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Fire Safety Strategies for Penthouse Designs

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Penthouses, with their luxurious amenities and uninterrupted 360-degree views over the city skyline, tend to be larger than normal apartments and often have unique design features that can create challenges in fire safety design. The critical questions are: can occupants escape safely from the top of a high-rise tower, and what are the conditions within the penthouse once the Fire Brigade has arrived at the top of the tower? This article outlines the fire safety strategy for a unique five-story open-plan penthouse in London. A fire engineering assessment was required, including the use of CFD simulations, to prove that the proposed design complies with the functional requirements of building regulations in the United Kingdom.

Introduction

Since the first penthouse apartments were built in New York City in the 1920s, penthouses have been popular and continue to carry a sought-after prestige in capital cities around the world. One Hyde Park's penthouse in London recently sold for US$208 million (Huffington Post 2014) and the penthouse in Monaco's New Odeon Tower is expected to sell for at least US$386 million (The Guardian 2014). Penthouses, with their luxurious amenities and uninterrupted 360-degree views over the city skyline, give the feeling of being located away from the city, as they are generally less noisy than apartments on lower floors. They also tend to be larger than normal apartments, sometimes accessed by a private elevator opening directly into the apartment. They can come equipped with a private terrace, a private pool, or other unique features.

A recent example of a unique penthouse apartment is the five-story penthouse on top of the 36-story 261 City Road development located in Islington, London. The development is composed of three buildings (Buildings A, B, and C), all designed by Skidmore, Owings & Merrill (SOM). Buildings A and C are both seven-story buildings served by two stairs, while Building B, also known as the Lexicon, is a single-stairway building with a height of 118 meters, and will be the tallest building in the area (see Figures 1 and 2). The development will offer more than 300 residences (both private and affordable units), amenities such as a spa, retail space, and a public courtyard, as well as a restaurant at ground floor level in front of the newly created City Road basin.

Figure 1. 261 City Road, London – overall view. © Mount Anvil

As penthouses are one-of-a-kind apartments with specific features and layouts, giving flexibility to the architect can be a challenge due to fire safety restrictions in many jurisdictions. In the United Kingdom, for example, justifying an open-plan layout is generally done through a fire engineering assessment, the principles of which, including evacuation time calculation and Computational Fluid Dynamics (CFD) modeling, are explained in this paper.

General Fire Safety Strategy

The general fire safety strategy for the development under study here was based on recommendations within Approved Document B (ADB) (DCLG 2013), which is the most common fire guidance in use in England and Wales. Buildings A and C are less than 30 meters in height, so the minimum fire resistance of the main structure is set at 90 minutes. Building B has 120 minutes' structural fire resistance, due to its height being greater than 30 meters, and is fitted with a sprinkler system throughout. Dry risers are provided to buildings A and C, while Building B has a wet riser.

All the buildings are greater than 18 meters in height, and therefore are all fitted with a firefighting shaft – consisting of a ventilated firefighting stair, a fire main provided at every level within the stair core, a firefighting lift provided with emergency back-up power supplies; and a firefighting lobby, which is the ventilated residential common corridor. The common corridor in Building B is mechanically ventilated via a 0.6-square-meter smoke shaft, while Buildings A and C use the 1.5-square-meter natural smoke shaft recommended within ADB. Finally, a conventional "defend in place" strategy is adopted for the residential levels, where only the occupants from the apartment of fire origin evacuate. This is a standard assumption for residential developments in the United Kingdom, as the neighbors, protected by a high level of fire compartmentation (at least 60 minutes' fire resistance), remain in place. In the case of Building B, each floor is also separated by 120 minutes' fire resistance.

ADB can be restrictive in terms of apartment layouts, as it generally requires all the habitable rooms to be approached via a sterile, 30-minutes fire-resistant, protected entrance hall with FD20 fire doors. Guidance within British Standard (BS) 9991:2011 (BSI 2011) offers more flexibility and allows open-plan apartments under certain conditions, such as a ceiling height above 2.25 meters, enhanced fire alarm and detection systems (i.e., one detector in every room), and a residential sprinkler system fitted throughout the apartment. When the dimensions of the apartments are greater than the maximum size allowed within BS 9991, or if it is a multi-level open-plan apartment, a fire-engineered assessment is generally used to justify the layout, by determining the conditions within the proposed apartments in case of fire, and by demonstrating an adequate level of safety for the occupants. Following this approach, several apartments within the development had to be fire-engineered, including the use of CFD modeling, with the most challenging apartment being the five-story open-plan penthouse sitting on top of Building B at more than 100 meters above grade.

Figure 2. Lexicon, London under construction. © Mount Anvil

The Penthouse

Geometry

The 385-square-meter penthouse (see Figure 3) is composed of five stories with:

- The entrance and reception lounge at Level 32;
- The kitchen and living room at Level 33;
- Bedrooms at Levels 34 and 35; and
- A roof terrace at Level 36.

Two stairs are provided within the penthouse: one open stair located within a void between Level 32 and Level 33, and another linking Level 33 to the upper floors. Additional measures include a residential sprinkler system, enhanced fire alarm and detection system, and an automatic openable vent (AOV) on top of the stair linking Levels 33, 34, 35, and 36. The penthouse has a height of 15 meters between the slab at Level 32 and the ceiling above the stair at Level 36.

Fire-engineered assessment

Due to the uniqueness of this five-story penthouse, it was considered to be more closely related to a "dwelling house" than to an apartment. Dwelling houses with more than one floor over 4.5 meters above ground floor level (typically a dwelling house of four or more stories), would typically require:

- A protected stair and a sprinkler system throughout; or
- A protected stair and an alternative means of escape for any level above 7.5 meters

The sprinklered penthouse in this study has been designed with open internal stairs, instead of the recommended protected stair, and no alternative means of escape has been provided. A fire-engineered assessment, based on a deterministic study, has therefore been used to establish if occupants asleep on the terrace at Level 36 would be able to escape safely during two different fire scenarios, via the open internal stairs to the entrance door at Level 32, before conditions

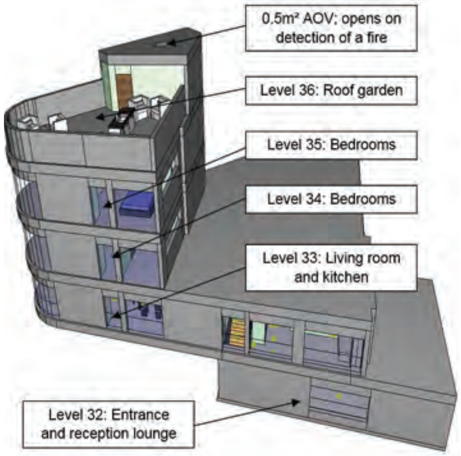

Figure 3. 3D geometry of the penthouse.

“…due to the intrinsic nature of a penthouse (i.e., being on the top of the building), there is no option to provide a second means of escape without changing the layout and reducing the net saleable area of the penthouse.”

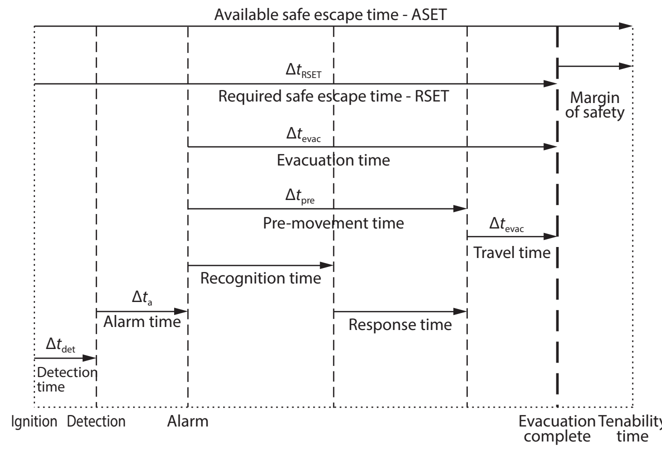

Figure 4. Example of a timeline comparison of the Available Safe Egress Time (ASET) and Required Safe Egress Time (RSET). Source: PD 7974-6:2004.

become untenable. This was considered to be the worst-case scenario, as the terrace does not contain any sleeping accommodation, and the only means of escape route from the terrace represents a travel distance of approximately 48 meters, including vertical and horizontal travel distances.

The deterministic study undertaken aimed to compare the Required Safe Escape Time (RSET) – the time required by the occupants to leave the penthouse and escape to a place of relative safety (the common corridor) – to the Available Safe Escape Time (ASET), defined as the time available for occupants to escape until conditions within the penthouse become untenable for escape due to fire and smoke spread (BSI 2004) (see Figure 4). The RSET was calculated using empirical data provided in several studies, whereas the ASET was determined using CFD modeling software called Fire Dynamic Simulation (FDS), which has an emphasis on smoke and heat transport from fires (NIST 2015). The latter provided numerical data on the levels of safety implied by the proposed design that were analyzed and compared against tenability criteria.

Two different fire scenarios have been analyzed: a living room and a kitchen fire. The fire statistics in United Kingdom from 2011–2012, compiled by the Department for Communities and Local Government (DCLG 2012), show that, out of 37,601 fatal and non-fatal casualties in accidental dwelling fires, 61.8% started in the kitchen, whereas only 9.2% started in the dining room or lounge. However, living-room fires lead to the most fatal casualties, due to the difference of fire size and fire spread opportunities between a kitchen and a living-room fire. Therefore, even if, in terms of occurrence, the kitchen fire would have been the most relevant, by including a typical kitchen and living room fire in the study, a full range of possible residential fires has been assessed.

This is not the first time this approach has been used on open-plan layouts, with dimensions exceeding the recommendations within the guidance, or for multi-story open-plan apartments. The fire-engineered assessment has been based on the proven benefits of not only the enhanced fire alarm and detection systems that would be present in a real fire scenario, but also the presence of a residential sprinkler system. This tried-and-tested scientific methodology has been developed through a process of discussions with building control bodies, the London Fire and Emergency Planning Authority (fire engineering team), and third-party checkers. Each comment received enriched the approach and provided further background to validate the level of safety provided in each open-plan apartment.

Several American and British studies have also been used to justify items such as an increase of the maximum travel distance within an apartment where sprinklers are provided (NFPA 2015), an increase of the level of safety when both sprinkler and enhanced detection are provided (NHBC 2009), the distance of the cooking appliance from the means of escape route (BSI 2011), and the effectiveness of the residential sprinkler system (BRE 2005). There are some studies of particular interest that document a number of experiments with and without sprinklers, and with the door to the room of fire origin opened or closed (NHBC 2009). The main conclusions from the above-mentioned publications were:

- Visibility is lost quickly during a fire;
- Tenable conditions (apart from visibility) for the rest of the house could be maintained by having sprinklers in the room of origin or by closing the door of the room of fire origin;
- Fire with the door open and no sprinklers would eventually cause untenable conditions throughout the house;
- Sprinklers did not improve the visibility, however they significantly improved the tenable conditions for heat, radiation, and toxic gases; and
- Death would not have occurred in any of the sprinklered fires.

The core of the fire-engineered assessment used to validate open-plan layouts that deviate from the guidance is therefore mainly based on all the above conclusions. This approach is nonetheless always evolving to address the specific needs of each project. For this specific penthouse, the main challenges were the layout – including the size, the geometry, the number of stories, the open stairs, the void connecting Level 32 to Level 33 – and the fact that, due to the intrinsic nature of a penthouse (i.e. being on the top of the building), there is no option to provide a second means of escape without changing the layout and reducing the net saleable area of the penthouse.

Required Safe Escape Time (RSET)

An analysis of the total time to evacuate the penthouse has been conducted. This analysis is based on the identification and quantification of the individual time elements, which contribute to the overall escape time. These elements include time periods related to the fire safety systems (e.g., time to detection and alarm), occupant pre-movement time (e.g., recognition and response time), and the time taken to actually travel out of the apartment.

Due to the enhanced fire alarm and detection system, the detection and alarm time analysis was done at the early stage of the fire: around 30 seconds after ignition. The pre-movement time took into account the fact that occupants could be asleep (leading to additional time to waken), then covered the time occupants would take to recognize and respond to the fire (BSI 2004). There is a psychological and physical process an individual might use to attempt to perceive, identify, structure, and evaluate the fire incident cue. Therefore, the pre-movement time will vary from one person to another, but it will also be different for the same person depending on external factors such as prior experience, physical condition, familiarity with the surroundings, family members present, etc., (Bryan 2008). Those factors are generally taken into account in the studies by giving the average pre-movement time and several percentiles. The pre-movement time provided in the fire engineered assessment therefore took into account all of those parameters in order to cover a wide range of scenarios. Finally, the travel time was calculated, taking into account the differences between vertical and horizontal walking speed (as most of the escape route is done vertically via the two open stairs), as well as the effect of smoke on walking speed.

By adding the time to detection and alarm to the pre-movement and travel time, the maximum expected RSET time for both kitchen and living room fire scenarios was determined.

Available Safe Escape Time (ASET)

In order to gather information on the ASET, the penthouse had to be created as a 3D model in FDS (see Figure 5). The aim was to mirror the proposed design to a level of detail that would be considered acceptable and would not affect the results. In addition, all input parameters had to be detailed and documented. This included the design fire for both kitchen and living-room fires: location of the fire, size, heat release rate per area, growth rate, effect of the sprinkler on the heat release rate, etc.

The reaction type (i.e., which fuel will mix with air), but also products of combustion, such as the soot yield (the mass of smoke produced per mass of fuel burnt) or the carbon monoxide yield, had to be specified in FDS in order to model a realistic residential fire. The sprinkler system also had to be specified (i.e., flow rate, activation temperature). Each obstruction created on FDS (i.e., walls, slab, ceiling, furniture) was assigned a material property to take into account any interaction they may have with the fire. A breakage temperature was assigned to the glazing, so as to provide enough oxygen to sustain the fire.

Furthermore, smoke detectors were added to compare the detection time in the fire scenario to the one found with the calculation in the RSET, and to activate the 0.5-square-meter AOV located on top of the stair, which opens automatically on smoke detection. All of these parameters and assumptions were made in excess of normal expectations, to take into account a factor of safety.

Two different fire scenarios have been simulated to represent fires of different size, in different locations, and with different fire properties. They included a polyurethane-based living room fire and an oil-based kitchen fire. The fire scenarios, fire properties, heat release rate (see Figure 6), and fire locations were discussed and agreed upon prior to modeling with the Authority Having Jurisdiction (AHJ). Finally, each fire scenario was provided with numerous outputs to be able to determine the ASET. They included visibility, temperature, and velocity slices, as well as devices located along the escape route measuring the radiative heat flux, the visibility,

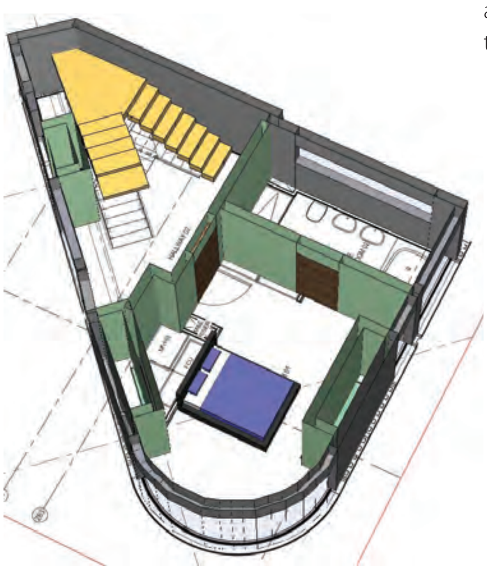

Figure 5. 3D geometry of Level 34.

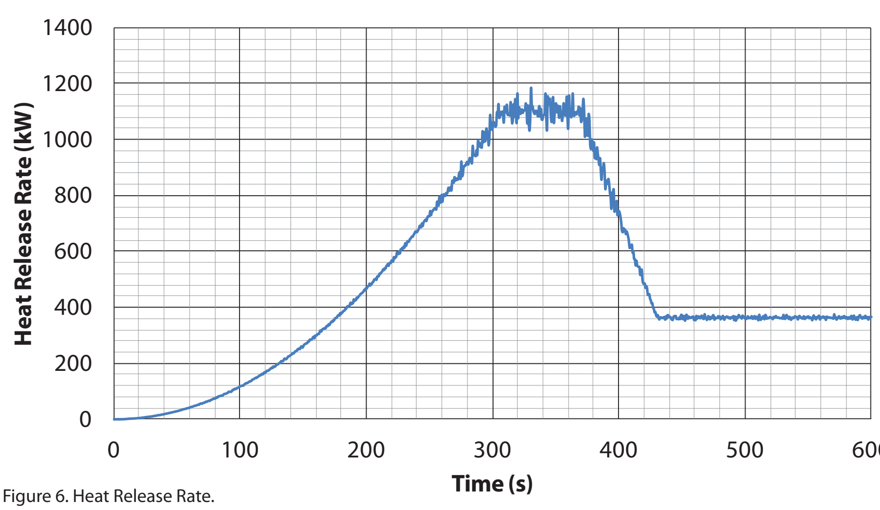

Figure 6. Heat Release Rate.

> “An occupant would need to be exposed for at least 30 minutes to 60°C in wet conditions before lung damage occurs. It was therefore concluded that temperatures between 60 and 80°C during approximately 2 minutes’ duration will not impede or prevent occupants from evacuating.”

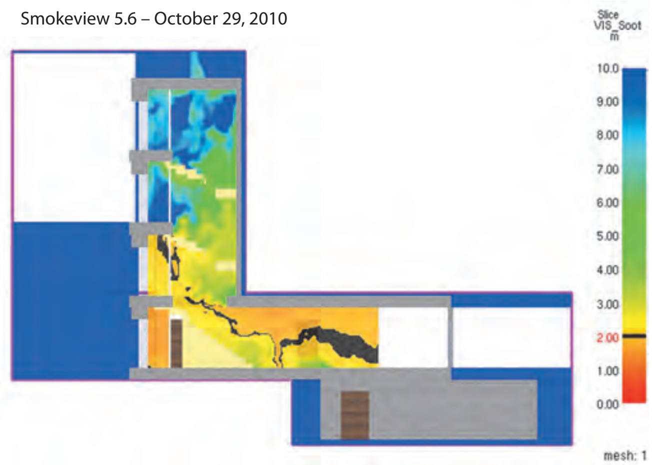

Figure 7. The visibility at 243 seconds in the upper stair. Blue shows good visibility (10 meters), red shows bad (0 meters).

the temperature, and the Fractional Effective Dose (FED) that is used to assess the toxicity of the atmosphere.

Results of The Fire-Engineered Assesment

All the output data gathered during the simulation were assessed against tenability criteria agreed with the AHJ prior to modeling. These included the temperature at which burning of the lungs and throat are likely to occur depending on the time of exposure, the level of radiation at which severe skin pain will occur, and the FED at which occupants, no matter their age or general health, would be considered to be incapacitated. The visibility condition during escape was also assessed against the criterion recommended in PD 7974, even though it is the authors' opinion that visibility does not play a key role in the occupant's ability to escape. It should nonetheless be assessed as part of a holistic deterministic study (see Figure 7).

The results indicated that the tenability criteria for FED and radiative heat flux were not breached (see Figure 8). The tenability criterion for temperature was breached during the simulation for the living-room fire. To assume a worst-case scenario, the living-room fire was located under the void between Level 32 and Level 33 (with a height of approximately 5.5 meters) and therefore grew until it reached one megawatt (the equivalent of a fire in a piled-high luggage trolley containing clothing and other representative materials) (Mayfield & Hopkin 2011), before decreasing following sprinkler activation. The temperature at Levels 32 and 33 breached the tenability criterion (60°C) in the entire area of both floor levels at the beginning of the fire (before sprinkler activation) for approximately 130 seconds (see Figure 9).

To provide a factor of safety, the tenability criteria are assumed to be breached if they exceed a set value for more than one second. In the case of the temperature, PD7974-6 states that an occupant would need to be exposed for at least 30 minutes to 60°C in wet conditions before lung damage occurs. It was therefore concluded that temperatures between 60 and 80°C during approximately two minutes' duration will not impede or prevent occupants from evacuating.

Due to the large fire size, a significant quantity of smoke was produced, and the large volume of the penthouse did not compensate for it. The visibility therefore dropped quickly below 10 meters, then 5 meters, before stabilizing at around 1.5 meters until the end of the simulation, with some local areas having better visibility.

Research studies show that, when confronted with low visibility, occupants are likely to turn back (Bryan 2008). It was nonetheless concluded that occupants would still be able to escape from the penthouse due to their familiarity with their surroundings and the geometry of the penthouse (the walls giving landmarks and allowing occupants to follow them to the exit). Additionally, while low visibility impedes the evacuation, it is not a direct threat to occupants' survival, unlike the temperature, radiative heat flux, or FED. Indeed, low visibility during escape will not lead to lung burns, unconsciousness, cerebral depression, or skin burns. The results also showed that the vent (activated following detection of smoke) on top of the stair, while allowing smoke to exhaust, does not have a key role in improving the visibility.

Approval Process

As this penthouse was the first of its kind in London, a unique approval process route was required. Lewisham Building Control was the AHJ approving the entire development, including internal apartment layouts and penthouse design. As the fire safety strategy for the five-story penthouse was based on fire engineering principles in line with PD 7974-0:2002 (BSI 2002), it was decided that an independent third-party reviewer would be appointed to assist Lewisham Building Control.

This third-party reviewer (Beryl Menzies & Partners) was contacted at an early stage. An initial meeting took place with the AHJ, its third-party reviewer and the design team, to introduce the penthouse, its characteristics, the architectural aspiration, the challenges and the proposed fire-engineered assessment; an approach was discussed. Following this meeting, an external memo describing the general fire-engineered approach and highlighting all the assumptions, input parameters, tenability criteria, fire scenarios, fire location, etc., was sent to the AHJ for approval as part of the Qualitative Design Review (BSI 2002).

Once agreement was received related to the approach and input parameters, initial fire simulation and calculations were undertaken. The results of these initial results were presented, reviewed, and discussed at another meeting with the AHJ. This ensured that all parties were involved and could influence the design if necessary.

Based on these discussions, further fire safety measures were introduced. For example, a larger AOV was located on top of the internal stair, and an upgrade of internal lighting was undertaken, so that it could function as emergency lighting if required. Further simulation and scenarios were agreed and undertaken. These were presented in the final report, suitable for the approval process.

The approval process was open and visible, as it involved the AHJ and its third-party reviewer from an early stage. Fruitful discussions ensured that all parties concerned were continuously involved during the approval process while design changes could still be made. This significantly assured confidence throughout the design team. The authors encourage other design teams to follow a similar approach for unique and outstanding projects that do not follow standard building regulations.

Conclusion

The five-story open-plan penthouse forming the top of the Lexicon will be a one-of-a-kind apartment situated on top of a landmark building overlooking London. It is the result of collaboration between client, architect, and design team – allowing them greater design freedom and more usable area in the apartment. It also involved discussions with Statutory Authorities, and compromising to find a common accord that would satisfy all parties and still provide an adequate level of safety, while pushing the limits of architectural possibility. ■

Unless otherwise noted, all photography credits in this paper are to the authors.

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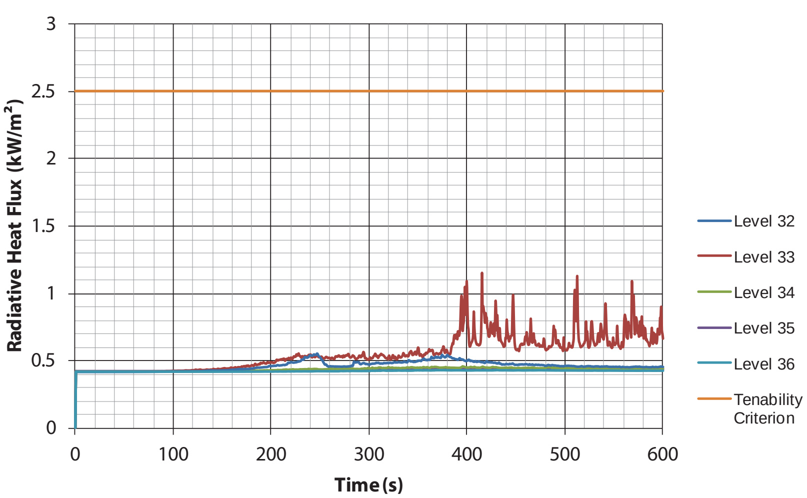

Figure 8. Radiative Heat Flux received from smoke during means of escape phase.

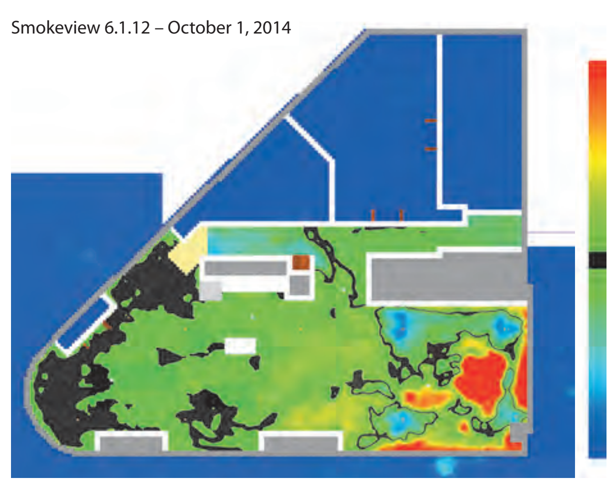

Figure 9. Temperature in Level 33 shortly after sprinkler activation. Red shows high temperatures (100°C or more), blue shows low temperature (20–35°C).