APPLICATION OF PERFORMANCED BASED DESIGN IN FIRE PROTECTION ENGINEERING

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ABSTRACT

Today's building and fire prevention codes are mostly prescriptive. Prescriptive codes are based on major fires in earlier years that created a need for specific building provision. These codes provide a minimum level of safety. As the general and engineering uses of computers have increased over the years, so has use of computers in the fire protection engineering. This has allowed fire protection engineers to develop alternative approaches to solve today's fire protection problems or to evaluate the performance of a specific fire safety goal.

A performance based approach to building and fire codes involves the following: 1) identifying specific goals, such as, safely getting out of the building in 10 minutes, 2) obtain conceptual approval from authorities, 3) define performance level, 4) develop design solutions and identify tools such as, fire tests, models, or methods, to demonstrate that a design will meet the fire protection objective 5) test solutions, 6) present test method and results to the authorities.

Some people in the fire protection community consider this to be nothing more than an intellectual exercise, while the others view it as a way to reduce expenses on large project.[4] Others in fire protection community view this as a way to refine the design process to design fire protection systems to better protect the fire hazards.

This paper will focus on application of these tools, specifically computer fire models, to actual cases such as: design of a smoke control system, heat transfer analysis and egress of building occupants during potential fires.

SMOKE CONTROL

In United States, the smoke control system requirement such as atrium smoke exhaust system and stairway pressurization system is written into the Model Building Codes. While, the design requirements are provided, the actual installation and design guidelines are lacking. This typically leads to wide variations in design and sometimes leads to systems that do not meet the design objective.

In this case, a performance based analysis should be provided to adequately design the smoke control system. One such examples is analysis of atrium smoke exhaust system for the Omaha Federal Courthouse. The design objective of this project was as follows:

1. To prevent migration of smoke from or through the atrium space to adjacent spaces.

2. To maintain the smoke layer above either the highest unprotected opening to adjoining spaces, or 6 ft (1.83 m) above the highest floor level of exit access open to the atrium for a period of at least 20 minutes, which is 6 ft (1.83 m) above Level 4 (See Figure 1).

The following engineering analysis consists of the following:

1. Identify design fires. This process consists of identifying areas where fire is likely to occur. Identifying the type of fuel package that may be present and develop appropriate rate of heat release curves.

2. Perform engineering analysis to determine how much smoke is generated from the design fire, what is the smoke temperature in the atrium, will the smoke generated by these fires stratify before it reaches the ceiling, and how long will it take for the ceiling smoke detectors to activate?

The engineering analysis will be analytical as outlined in BOCA National Building Code and NFPA 92B, and be computer based. The computer based analysis is to supplement analytical analysis in the areas where transient analysis is needed to review transient input fire data. This is done using FASTLite. FASTLite is a computer program developed by the National Institute of Standards and Technology (NIST). FASTLite is a three-zone fire growth and smoke transport program that is a simplified version of CFAST, also developed by NIST.

The computer based analysis is also performed to validate analytical results. This is done using FPETOOL. FPETOOL is a compilation of equations translated to a computer program by NIST.

Design Fire

The design fire is a fire that the smoke control system is intended to handle during an emergency. We have identified three possible fire scenarios or design fires that should be considered based on their use and arrangement of combustibles. The design fires are as follows:

- Design Fire 1 (DF1) - a steady state fire in the center of the atrium on Level 1.
- Design Fire 2 (DF2) - an unsteady state fire in the center of the atrium on Level 1.
- Design Fire 3 (DF3) - an unsteady state fire in the lobby security check point on Level 1.

The location of the design fires are shown on Figure 1. The heat release rate curves for the design fires are shown in Figure 2.

Smoke Production Rates

For a steady state fire, the amount of smoke produced is based on the height from the floor of the atrium to the critical level or smoke interface level. In our case, the critical level, Z, is 59 ft (18 m). Also, smoke production is dependent on the size of the fire in terms of its rate of heat release, Q, a steady-state fire of 2,000 Btu/sec (2108 kW).

The interface level is above the limiting elevation, therefore, the following formula should be used for calculating the rate of smoke production, V(cfm).

$$V = 17.6Q_c^{1/3}\,Z^{5/3} + 3.36Q_c$$

$$V = 17.6(1400)^{1/3}\,(59)^{5/3} + 3.36(1400)$$

$$V = 180{,}714 \text{ cfm } (85{,}297 \text{ L/s})$$

Thus, the required rate of smoke exhaust, to keep the smoke layer at 59 ft (18 m) above the atrium floor for an indefinite period of time, based on a steady-state fire of 2,000 Btu/sec (2,108 kW), must be at least 180,720 cfm (85,297 L/s). This value was compared with computer program FPETOOL. The comparison of the results were found to be in good agreement.

Similarly for Design Fire 2 and 3, we calculated the smoke production rate to be 119,749 cfm (56,521 L/s) and 94,984 cfm (44,832 L/s), respectively.

Equation (1) shows that the volumetric smoke production rate is a function of $Q_c^{1/3}$ and $Z^{5/3}$. As anticipated, the reduction of HRR has a much smaller effect on the smoke production rate than does the limiting elevation (Z_1).

Atrium Smoke Temperature

The exhaust fans should be selected to operate at the design conditions of the smoke and fire. We calculated the atrium smoke temperature by using the Atrium Smoke Temperature program in FPETOOL for the steady state fire in the atrium on Level 1.

Using this program, we calculated the atrium smoke temperature for each of three cases. The atrium smoke temperature for the DF2 and DF3 is based on using the peak HRR as the steady state HRR. The printout of the results are shown in Appendix B. The results are as follows:

- Design Fire 1 - the temperature increase is approximately 13°F (7°C).
- Design Fire 2 - the temperature increase is approximately 6°F (3.4°C).
- Design Fire 3 - the temperature increase is approximately 4°F (2.2°C).

For the DF2 and DF3, we compared the above results with the results of the FASTLite simulation with the atrium smoke temperature. This showed that the peak atrium smoke temperature is approximately 16.2°F (9°C) and 3.6°F (2°C) respectively.

While the temperatures vary between the two calculations, the smoke temperature in either case should not be high enough to effect the selection criteria for the exhaust fans.

Stratification of Smoke

Stratification occurs when air containing smoke particles is heated by burning material and, becoming less dense than surrounding cooler air, rises until it reaches a level at which there is no longer a difference in temperature between it and the surrounding air.

Using the following equation, we can see if smoke will reach the ceiling or stratify at some distance below the ceiling.

$$H_{max} = 74\ Q_c^{2/5}\ \Delta T_o^{-3/5}$$

where,

H_{max} = maximum ceiling height which a plume can rise (ft)
ΔT_o = difference between ambient temperature at the ceiling and ambient temperature at the level of the fire surface. (50°F)

therefore,

$$H_{max} = 74\ (1400)^{2/5}\ (50)^{-3/5} = 128 \text{ ft } (39.1 \text{ m})$$

Since H_{max} is greater than the ceiling height, the smoke is likely to reach the ceiling and not stratify prematurely.

An equation to calculate stratification of smoke under an unsteady state fire condition is not provided in NFPA 92B. Therefore, stratification of smoke can be calculated similar to calculation of the volumetric smoke production rate using the peak HRR as the steady state HRR for DF2 and DF3.

For DF2:

$$H_{max} = 74\ (425)^{2/5}\ (50)^{-3/5} = 81 \text{ ft } (24.6 \text{ m})$$

For DF3:

$$H_{max} = 74\ (215)^{2/5}\ (50)^{-3/5} = 60 \text{ ft } (18.3 \text{ m})$$

These calculations show that the smoke generated from DF2 and DF3 are likely to stratify, particularly during the growth phase of the fire's development. Therefore, beam-type smoke detectors could be provided at the intermediate level in order to improve smoke detection times. The effectiveness of the ceiling-mounted smoke detectors are discussed in the following section.

Ceiling Smoke Detector Activation

From the stratification of smoke calculation, we determined that smoke is likely to reach the ceiling for DF1. Next, activation time of ceiling mounted spot-type smoke detectors will be calculated to see if they activate early enough to initiate a building alarm and notify occupants to evacuate while the exit access balconies are still usable.

Using Equation 9 from Section 3-5.2.1 of NFPA 92B for steady state fires, the height above the fire at which smoke will be visible at the time ceiling smoke detector activation can be predicted:

$$z/H = 0.67-0.28 \ln [(Tq^{1/3}/H^{4/3})/(A/H^2)]$$

where,

z = height of the first indication of smoke above the fire surface (ft)
H = ceiling height above the fire surface (ft)
t = time (sec)
Q = steady state heat release rate (Btu/sec)
A = cross-sectional area of the space being filled with smoke (ft^2)

Using Equation 3 from Section 3-3.4 of NFPA 92B, the activation time (t) is calculated as follows:

$$X = 4.6x10^{-4}Y^2+2.7x10^{-15}Y^6$$

where,

$X = t\,Q^{1/3} / H^{4/3}$
$Y = \Delta T\,H^{4/3}/Q^{2/3}$
ΔT = temperature rise within the ceiling jet to activate the spot smoke detector (typically between 18 - 23°F per FPETOOL User's Manual, use 20°F in this case)

therefore, for Design Fire 1,

$Y = 20 * 95^{4/3}/2000^{2/3} = 249$
$X = 4.6x10^{-4} * 249^2 + 2.7x10^{-15} * 249^6 = 29.2$

$t = X / (Q^{1/3}/H^{4/3}) = 29.2 / (2000^{1/3}/95^{4/3}) = 1004$ sec or 16.7 min

therefore, using equation (6),

$z/H = 0.67 - 0.28 \ln[29.2 / (3767/95^2)] = -0.5194$

$z = -49$ ft (14.9 m)

This calculation shows that a smoke layer completely fills the atrium and more before the smoke detector activates.

Using the DETACT QS algorithm in FPETOOL, we verified the above calculation (See Appendix B). Using ambient room temperature of 68°F (20°C) and a smoke detector device rating of 88°F (31°C), we saw that the smoke detectors will not activate under this condition. This agrees with the above calculation which shows that spot-type smoke detectors installed at the top of the atrium would not be effective.

Design Fires 2 and 3

For DF2 and DF3, the activation of ceiling smoke detectors were analyzed by directly inputting smoke detectors within FASTLite. FASTLite showed that for both DF2 and DF3, the smoke detectors located at the top of the atrium were not effective in detecting both fires.

Therefore, beam-type smoke detectors should be provided at an intermediate level to detect DF1, DF2, and DF3. Since the possibility of fire from the upper level above the location of the beam detectors exists, beam-type smoke detectors should also be considered for the top of the atrium.

Results

Based on the above analysis, we calculated the smoke production and smoke exhaust rates, temperature of the upper layer, smoke stratification and smoke detector activation.

HEAT TRANSFER ANALYSIS

As stated earlier, today's building codes are mostly prescriptive. Therefore, a need for heat transfer analysis is seldom needed during a building development. One such case where this type of heat transfer analysis was needed was in a fire effects theme show at an theme park. This theme show was developed as a walk-through show experience, moving 200 guests through the building every 6 minutes. The show sequence include a queue, a pre-show assembly area and fire effects scene. The principal show experience occurs in fire effects scene. During which major fireballs erupt in front of the guests. The smaller fire effects from the continuous burning flames are on throughout the show.

Our analysis for this building consisted of calculating the effect of the flames on the occupants and on the enclosure, including, upper layer temperature, sprinkler activation and smoke layer decent.

Affect of Radiative Heat Transfer on Guests

The calculation of affect of flames on the guests consist of calculating the radiant heat flux impinging on the guest closest to the largest flame. The conductive and convective mode of heat transfer can be neglected for this analysis.

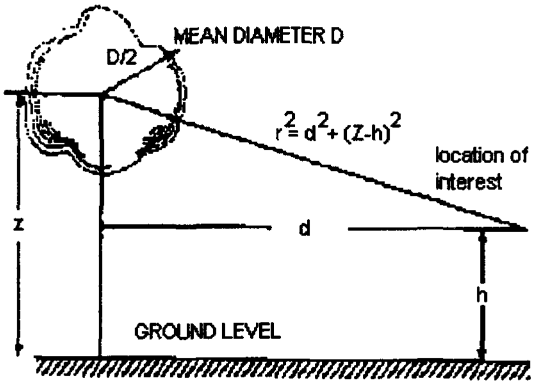
Because the fire effects occur independently over short duration, we calculated the effect of large flame balls from Fireball #1 and Lamp #1 (large fire lamp with fireball) only. The effect of other fireballs are similar to these fireballs were not calculated, as these fireballs. Our calculations are based on the empirical correlation for fireballs found in Section 3, Chapter 11 of The SFPE Handbook of Fire Protection Engineering, 2nd Edition.

The estimated radiant heat flux as a function of time at any radial location in the vicinity of the fire ball is given as (see Figure 3-11.36 of SFPE Handbook on next page),

$$q'' = \frac{\bar{v} f \tau g^{1/2} \rho h V^{5/6}}{4\pi((d^2 + (Z-h)^2)}$$

where,
q'' = heat transfer rate (kW/m^2)
$\bar{v}$ = normalized heat transfer rate (0.17, most conservative from Table 3-11.15)
f = fraction of combustion energy radiated to the environment (0.2 per handbook)
τ = atmospheric transmissivity (this value varies but can be assume to be 1)
g = gravitational constant (9.8 m/sec^2)
h = heat of combustion (50,000 kJ/kg)
V = volume of fuel (m^3)
d = horizontal distance to the location of interest (m)
Z = height to the center of the fire ball (m)
h = height above ground level of location of interest (m)

Note: Natural gas is used for the flame effects. Natural gas is approximately 94% methane. Therefore, the properties of methane were used in our analysis.



Schematic Diagram of Fireball Radiation Model
From Figure 3-11.36 of SFPE Handbook

For Fireball 1, the total mass of fuel used is 107.10 scf (3.65 kg). Therefore, the volume of fuel can be calculated as

$$V = M / \rho = 3.65kg / 0.7161 {}^{kg}\!/_{m^2}$$

Using the above values, we calculated the radiant heat flux as

$$q'' = \frac{\bar{v} f \tau g^{1/2} \rho h V^{5/6}}{4\pi((d^2 + (Z-h)^2)} = \frac{0.17 * 0.2 * 1 * 9.8^{1/2} * 0.7161 * 50{,}000 * 5.1^{5/6}}{4\pi(7.62^2 + 6.1^2)} = 12.5 {}^{kW}\!/_{m^2}$$

The time required for pain when exposed to radiant heat flux can be calculated as

$$t_p = (35/q'')^{1.33} = (35/12.5)^{1.33} = 3.95 \text{ seconds}$$

Since, the duration of the heat exposure is 2 seconds and the time when the pain starts to increase on a person is approximately 3.95 seconds. The guest in the Temple Scene should not be affected by the fire balls.

Similarly for Lamp 1, we calculated radiant heat flux as

$$q'' = \frac{\bar{v} f \tau g^{1/2} \rho h V^{5/6}}{4\pi((d^2 + (Z-h)^2)} = \frac{0.17 * 0.2 * 1 * 9.8^{1/2} * 0.7161 * 50{,}000 * 1.063^{5/6}}{4\pi(3.05^2 + 6.1^2)} = 6.72 {}^{kW}\!/_{m^2}$$

and

$$t_p = (35/q'')^{1.33} = (35/6.72)^{1.33} = 9 \text{ seconds}$$

The total mass of fuel used by Lamp 1 is 21.77 scf (0.742 kg).

Above calculations show that the fire effects from fire ball effects should not have any harmful effect on the quests.

Affect of Convective Heat Transfer on the Enclosure

A second portion of the heat transfer analysis is the convective portion of the fires. The hot gases and products of combustion, i.e., convective portion of the flames, generated by the flames will affect sprinkler activation, upper layer temperature, smoke layer decent, etc. We calculated these affects using computer program FASTLite.

The engineering analysis consisted of developing the heat release rate and modeling the enclosure. Since, the large fireballs only occur over short duration, the cumulative effect of all the fires, including continuous burning flames, were neglected for the thermal radiation analysis. However, for the convective heat transfer analysis, the cumulative effect all fires must be considered.

Based on the net heat load data provided, we generated the heat release rate of all fires occurring in the enclosure. This is provided in Figure 3. The cumulative fire effects were inputted as a single source of fire. Therefore, the affect of the fire will be more severe than if the fires are distributed throughout the enclosure.

There are approximately 11,000 square feet of circular ground floor area. However, the smaller dimensions of Catwalk Level (68' by 112') at elevation 39 feet was used (see Appendix 2). This will simplify the modeling process and will result in more conservative results. To simulate the louvered openings above the intermediate level ceiling, the room was divided into two sections one on top of the other with 70% opening between the two rooms.

The effect of normal HVAC system of 150,000 cfm and general building exhaust system of 75,000 cfm were not included in the analysis. The effect of exhaust hoods over the flame effects were accounted in the reduced heat output to the room as provided. The fire was placed in the center of the room. The sprinklers were placed directly over the fire at the temple ceiling (elevation 39 feet) and at the building ceiling (elevation 79 feet). A typical commercial sprinkler with RTI of 180 $ft^{1/2}sec^{1/2}$ and 165°F was used.

The result of the simulations shows that the upper layer temperature of would not increase above 110°F and sprinklers should not activate. Also, the smoke layer height would not reach below 6 feet above the highest guest level.

The above calculations are based on calculating the upper layer temperature of the enclosure. The ceiling jet temperature, which is higher than the upper layer temperature, was not included in the above analysis. To calculate the effect of ceiling jet temperature on the sprinklers, we used the DETACT algorithm in FASTLite. This algorithm calculates the thermal response of a sprinkler located near the unconfined ceiling without any opening. Because, this algorithm account does not account for louvered openings, our calculations should be conservative.

The net heat load provided by the fire effects specialists of the show states that large continuous burning flames will have the biggest impact on the sprinklers. Since, these flames are symmetrical, only one was considered in our analysis. The input parameters are as follows:

- Sprinkler location - 8 feet from the center of Lamp 1. (as shown on sprinkler system design drawings)
- Ceiling height above the base of fire - 14 feet
- Sprinkler actuation temperature - 165°F
- Sprinkler RTI - 180 $ft^{1/2}sec^{1/2}$

The calculations show that with the ceiling jet temperature at 8 feet from the centerline of the plume is approximately 170°F. For the sprinkler closest to flames with an actuation temperature of 165°F, the sprinkler activated. When the sprinkler actuation temperature was increased to 212°F, the sprinkler closest to flame did not activate.

TIMED EGRESS

Egress requirement found in building codes are do not fit all buildings. While today's codes, such as smoke protected assembly seating requirements acknowledges that normal egress requirement will not be applicable to this type of occupancy. But, there are other instances where alternative approaches to prescriptive egress requirements are needed. One such cases is in large open areas where smoke can log before it will effect the occupants capacity to egress is increased. Therefore, in this type of conditions, timed egress analysis can be performed to determine the egress time in relation to the fire hazard.

One example of this type of analysis is the Samsung Museum of Modern Arts (SMOMA) Building. This building will consist of 9 stories above grade and 7 stories below grade (See Figure 4). SMOMA will contain exhibition spaces, bookstores, an auditorium, offices, and other public spaces. There are many levels of galleries that are interconnected. The building as designed will not meet the compartmentation requirement found in the Korean Building Code.

The travel time to a safe place was determined with an EVACTNET+ computer egress model modified for MS Windows. The building is entered into the model as a series of nodes connected by arcs. Nodes represents areas where occupants could be and arcs represents the path of travel between nodes. EVACTNET+ then calculates the flow of people from node to node through arcs much the same way as hydraulic model calculates sprinkler flows.

The model was run for two scenarios. The fire had 1.2 m stairs width double doors at the discharge level. The second scenario had 1.5 m stairs two levels above and below grade and 1.2 m stairs elsewhere.

The time to exit an area or building can be estimated using the following equation:

$$t_{ev} = (t_{detection} + t_{notification} + t_{occupant\ response} + t_{investigation} + 2(t_{travel})$$

where,

t_{ev} = evacuation time
$t_{detection}$ = *fire detector response time (60 seconds)*
$t_{notification}$ = time from detection to notification (10 seconds)
$t_{occupant\ response}$ = time from occupant notification to occupant response (30 seconds)
$t_{investigation}$ = time to investigate the fire/collect belongings (30 seconds
t_{travel} = occupant travel time to safe time

The calculated travel time from EVACTNET+ has been multiplied by a safety factor of 2 to ensure that the calculated travel time is conservative.

The results of the timed egress analysis was then compared with time when the enclosure or building becomes untenable or hazardous to life. This time is denoted as t_{haz}, which must be greater than the evacuation time. These calculations were done using ASET-B and CFAST fire models for various of fire scenarios.

Once, the egress times were calculated, we compared this against the smoke exhaust rated required for each area to determine the level of protection that should be provided. Based on this we sized the stairs and the smoke control system. The results are shown in Table 1.

CONCLUSION

In United States, the performance based engineering has been gaining acceptance over the last few years. It is clear that many of today's new buildings will continue to be built using prescriptive building codes and many will incorporate performance based engineering. This paper clearly shows that there are many application of performanced based engineering and that these applications provide a valuable means of providing alternative to the prescriptive code requirements.

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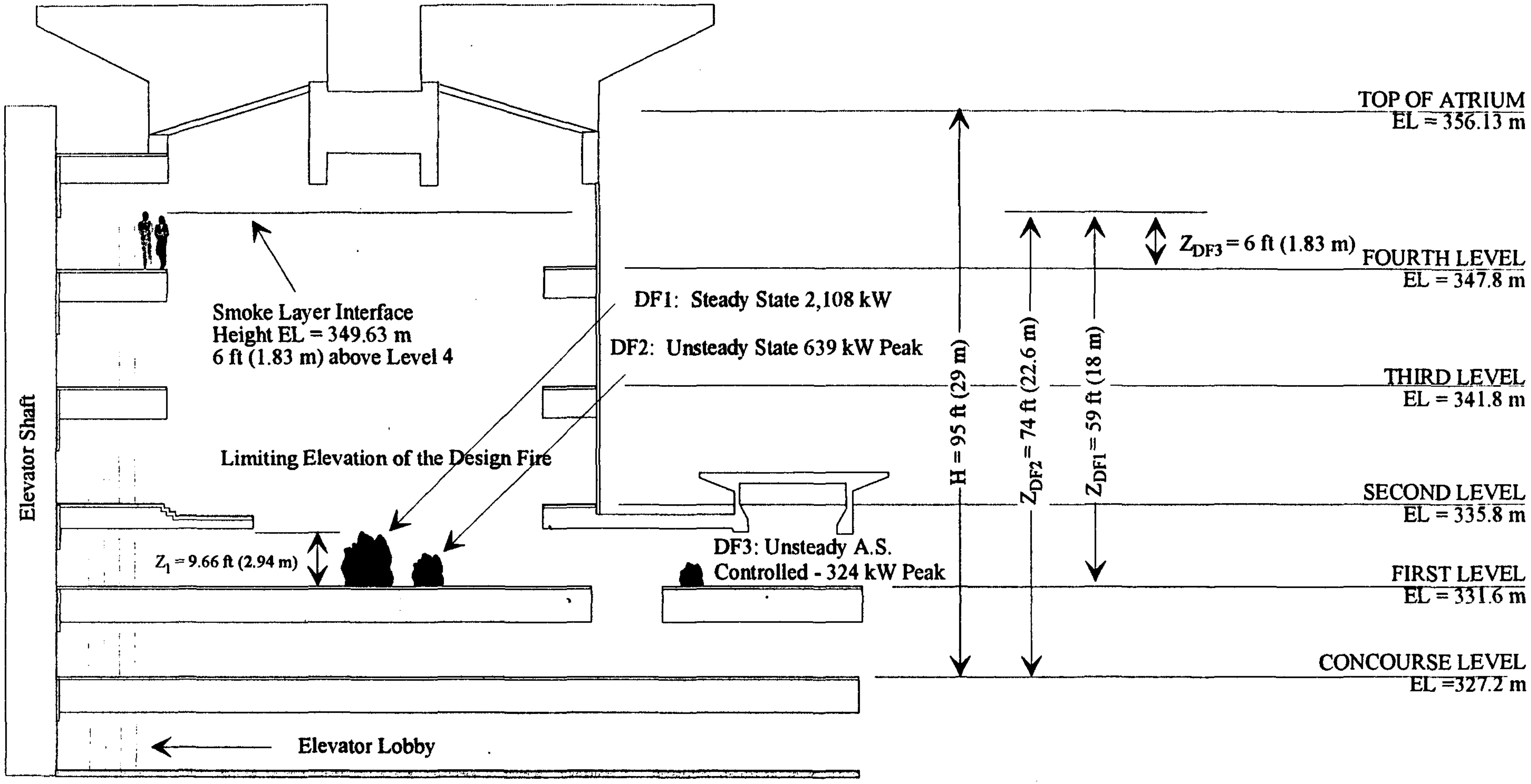

Note: The total gross area of the atrium is 3,770 ft² (350 m²) without including the area of the corridors open to the atrium. If the corridor open to the atrium is included, then the total gross area is approximately 5,600 ft² (520 m²).

Figure 1 - Building Section/Design Fires

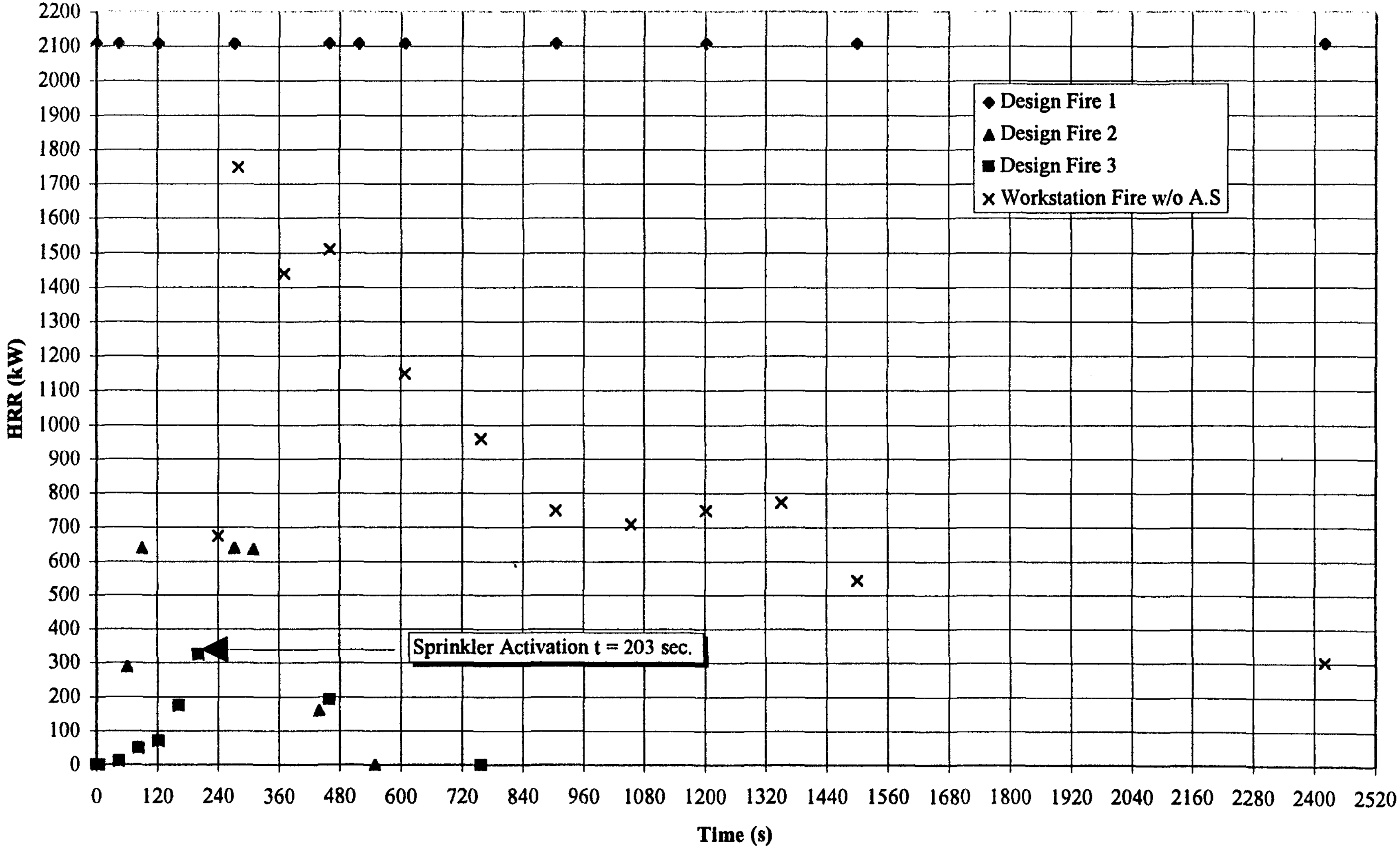

Figure 2. Heat Release Rate Curves

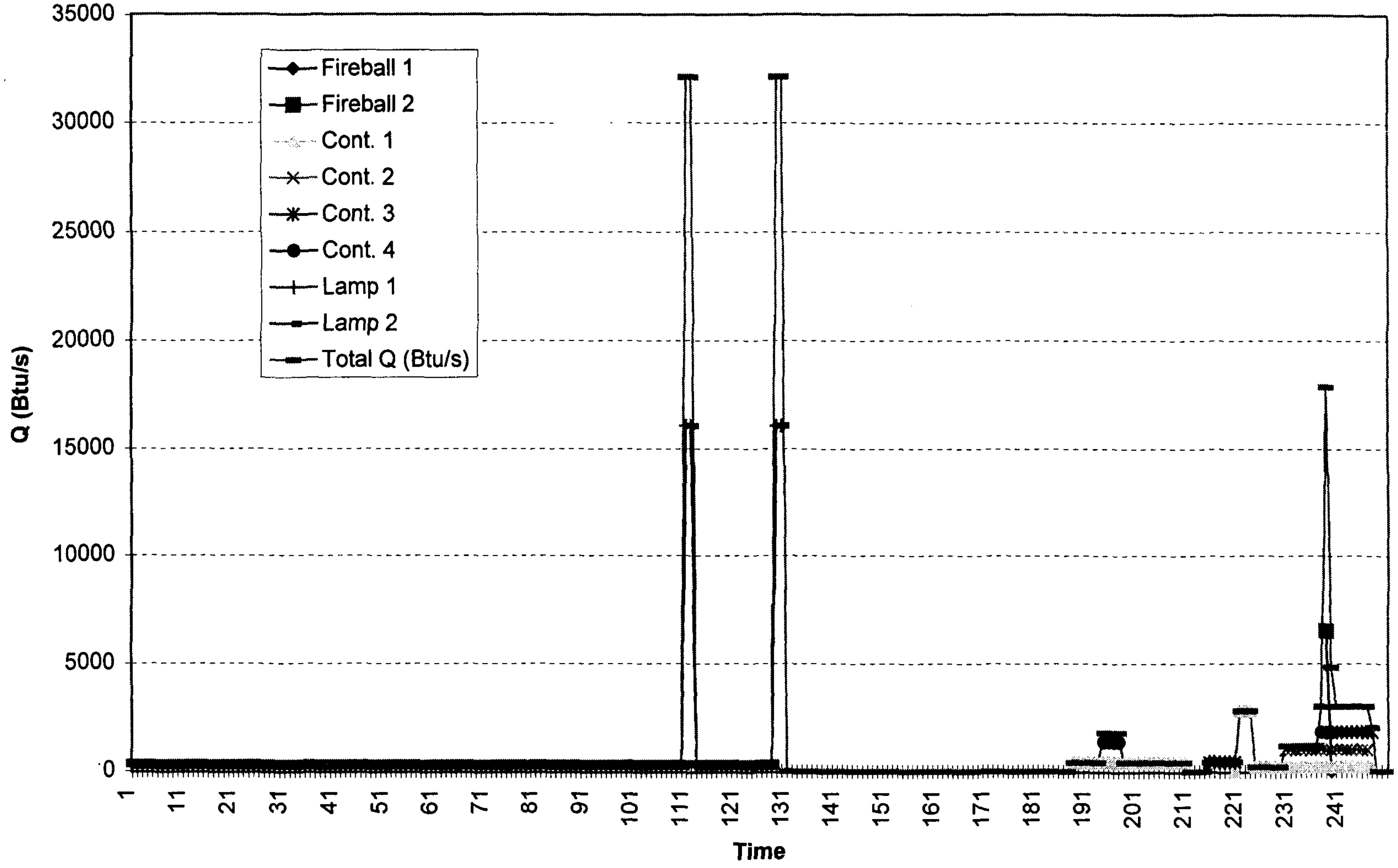

Figure 3. Fire Effects Heat Release Rate

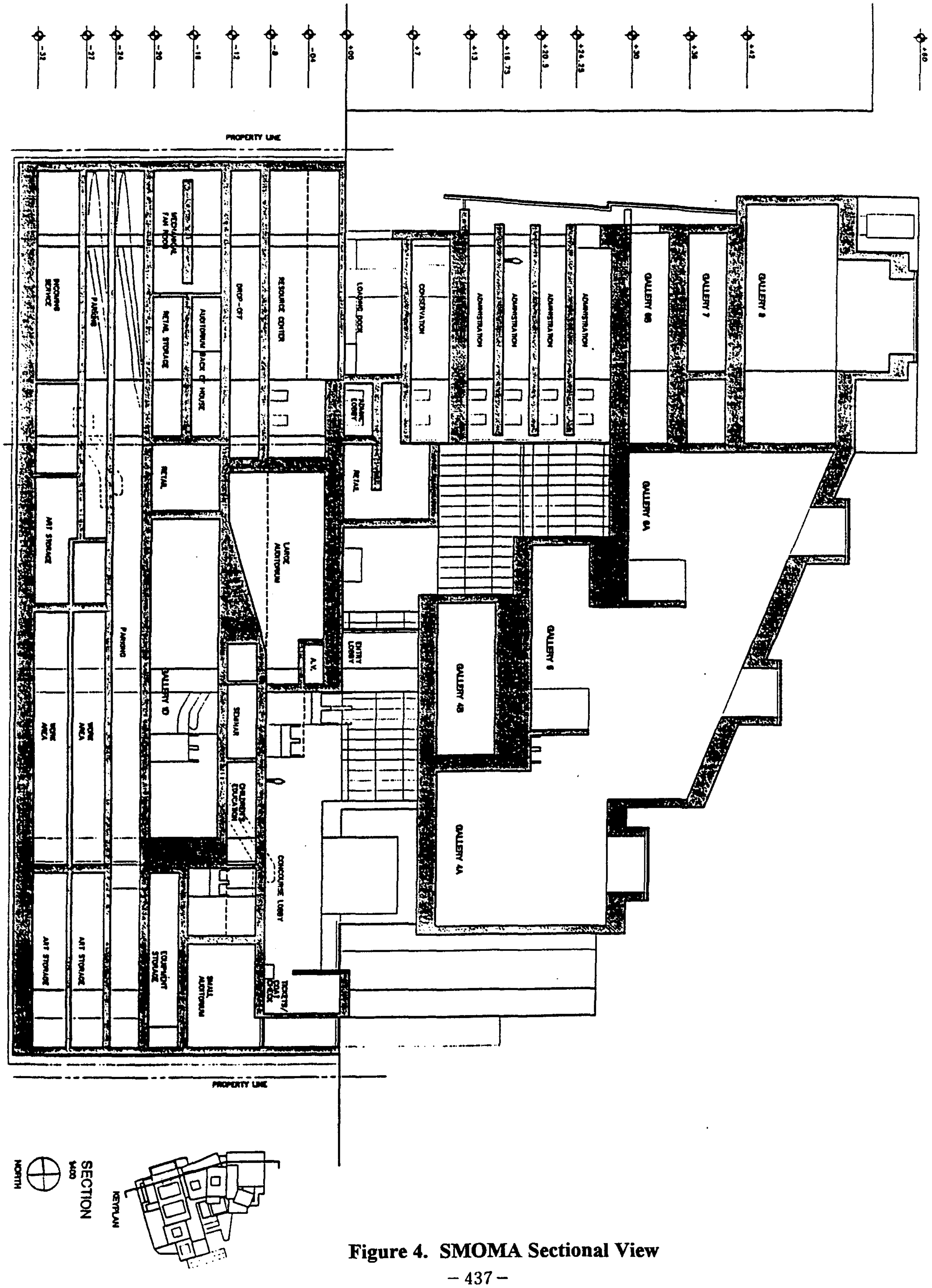

Figure 4. SMOMA Sectional View

TABLE: TIMED EGRESS, HAZARD ANALYSES, AND SMOKE CONTROL SUMMARY

Room	Floor Level (m)	t_w 1.2[1] (seconds)	t_w 1.5[2] (seconds)	t_{haz} (seconds)	Smoke Control		
					Static (m^2)[3]	Mechanical Exhaust (cfm)	Mechanical Supply (cfm)
Administration	+25	246	246	408		(10,500)[4]	2,500
Administration	+20	1,566	1,356	408		10,500	2,500
Administration	+17	1,536	1,056	408		10,500	2,500
Administration	+13	816	366	408		10,500	2,500
Gallery 8	+42	636	576	360	86	226,000	22,000
Gallery 7	+36	1,116	786	360	8.5	22,000	15,500
Gallery 6A	+30	1,506	1,380	1,080	10.5	27,500	19,250
Gallery 6B	+30	1,596	1,476	1,380	8.5	22,000	15,400
Gallery 5A	+20	1,506	1,236	540	10.0	26,000	18,200
Gallery 5B	+20	276	276	600	(14.0)	(37,000)	5,000
Gallery 4A	+10	2,046	**516**[5]	**420**	**19.0**	**50,000**	25,000
Gallery 4B	+10	1,926	**486**[5]	**420**	**15.5**	**40,000**	28,000
Gallery 3/ Lobby	0.0	665	665	500	235.0	600,000	12,5000
Gallery 2/ Concourse	-8	2,406	1,426				125,000
Auditorium Balcony	-14	1,656	696				125,000
Gallery 1	-20	2,196	2,046				125,000

1. The minimum time for all occupants to exit into a safe location based upon the current exit system design, which incorporates 1.2 m stairs.
2. The minimum time for all occupants to exit into a safe location based upon an increase in stair width by 0.3 meters for two levels above and below grade.
3. The minimum vent area to be located at the ceiling/roof in each space to provide equivalent smoke exhaust.
4. The parenthetic numbers represent the calculated exhaust which is no longer required due to the results of the hazard analysis.
5. Rooms with numbers bolded will not require smoke control if the exits are widened per t_w 1.5 and detection time is decreased with additional detection.