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SMOKE MANAGEMENT AND EGRESS ANALYSIS OF A SPORTS ARENA USING THE PERFORMANCE-BASED DESIGN

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ABSTRACT

A 15,000 seat indoors sports arena following the performance-based fire engineering design was analyzed in this paper. 3D CFD analysis using FDS software indicated that the original dome design was inefficient as a smoke reservoir and fails to provide a smoke-free escape route during evacuation. Therefore, the whole architectural design was modified with dome reshaped, and with mechanical fans and natural vents added, until the smoke-descending rate was controlled effectively. The egress simulation also pointed out several bottlenecks formed by evacuees, leading to relocation of staircases and facilities, until the evacuation time allowed is within the limit provided by the smoke management systems with some tolerances. The iterative design process proves itself a successful and effective procedure and is discussed in detail in this paper.

1. INTRODUCTION

Due to the persistent urge from the citizens for a large-scale indoor stadium to host gymnastic activities, the city of Taipei decided to construct a 15,000 seats sports arena in downtown area, by scraping an old outdoor baseball field. To minimize the traffic impact to this already crowded district, more seats were allocated near the left-hand side entrance, instead of evenly distributed along the circumference. Fig. 1 showed a Bird's Eye view of the architectural design of the arena.

- **Conceptual Design of the Smoke Management System**

The local fire code is prescriptive in nature, and was inadequate to provide an effective design guide for such a large area indoor sports arena. Instead, the NFPA 92B [1] was adapted for a performance-based smoke management system design. As shown in Fig. 2, the top of the dome was treated as smoke reservoir to alleviate the smoke descending rate, while the natural vents with 240 m^2 opening area and five mechanical smoke exhaust fans with 40 m^3s^{-1} capacity each further controls smoke to a favorable clear height and providing a smoke-free evacuation route. Make-up air was provided through the exits inward to the arena, providing further protection to the evacuee while they are passing through the exits in opposite directions. Furthermore, four stairwells were pressurized to keep the escape routes smoke-free leading to points of safety. The indoor environment was fully air-conditioned, with cold air supply from the upper level of the dome so that temperature stratification during the summer is unlikely to happen.

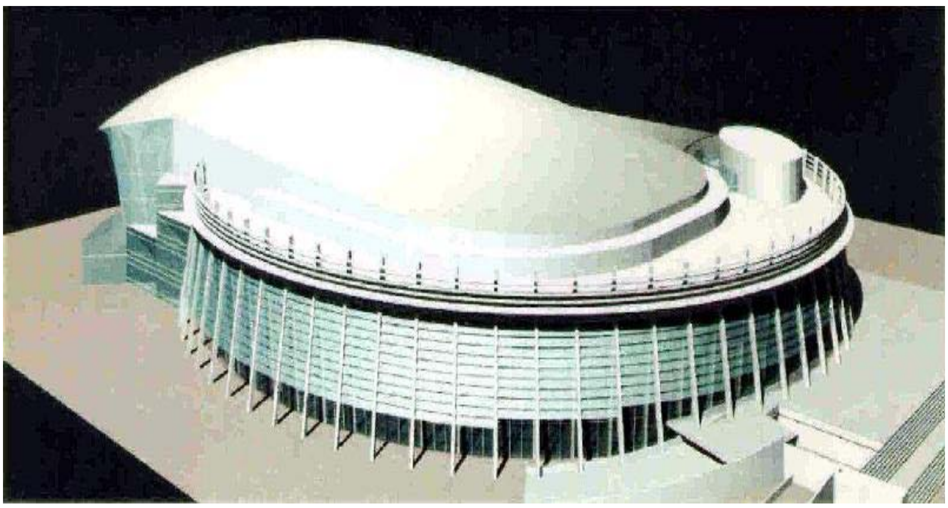
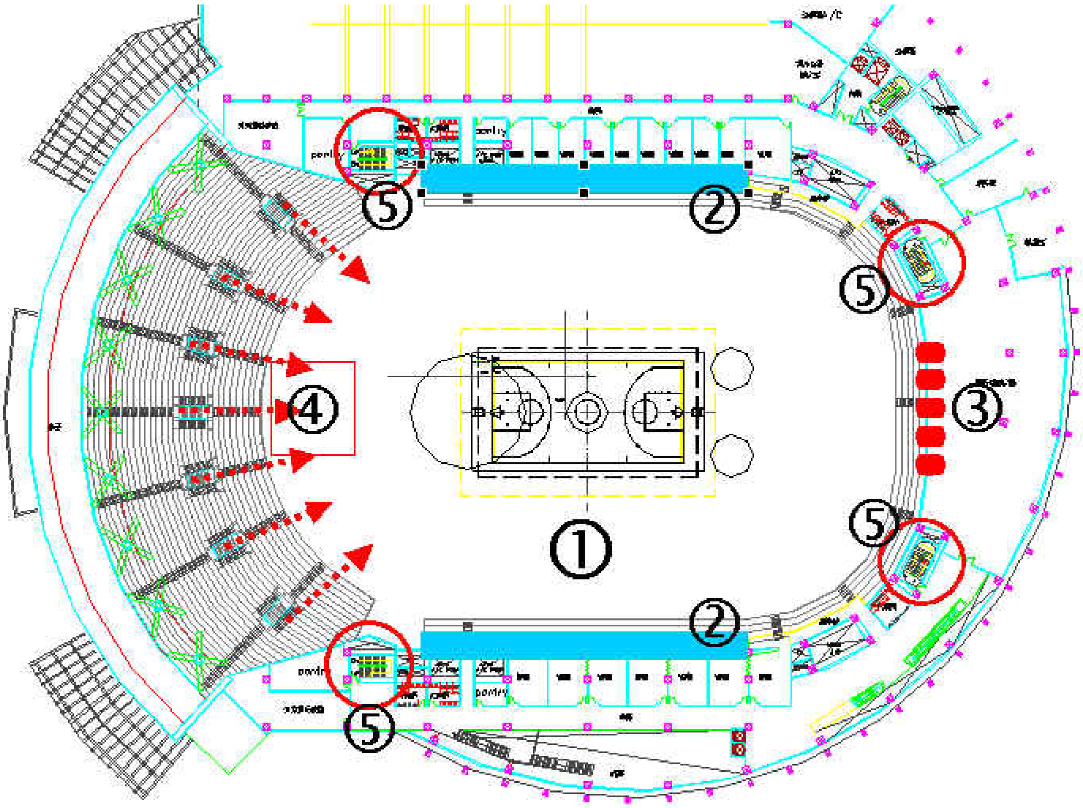


Fig. 1: A Bird's Eye view of the Taipei Arena



① Smoke Storage Design
② Natural Vent Openings, total areas = 240 m^2
③ Mechanical Exhaust Fan, 40 cms × 5 = 200 cms
④ Make-up Air Design
⑤ Stairwell Pressurization

Fig. 2: Design concept of the smoke management system

- **The Re-shaped Dome**

A major concern was raised about this original architectural design that the "tip" of the dome was located very close to the highest row of seats where it would quickly became smoke-logged in case of fire, while the occupants there were still jamming in a long line waiting to evacuate. 3D CFD using the FDS software [2] was performed to analyze the smoke natural-filling process and the smoke-descending rate, in case a 5 MW fire occurred in the middle of the arena. The simulation result indicated that within 100 s, the top of the arena was totally smoke-logged. In 180 s, smoke clear height is reaching the last row of seats, imposing an imminent danger to the occupants there. Within 210 s, the last 10 rows of seats were filled with dense smoke, creating a "Dead Zone" as shown in Fig. 3. A catastrophe will occur.

Therefore, we proposed to remodel the dome shape to tackle this problem, resulting in the final design as shown in Fig. 4. Although it might have indicated a much improved design, but it can only be finalized until satisfactory iterative comparison of the total evacuation time needed for 15,000 people to reach points of safety, vs. time allowable provided by controlling smoke descending through smoke management systems. Failure to make both ends meet would result in relocating, adding, or widening of staircases and/or public facilities, to shorten the evacuation time needed. Or efforts could be concentrated to manage the smoke descending rate by providing larger smoke reservoir so that the dome would be reshaped again, or adding more capacity to the natural / mechanical smoke exhaust systems.

In the following, several fire scenarios will be presented following this design procedure until successful result was obtained.

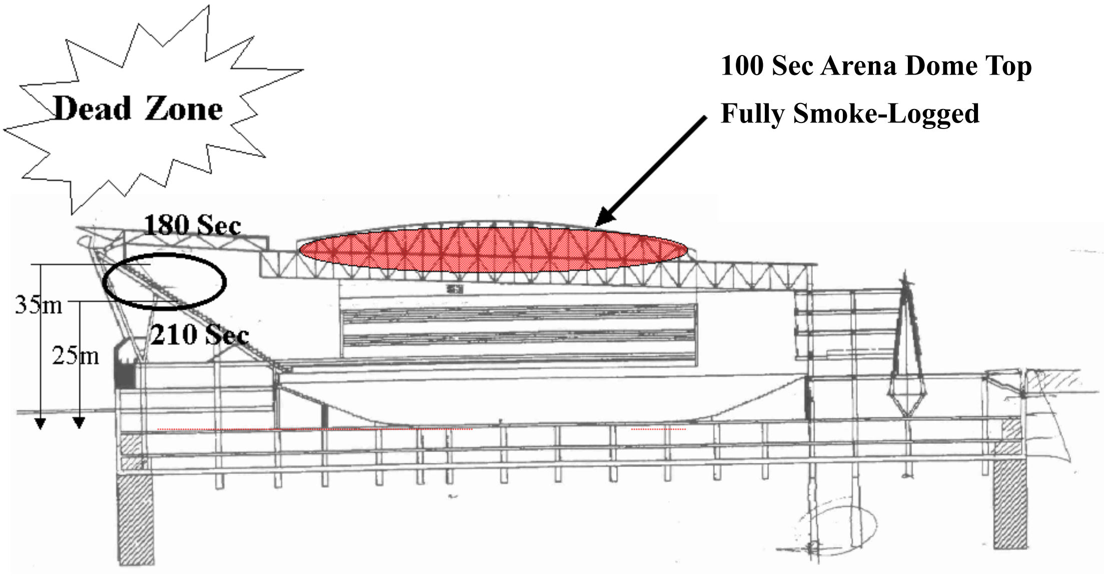


Fig. 3: Simulation result of the smoke natural filling process of the Taipei Arena

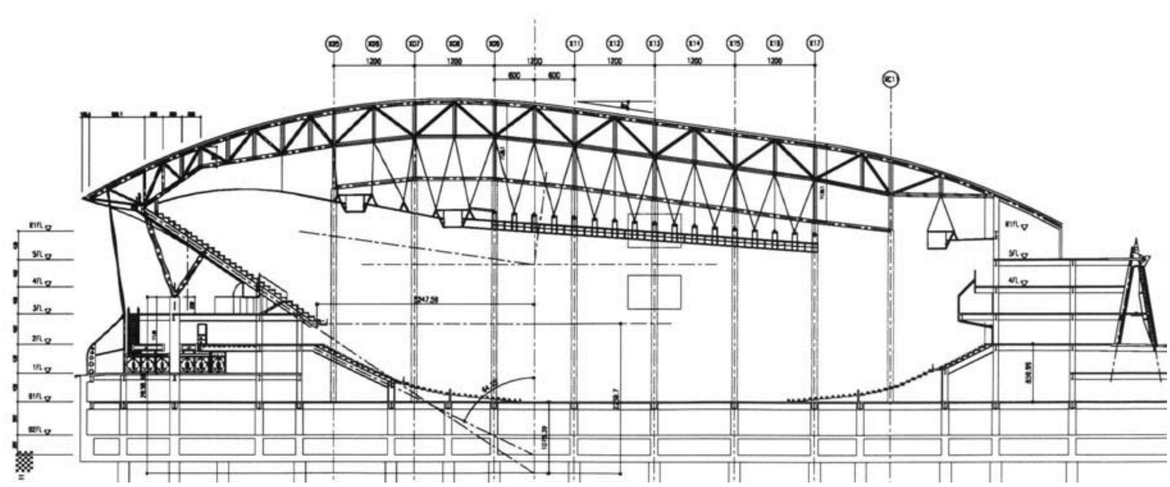


Fig. 4: The modified architectural design of the Taipei Arena

2. SMOKE MANAGEMENT SYSTEM SIMULATION RESULTS

- **Fire Scenario-1: a 5 MW fire occurring at B1 floor**

This is essentially a free-plume fire with strong air entrainment. Fig. 5 indicated the temperature distribution of this scenario after 14 mins when the fire occurred. The temperature difference between smoke and the environment was then calculated. Following the "N% temperature difference" method as proposed by the NFPA 92B [3], the smoke clear height can be plotted as shown in Fig. 6. This method uses the temperature difference between the smoke layer and the indoor environment as an indicator for smoke clear height. An optimistic evaluation of the smoke clear height would probably choose N to be 90. However, a more conservative design would be more likely to choose N to be 50, such as in our case. That is, the smoke clear height, which is 8.5 m above the last row of seat, can be maintained for longer than 30 mins, which is longer than the time needed for evacuation. The smoke clear height will be maintained as the mechanical and natural vents system keeps on operating until the local fire marshals take over for fire fighting procedure.

Another concern is that whether the cold make-up air, at the temperature of 10^{o}C during the winter, will affect the smoke plume during the fire. Another simulation has been conducted to indicate in Fig. 7 that the cold air jet has minimal effect on the free-rising smoke plume and thus can be neglected.

- **Fire Scenario-2: a 5 MW fire occurring at the 3F seats**

This is to simulate an arson case that someone brings in 2 kg of gasoline and set the chairs on fire at the 3rd floor. Fig. 8 showed the temperature distribution of this scenario after 8 mins when the fire occurred. Due to the shorter distance to the dome ceiling, the smoke ceiling jet is significant, and the clear height to the last row of seats is 5.5 m and can be maintained for longer than 30 mins as indicated by the smoke descending curve in Fig. 9. This is considered satisfactory for the time being yet has to be validated by the egress results later. To double-check the smoke management system performances, the CO distribution is shown in Fig. 10 yielding the same conclusions.

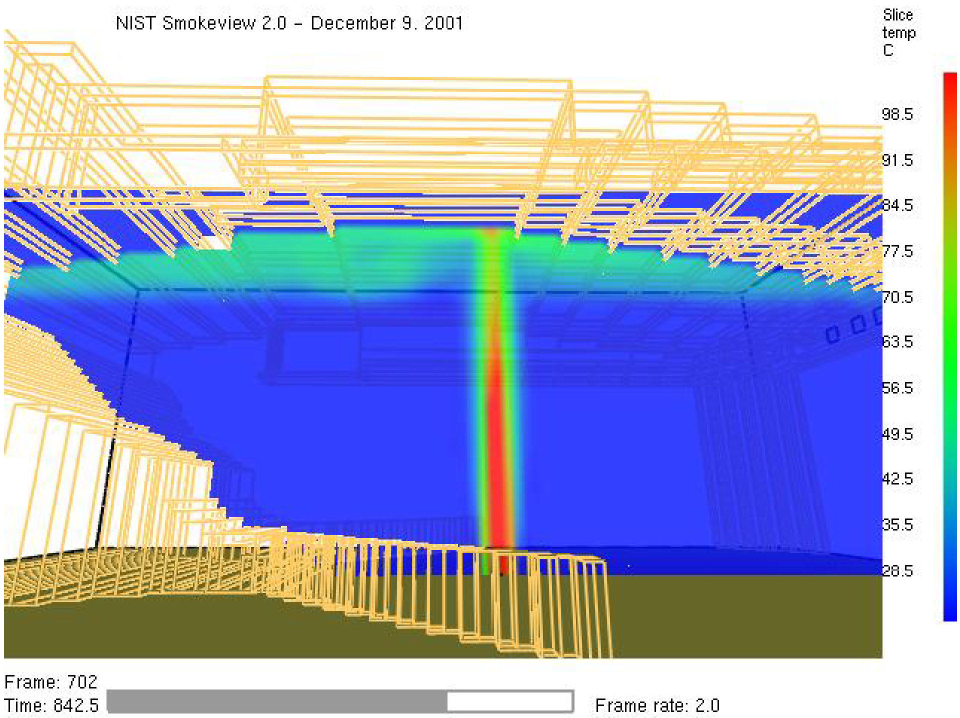


Fig. 5: 3D CFD simulation results of Fire Scenario-1 at 14 mins after the 5 MW fire occurred

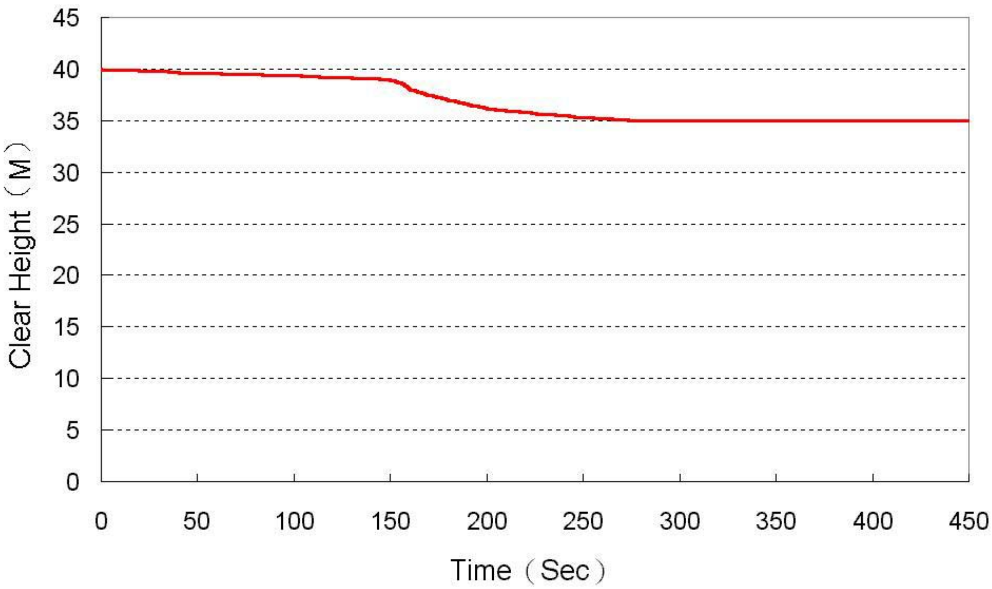


Fig. 6: Smoke clear height vs. time of Fire Scenario-1

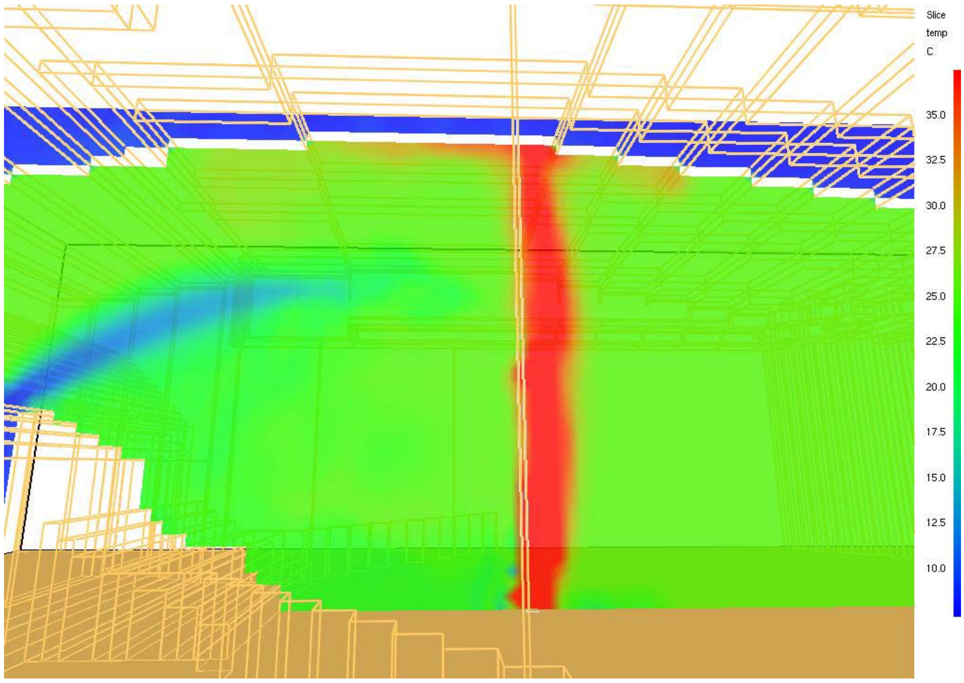


Fig. 7: An evaluation of the effect of cold make-up air at 10°C on smoke plume during a 5 MW fire

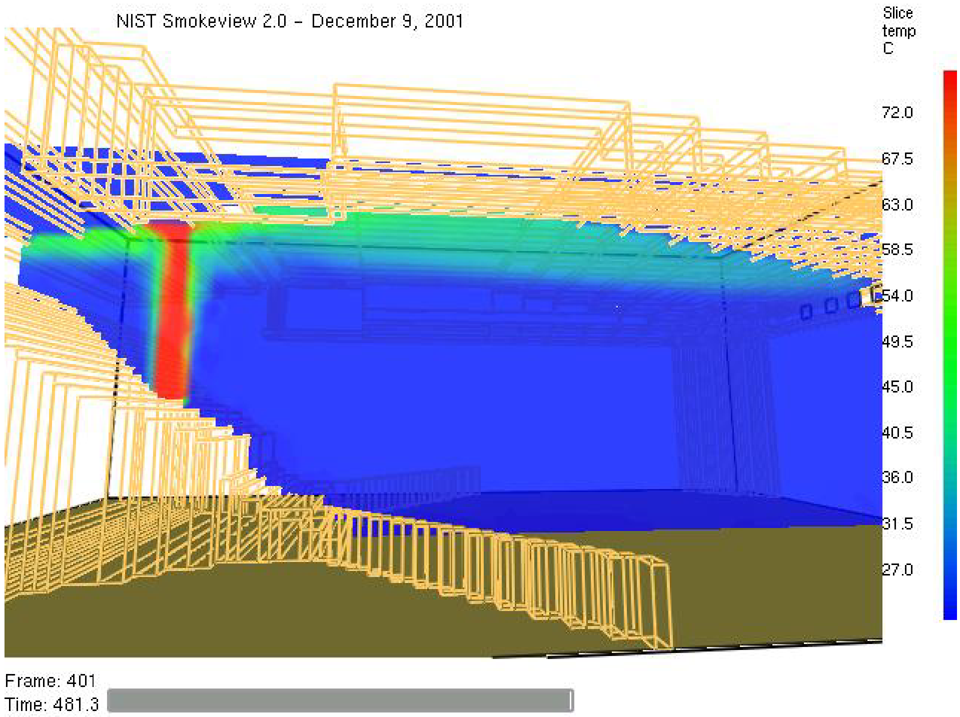


Fig. 8: Temperature distribution of Fire Scenario-2 at 8 mins after the fire occurred

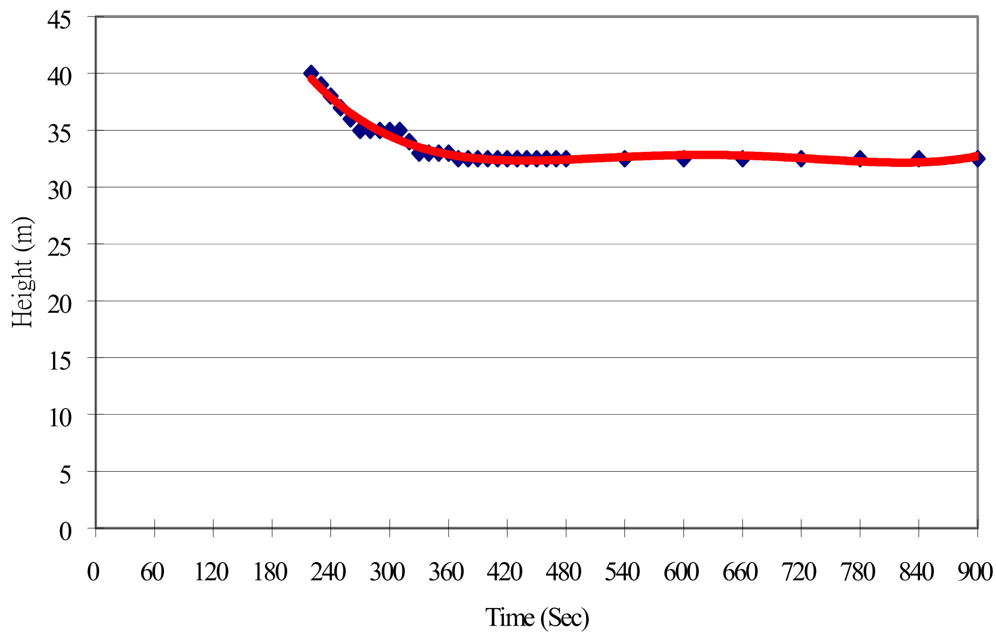


Fig. 9: Smoke clear height vs. time of Fire Scenario-2

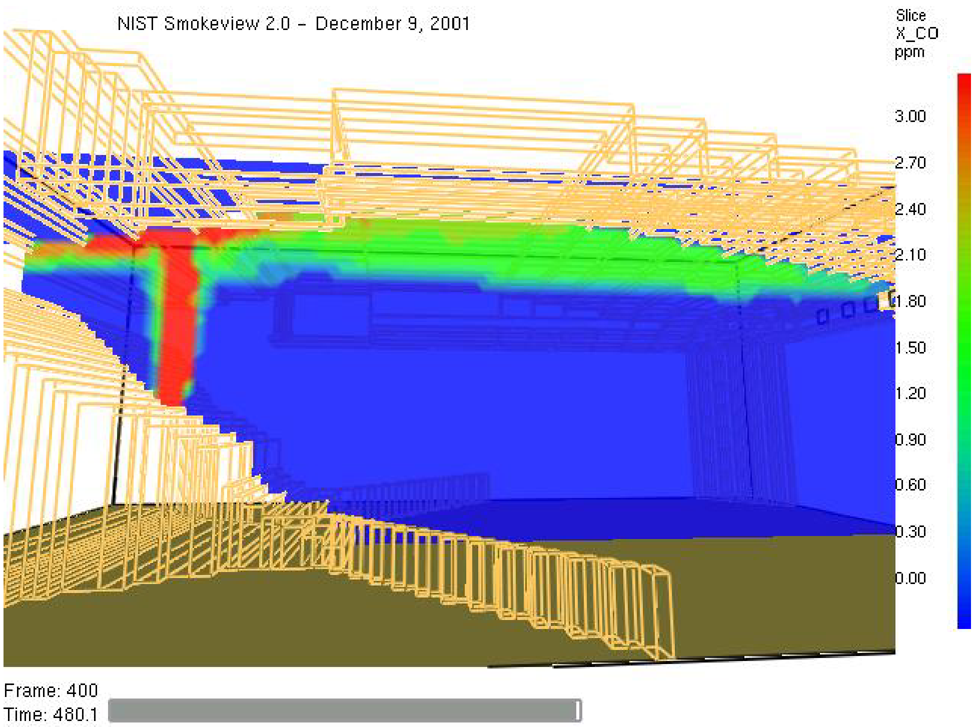


Fig. 10: CO distribution of Fire Scenario-2 at 8 mins after the fire occurred

3. EGRESS SIMULATION RESULTS

Conventionally, the architect to evaluate the distance between the occupant and the farthest exit performs egress analysis. And the local code gives a threshold value, for example 45 m, which cannot be exceeded or an additive exit should be provided. That is an over-simplified model based on the steady foot-traffic flow model. For a sports arena with 15,000 occupants, the dynamic behavior of the crowd should be considered further. First of all, the foot traffic of an evacuee should never be constant but varies with the population density instead. When the density becomes higher, the moving speed decreased correspondingly, eventually forming a bottleneck at the exit.

Over-taking should be allowed in simulation since it will actually happen in the real world. This important humane behavior should all be considered, and we have used the SIMULEX program to perform this analysis.

- **Egress Scenario-1**

Fire occurring at the B1 floor, with 1,500 occupants egress through 4 exits

This is to simulate a basket ball game where the basement floor was occupied. Based on the designed egress routes, the occupants should leave the arena through the 4 exits as shown in Fig. 11. Fig. 12 gives a snapshot during the simulation. And the total time it takes for the 1,500 occupants to reach the points of safety is 4 mins and 7 sec. This is apparently a satisfactory result since the smoke clear height as shown earlier can be maintained around 30 m above grade for more than 30 mins.

- **Egress Scenario-2**

Fire occurring at the B1 floor, with 1,500 occupants egress through 2 exits

This is to simulate that during the basket ball game, someone throws 2 kg of gasoline near the right hand side gates, making 2 exits unavailable for egress. Figs. 13 and 14 showed that the crowd is now heading for the left hand side as expected. The forming of bottleneck is unavoidable; causing the total time it takes becoming 5 mins and 21 sec. This is again still acceptable due to the effective smoke management system to provide a smoke-free escape route long enough for the evacuation to complete.

- **Egress Scenario-3**

Fire occurring at the 3rd floor, with 15,000 occupants evacuate through all exits

This is simulating the major event, such as a football game, when all seats are taken. A snapshot is given in Fig. 15. The total evacuation takes 14 mins and 18 sec to complete. Thanks to the smoke management system, at least a safety factor of two can be obtained in this case.

The satisfaction of this worst-case scenario warrants the successful egress designs.

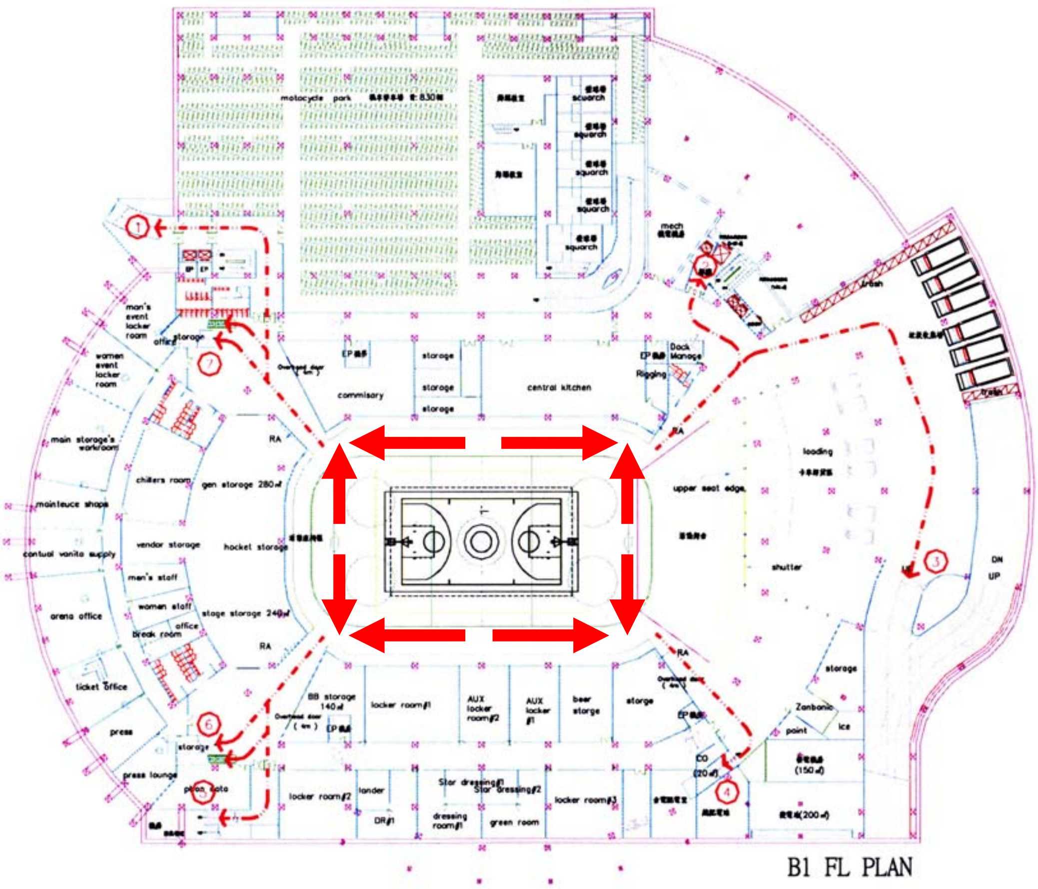


Fig. 11: Evacuation routes of the Egress Scenario-1

On the other hand, to prevent an arson case from occurring during the major event with 15,000 audiences, a long-range water gun system with four nozzles equipped and with guarded areas is shown in Fig. 16. This water gun system will be actuated within 90 s by Infra Red scanners at the first phase should a fire occur. Then, the smoke plum will be detected by 16 beam detectors, which were located along the inner circumference of the arena. Among them, 13 beam detectors are located with projecting distance for less than 45 m as shown in Fig. 16. A beam detector signal will be picked up as pre-alarms, until a second signal to reconfirm a real fire with humane intervention, which is expected to take 90 s. Then, the smoke exhaust fans will "kick-in" with the natural vents opened, at about 240 s after a fire occurred. The design concept is that the smoke reservoir will be responsible for the first phase of smoke management, which also prevents a pre-mature start of the mechanical smoke exhaust fans causing plug-holing effect.

4. QUANTITATIVE RISK ASSESSMENT

A probabilistic model using the Monte Carlo method was adapted for quantitative risk assessment of the whole emergency procedure. Starting from smoke detection, fire confirmation through humane intervention, public annunciation of the fire, followed by humane perception, and then the actual evacuation, each time step was evaluated and assigned a probabilistic curve. The Monte Carlo method yielded the calculation result as shown in Fig. 12, so that the most probable case occurred at 1038 s (17 mins and 18 sec) for the whole emergency process to complete. The least probable case will occur, either at 990 s when everything works most effectively, or at 1100 mins when the worst case occurred, that is, smoke was detected late, followed by slow identification procedure and slow response of evacuees, etc. On the other hand, smoke has been kept at a high level after 190 s and maintained there due to the mechanical and natural smoke vent system and allowing for a egress time for more than 30 mins. The comparison of the two warrants a successful performance-based fire engineering design.

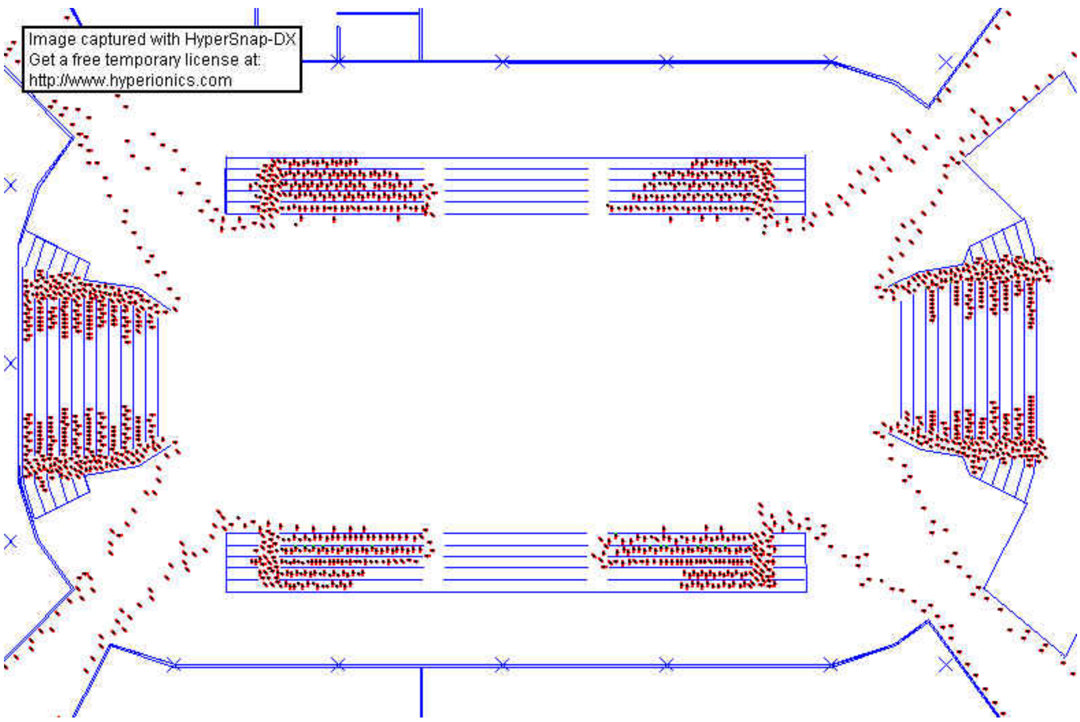


Fig. 12: A snap shot of the simulation process of Egress Scenario-1

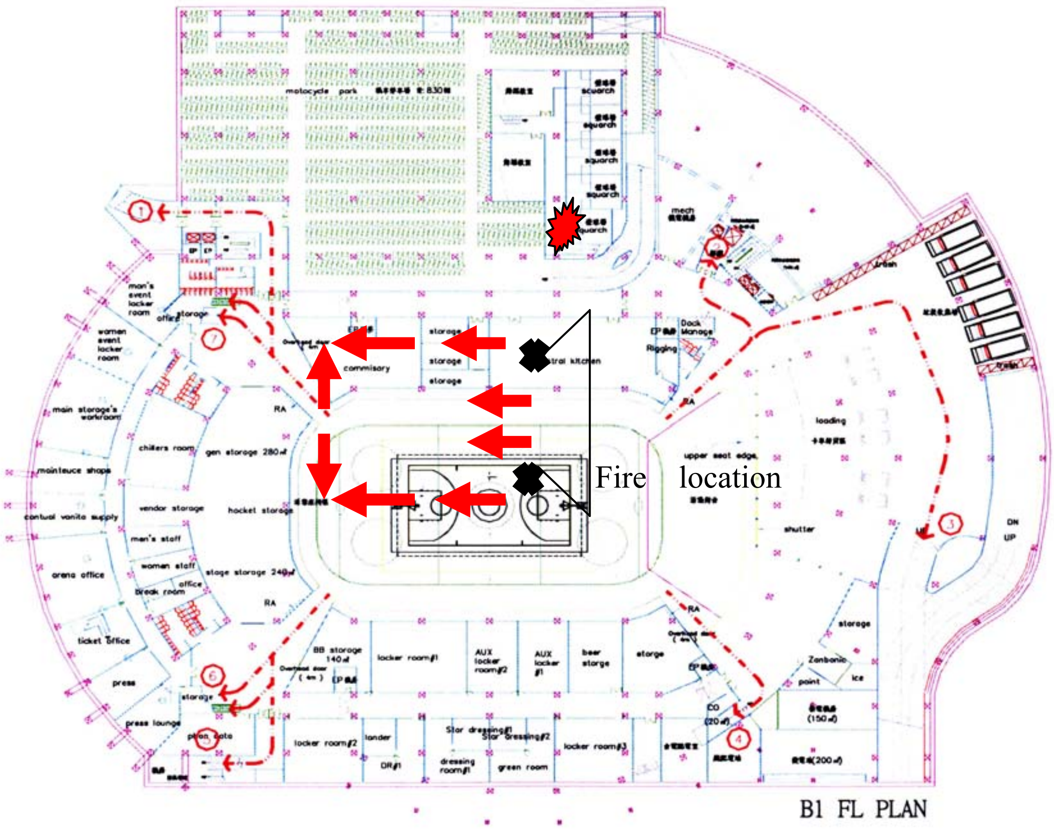


Fig. 13: Evacuation routes of the Egress Scenario-2

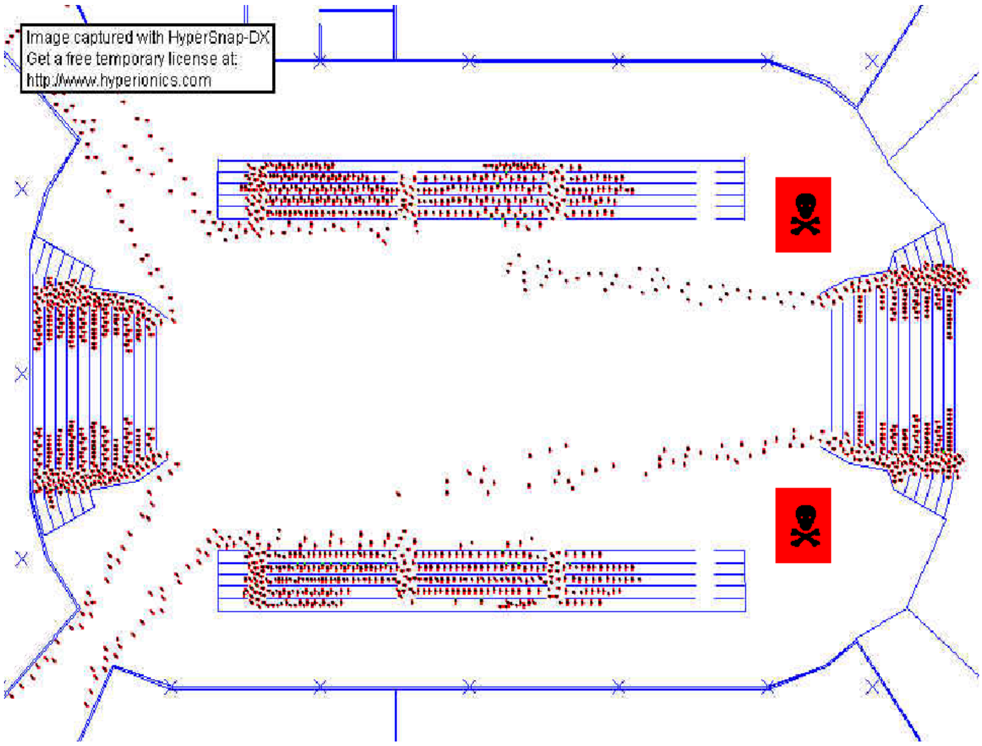


Fig. 14: A snap shot of the simulation process of Egress Scenario-2

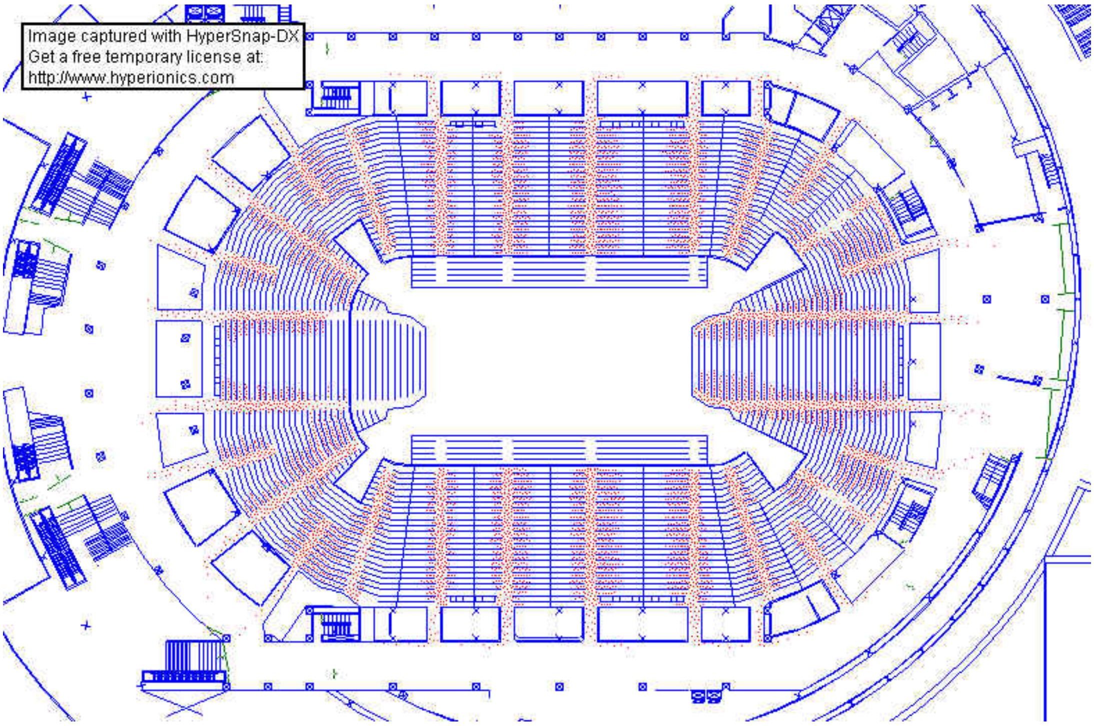


Fig. 15: A snap shot of the simulation process of Egress Scenario-3

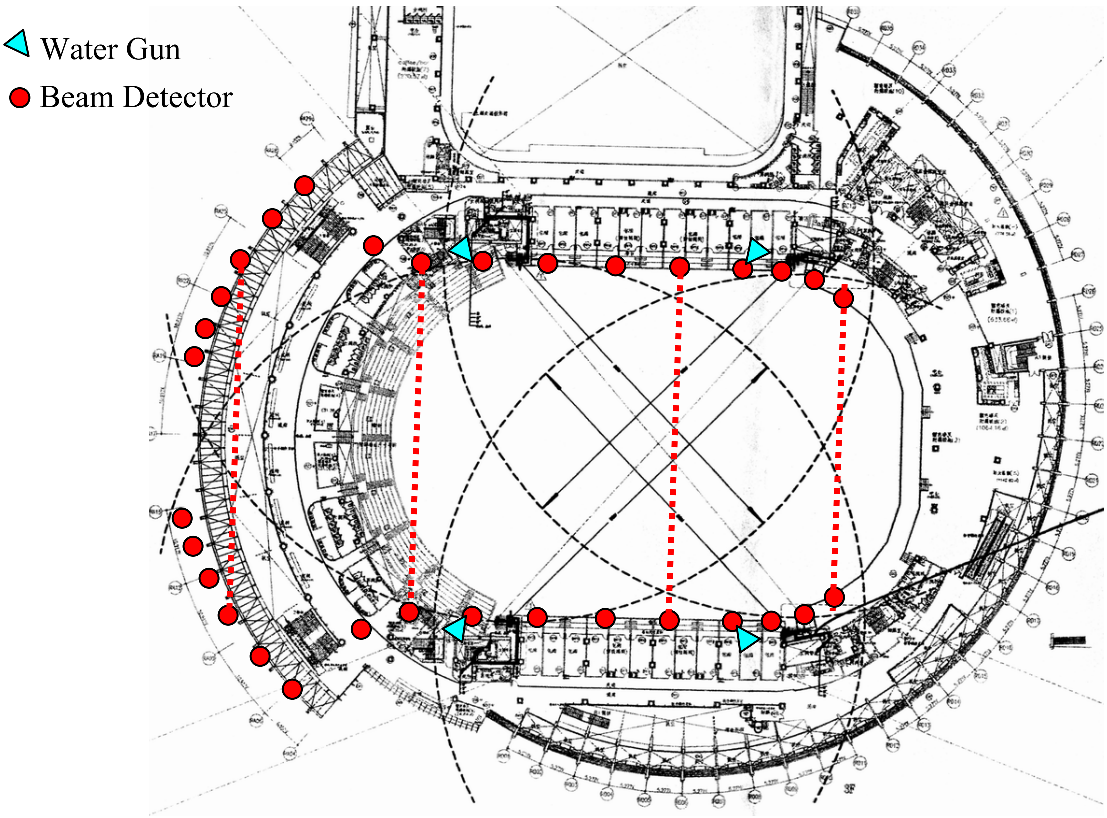


Fig. 16: A schematic diagram indicating the location of the long range water gun system and beam detectors

5. CONCLUSIONS

The 15,000-seat Taipei arena smoke management system was designed following a performance-based fire safety engineering concept. The 3D CFD simulation result indicated that a smoke-free escape route could be maintained to facilitate a safe evacuation of all audiences. The quantitative risk assessment further validated that, even in a most severe and least probable case, the smoke management system can provide a safety margin of over 100 % to safeguard the evacuee from smoke successfully.

REFERENCES

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