alarm systems, further reducing the likelihood of downward fire spread. (Detectors are located on all floors other than the open refuge floors.)

From the area of refuge, a single stair leads down through the shaft of the tower to grade. The primary evacuation route from the area of refuge involves the elevators. These elevators have two levels and travel at a speed of up to 1,800 ft/min. They can discharge either within the main casino or at two specially designed discharge levels at the roof of the base building. These discharge levels are enclosed in 2-hour fire-resistant construction from the roof to grade and are separated from all other areas by 2-hour fire-resistant construction.

Special Elevator Shaft Protection

To increase the reliability of the elevators and the safety of the elevator car occupants, special protection
has been provided. The tower design was undertaken during the same time period in which the National Institute of Standards and Technology (NIST) was initiating studies on the use of elevators for building evacuation. Many of the recommendations developed by NIST have been incorporated as design concepts for the tower. The concepts include the following:

1. Elevators open into 2-hour fire-resistance-rated elevator lobbies on all floors, at both the top and the bottom of the building.
2. There are four elevators that travel through the shaft from the base to the top. Two independent elevator machine rooms serve these elevators. The elevator machine rooms are separated by 2-hour fire-resistant construction and have a 4-in. curb installed between them so that water flow in one machine room will not affect the other.
3. Elevator lobbies are on a separate smoke control zone to maintain pressurization with relation to adjacent spaces. Therefore, smoke in an adjoining area will not spread into an elevator lobby.
4. Openings into the elevators are slightly raised from the remainder of the floor, preventing water flow on a floor level from spilling into the elevator hoistway.
5. Because the areas of refuge are at the two lowest floor levels of the pod, the elevators will not need to travel past a fire floor. Elevators will travel only between the areas of refuge and the base building. Areas of refuge for disabled persons are provided within the enclosed pressurized stairwells at each level.
6. Elevator shafts are vented to the outside at the top, and the vents are separate from the machine rooms. In addition, the machine rooms form sep-
rate smoke control zones, and air-conditioning for the machine rooms is on emergency power.

7. All four elevators are on emergency power. The emergency power riser is in a separate dedicated 2-hour shaft.

8. Only three of the elevators are assumed to be available for evacuation purposes. The fourth elevator is dedicated for use by the fire department.

Stairs

In addition to the elevator evacuation, a single stair leads down through the tower and discharges to grade. The stair enclosure is pressurized and remains independent of the base building. Enlarged stair landings at predetermined levels allow occupants to stop and rest as they descend through the building. In addition, the three stairs in the pod of the building are enclosed in 2-hour fire-resistant construction and pressurized. Each of these stairs has areas of evacuation assistance, with communication capability to the central control room.

Occupant Load Determination

With a building of this type, it is important to understand and control the occupant load. Three methods were used to determine occupant load. Once the three calculations were performed, the lowest occupant load calculated was used as the limiting factor for the building.

Areas of Refuge. Building codes and the Life Safety Code typically allow holding areas or areas of refuge for horizontal exits. Where those holding areas are used, the codes require a minimum of 3 ft² (0.28 m²) per person. Therefore, one of the limiting factors for this building was the size of the areas of refuge. De-
Egress from an Observation Tower

The second means of determining the occupant load of the building was based on code calculations. The expected occupant load, based on the applicable building code, was calculated for each floor of the building. The load was then totaled for the entire building, and this occupant load was used as a limiting factor for the number of people in the building.

Evacuation Capacity. The third determining factor was the capacity of the elevators to evacuate occupants. The speed of evacuation was based on calculation methods for elevator evacuation contained in determining their maximum holding capacity provides a factor of safety for several reasons, as follows:

1. The area of stairs leading to the areas of refuge was not included in the holding area. These stairs would significantly increase the number of people that could be safely accommodated within an area separated from the fire by 2-hour construction.
2. The calculations assume that no occupants are leaving the building via elevator or stair. Instead, they assume that all occupants are contained within the areas of refuge.
3. The evacuation scenario is to evacuate the floor of origin, the floor above, and the floor below. Therefore, only a portion of the building would be simultaneously evacuated. However, the occupant load of the entire building is limited by the size of the area of refuge.

Exhibit S7.3 Observation tower, pod level 1.
Supplement 7 • The Application of Performance-Based Design Concepts for Fire and Life Safety

The design concept for the upper floor of an art gallery called for a unique roof/ceiling structure con-
Sprinkler Placement in an Art Gallery

Locating sprinklers in the supporting grid at the base of the pockets appeared to offer the best option. However, because of the depth of the pockets, the sprinklers would be positioned more than the distance permitted by NFPA 13 from the top of the skylight pocket. In this case, proper sprinkler spacing needed to be determined.

Fire engineering employing computer fire models offered an effective means of analyzing how sprinklers would perform under the skylights. During a fire, the skylight pockets, because of their depth and number, would serve as heat reservoirs and have an impact on sprinkler activation. How much of an impact would be a function of numerous factors including the design fire, fire dynamics, ceiling and room geometry, and sprinkler type, spacing, and positioning. It is important to note that NFPA 13 only provides information on how to install sprinklers; it provides no information or criteria for how soon after the start

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of a fire the sprinklers are to activate. It is understood, however, that sprinklers need to activate during the early stages of fire development to be effective in controlling the fire.

Computational fluid dynamics (CFD) was applied to help understand the performance expected from an NFPA 13–specified system, to quantify the associated delay caused by the skylight pockets, and to help determine appropriate sprinkler spacing and positioning to achieve the intent of NFPA 13. In this regard, design fires representative of the fuel load in the gallery were quantified, and acceptable sprinkler activation performance criteria were determined. Sprinkler positioning and spacing appropriate to meet the activation criteria for the design fires were identified. Exhibit S7.6 illustrates one scenario modeled and analyzed using Fire Dynamics Simulator, a CFD computer fire model developed and maintained by NIST.

The overall approach was to establish design fires representative of the types of fires expected in the gallery space. Various ceiling/roof arrangements permitted by NFPA 13 were then evaluated, using CFD computer models for the specified design fires, to determine sprinkler activation times. These activation times were established as acceptance criteria. Various sprinkler spacing configurations under the roof structure proposed for the upper gallery were evaluated to determine those that would result in a time to sprinkler activation that was less than that established as the acceptance criteria.

The analysis established sprinkler activation time criteria for ceiling arrangements addressed by NFPA 13. Three cases (smooth, flat ceiling; ceiling channels; and ceiling grid) were evaluated for the types of fires expected in the gallery. The maximum sprinkler spacing and maximum distance between the sprinkler deflector and ceiling were evaluated to determine acceptance criteria.

The engineering analysis included several factors that allowed a degree of conservatism to account for uncertainties in both the analysis and the forthcoming installation process and allowed some flexibility in potential future modification of the design concept. These factors included the following:

1. Using ceiling heights less than that proposed for the upper gallery in the determination of acceptable criteria as allowed by NFPA 13. This created shorter sprinkler activation times.
2. Spacing ceiling members closer than the maximum permitted by NFPA 13 in the determination of acceptable criteria. This created shorter sprinkler activation time.
3. Establishing a design fire with higher rates of heat release than those for the types of combustibles evaluated to determine those that would result in a time to sprinkler activation that was less than that established as the acceptance criteria.

Exhibit S7.6 CFD analysis of sprinkler activation.
typically expected in the gallery. This flexibility allowed for contents that might be present in the gallery for special exhibits and functions.

The analysis of the gallery roof structure indicated that a sprinkler spacing arrangement could be developed that would result in a sprinkler activation time shorter than that derived from NFPA 13. A performance-based approach was used to develop a means of protection equivalent to that prescribed by NFPA 13.

STRUCTURAL FIRE PROTECTION FOR A STUDENT CENTER

One of the design objectives for a university student center project was to create an open and uncluttered feel for the atrium. The intent was to use exposed slender structural steel elements to support the glazed façade, the circulation ramps, and the roof.

According to the applicable building regulations, the structural elements in the atrium needed to have a certain fire resistance rating. Conventional methods of achieving such a rating — such as cladding or coating the structural members with a cementitious material or intumescent paint — would have been effective but would have diminished the desired architectural effect and negatively affected overall project functionality.

A performance-based design approach was developed as an equivalent means of meeting the building code requirements. A code analysis was conducted, and a fire strategy outlining the approach to resolve the relevant issues was prepared. The concerns of the associated stakeholders, including the local enforcing authorities, were identified and articulated, as were the design fires and criteria for determining acceptance of the alternative design.

Risk analysis principles were used to determine the likely fire hazards expected in the atrium space. Design fires were developed to quantify the relative size, duration, and characteristics of the fires anticipated. At the same time, the failure criteria — in terms of fire resistance — of the structural steel members proposed were also determined. It was agreed that the alternative design would need to withstand the impact of the design fires for a minimum time period of hourly fire resistance rating specified by the building code.

The performance of the structural steel members when exposed to the specified design fires was evaluated through the use of modeling and with the collaboration of structural engineers. The analysis included the effect of the structural member composition, as well as the means and spacing of structural supports and the methods of fastening. The analysis indicated that the structural elements could withstand the respective fire loads represented by the design fires for the time period associated with the code-prescribed fire resistance rating.

To account for a degree of uncertainty and to provide for a factor of safety, it was proposed that the spacing of the structural members supporting the walkways and roof structure be decreased from what was initially specified, resulting in some redundancy of the structural support system. The effect of this arrangement was that, should a given structural member prematurely fail, there was a reduced likelihood that the entire structure would fail. Thus, it was demonstrated that the conventional fire resistance rating of the structural elements could be achieved through other means, and that an equivalent means of protection could be provided for the anticipated design fires. A timed egress study was also undertaken to verify that occupants could evacuate from this space before the building structure suffered any negative effects from the fire.

An approach based entirely on prescribed code requirements does not specifically consider building performance or occupant response under expected fire conditions. Building codes consider classes of buildings generically and do not address specific fire hazards, unique building features, and occupant characteristics. As a result, code-prescribed solutions can provide for excessive fire protection in some instances and inadequate protection in others. With a performance-based approach, the architects in the university student center project were able to implement their design vision while adequately addressing applicable fire safety concerns.

LIFE SAFETY FOR A BOTANICAL GARDEN PROJECT

The design of a botanical garden project consisting of multiple floor levels carved into the surrounding hillside presented unusual challenges for fire and life safety. The project entailed a freestanding structure reaching 180 ft (55 m) at its highest points and covered an overall area of 5.4 acres (21,853 m²). From the outset, it was clear that a prescriptive code approach would be of limited value for the project.

The applicable building regulations classified the structure as an assembly occupancy, but if the project had been designed to fit the requirements of the prescriptive code, the design team would have been faced with trying to make the building conform to requirements derived from safety measures intended for theaters, arenas, and other more conventional
public buildings. The relevance of the prescriptive requirements was clearly limited for the project — there was no “rule book” to follow.

Early on in the design project, it was proposed that fire and life safety provisions be developed through performance-based design. This was discussed and agreed upon with the client and the local building and fire authorities.

The fire hazards in a building like this are very different from those typically encountered in conventional buildings. The vegetation clearly constituted a fire load, potentially an extremely large one, so the potential for a forest fire-type scenario was discussed. The team carried out a qualitative hazard analysis of the risk — in terms of frequency and consequences — of a vegetation fire in the structure, but this showed such a fire to be of sufficiently low probability that it was an impractical design parameter.

The examination of fire loading, therefore, turned to items other than the vegetation. Throughout the structure, huts are provided as information points for visitors. The huts are built of timber, with thatched roofs, and also have electrical power. Scenarios involving a fire in a hut were therefore developed as the basis for the fire safety design.

Because large visitor populations were anticipated, safe and efficient evacuation was a key concern in developing the fire strategy. The circulation (and, hence, evacuation) routes are far from conventional, as visitors walk around the botanical gardens on winding pathways linked to exits around the perimeter. Also, because the structure cuts into the hillside, pathway elevations vary considerably. A major challenge was to address the scale of the building, reflected in the length of the travel routes. If travel distance requirements of the building regulations were to be met, escape from the upper parts of the structure would require tunnels cut through the side of the hill. Such tunnels would probably need to have been pressurized, as they would have been at the upper levels of the project near potential smoke layers. Other options were needed.

The fire engineers proposed that evacuation be based on the time period necessary to egress the building rather than strictly on the distance to be traveled. The approach was to demonstrate that occupants could egress the facility prior to the onset of untenable conditions. The majority of the exits were located on the lower grades of the project, so, in the event of a fire, the occupants would travel to lower-level exits rather than use exits at the top of the botanical garden. Lower-level exits were also preferred as they encouraged the population to move away from the upper levels, where smoke would accumulate. While this route would result in evacuation distances of up to 450 ft (137 m), these distances were demonstrated to be acceptable due to the overall low level of hazard and large size of the space.

To verify the proposed strategy, combined smoke and evacuation calculations using computer models were undertaken. Based on the design fires, this allowed for a dynamic fire and smoke spread analysis of the actual geometry of the space. The timed egress study also considered various scenarios, such as the effect of blocked exits.

Due to the structure’s unique geometry, conventional smoke modeling software packages — which assume rectangular “box-type” enclosures — were unsuitable for calculating the rate of smoke fill. Project-specific calculations were therefore developed that allowed for the geometry of botanical garden spaces, using a three-dimensional model of the structure. From the model, it was possible to accurately determine the cross-sectional plan area of the project at various heights, and hence assess smoke filling rates using design fire scenarios agreed upon with the local authorities.

The egress modeling showed that the project could be evacuated in 5 to 6 minutes, while the smoke modeling indicated that a smoke layer would not descend to levels where it would impede evacuation for 15 to 25 minutes (depending on the fire scenario). The team concluded that the escape distances could be safely extended and evacuation conditions would be acceptable under the conservative scenarios studied.

Many fire safety systems conventionally associated with public assembly spaces were unsuitable. Detection methods including optical and aspirated smoke detection were found to be ineffective, due to the potential for smoke stratification to delay detection at high levels and plants obscuring optical detection sight lines.

Although the associated structures are essentially low fire hazard spaces, the fire safety strategy had to be developed from a common-sense, first principles point of view. The recognition that there was little relevant guidance for the project, and that adherence to conventional codes would result in unnecessary, costly, and ineffective measures, unlocked the design process. Close collaboration with the architect, enforcement officials, and other engineering disciplines allowed each team member to fully participate in developing the design and clearly understand the thought process and reasoning behind the proposed strategy. The result is a simple, robust, and cost-
effective strategy that provides a high level of fire safety for the botanical garden’s occupants.

**CULTURAL PRESERVATION OF A HISTORIC BUILDING**

For historic structures, performance-based design concepts often offer the most viable and effective solution for meeting both fire safety needs and cultural preservation goals. One such project was a designated landmark building consisting of cast iron and decorative masonry construction with ornate public and ceremonial spaces centered around an open atrium. The building was originally constructed in the mid-1800s to operate as a courthouse. It consisted of approximately 150,000 ft² (14,000 m²) over several floors.

The proposed design concept for the courthouse building called for a comprehensive, government-funded restoration and rehabilitation program to prepare the building for adaptive reuse as a multifunctional public and cultural facility with exhibition space, offices, and a restaurant. The design concept for the project called for the preservation of a number of areas and building features, including the open atrium, the ornate original wood doors, and numerous cast iron columns.

Although building code requirements are relaxed somewhat for specific features of historic structures, imposing the applicable prescriptive requirements on the project would have affected the overall historic authenticity and compromised the functionality and significance of the public spaces and unique architectural features. Therefore, the overall fire strategy was to identify and meet the intent of the applicable building regulations regarding life safety, while minimizing the aesthetic and visual impact of new construction and maintaining the open environment and original design features to the greatest degree possible. During the early stages of the development of the fire strategy, it became obvious that a conventional, prescriptive code-based approach would have forced a dramatic change to the proposed design concept and that an alternative approach could provide for a more effective and robust level of fire and life safety.

In most code-mandated prescriptive designs, the various fire safety features and systems are addressed independently of one another. The performance-based concept calls for an integrated approach of fire and life safety systems. Such an approach is especially pertinent to existing and historic building projects because it can result in less intrusive fire and life safety systems and features while meeting the required level of safety. In historic landmark buildings, this integrated approach typically results in improved building functionality and more cost-effective fire protection systems.

One of the major fire and life safety challenges in this courthouse building pertained to the compartmentation of building spaces. Building regulations require compartmentation to help prevent the horizontal and vertical spread of fire through the building. The existing building construction did not provide for the rated fire separations required by building regulations. Many doors were of original heavy wood construction with decorative wood and glass features and did not meet current fire protection ratings. It was proposed that the atrium remain open to multiple floors, existing non-rated shafts be reused as mechanical shafts, and certain building areas be open to each other through open stairways.

In developing an appropriate strategy, the aim was to assess the inherent fire protection qualities of existing building features (such as substantially constructed walls and high ceilings), to take advantage of the inherent degree of fire protection, and to supplement it with certain new active systems where necessary. The overall approach was to identify the fire loads (design fires) to be considered and then demonstrate through fire engineering that sufficient fire safety could be provided for the time period intended by the building regulations. In some cases, it was determined that the prescribed fire resistance rating would be needed; for other situations, a performance-based solution was developed.

In general, a fire that starts in the non-public areas is to be controlled so that it does not develop and grow to a point where it could threaten occupants in public spaces. Therefore, it was proposed that non-public areas — the attic and basement, mechanical spaces, and kitchens — be separated from public spaces by fire-rated construction. Additionally, areas traditionally constituting a higher fire hazard, such as electrical switch gear rooms, mechanical rooms, and storage areas, were also constructed to form separate compartments. As most of these spaces were non-public spaces, the new construction had a limited impact on the aesthetic features of the building.

In addition to compartmentation, other fire and life safety issues were identified and addressed through a performance-based approach. Issues regarding smoke management, egress, structural fire resistance, active systems, and fire-fighting facilities were addressed in a comprehensive manner. The overall fire safety solution integrated existing features with new systems and construction so that the
level of safety provided by the building code was satisfied, while preserving the historic value of the building to the extent possible.

CLOSING REMARKS

While considered by some a relatively new approach, performance-based design has been practiced for many years through the equivalency option in many codes and standards. The past several years have seen the development of a more formalized approach for practicing performance-based design, as well as the revision of codes and standards that specifically address performance-based design approaches. Even so, where a performance-based design is pursued, it usually involves a variance by the local building official or regulating body. However, the development of guidelines and definitions of applicable terms serves to better facilitate the discussion between designers and enforcers and allow for better-informed decisions.

This supplement has provided a brief overview of the types of projects in which performance-based design has been successfully applied and accepted by the authorities having jurisdiction. Even though performance-based design is gaining more acceptance, the prescriptive code is likely to remain the first means of developing a fire safety strategy for a building. Enforcing authorities have a greater comfort level with the prescriptive rules that are, in essence, the law. As such, code reviews and interpretations are often the first step in developing the fire safety design process.

For certain projects or for specific aspects of projects, the prescriptive code does not adequately address a given situation or would be incompatible with the developer’s or architect’s design vision. In other cases, a more cost-effective alternative would result in the same level of protection as that required by the prescriptive building code. In such cases, performance-based design concepts can be used to develop solutions that address specific issues while complementing the requirements prescribed by traditional building and fire codes.

REFERENCES

2. Performance Based Primer for Codes and Standards Preparation, National Fire Protection Association, Quincy, MA, 2000.