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MODELING FIRE SAFETY IN MULTI-USE, DOMED STADIA

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SUMMARY

Smoke control system design for domed, multi-use stadia is discussed. Two design fires were considered, one on the playing field, or the large open assembly area associated with a nonsports use of the stadium, and one under the stands, typically a fire in a concession. The open assembly area (playing field) fire included a tall fire plume which entrained a great deal of air. This resulted in diluted smoke arriving at the top of the dome, sometimes in concentrations which would pose minimal threat to occupants in the structure. Very large volume air movements were involved in venting this dilute smoke. A concession fire, under the stands on a concourse was simulated. Concourses usually loop completely around the stadium. Smoke flow laterally along the concourse, if controlled, can impact ventilation requirements. The movement of patrons to the exits involved bridges across the upper concourse. Smoke density at these bridges and/or the vomitories was a major design constraint.

INTRODUCTION

Over the past several years there has been an expansion in the development of multipurpose domed facilities for use by all types of sporting and assembly occupancies. This has been due to the large financial investment necessary to build these facilities, the recognition of the value of year-round controlled environments, and the ability to accommodate a wide variety of needs of the surrounding community. The financial rewards of increasing the use of such a large facility by providing a design which will accommodate multipurpose use is obvious.

In this paper, the design of fire safety measures is discussed for two of the more challenging out of six covered multi-purpose stadia so far examined. The six stadia varied in size (seating capacity) from 10,000 to 80,000 spectators. The larger stadia had sports playing fields sized for American football, and the smallest sized for basketball. The playing field of all stadia would be used, from time to time, for other sporting and non-sporting assembly events, including boxing matches, pop concerts, tractor-pulls, trade shows and dramatic productions.

The scale of large sports domes requires some orientation. In the largest studied (see Figure1), the height from the playing field to the underside of the dome at its center was 74 m (243 ft), and the volume over the playing field and seats (*i.e.*, exclusive of space under and behind the stands) was about 1,750,000 m^3 (61,552,000 ft^3). The oval concourse atrium surrounding the stands of the stadium was 29.5 m (97 ft) high and about 18.3 m (60 ft) wide

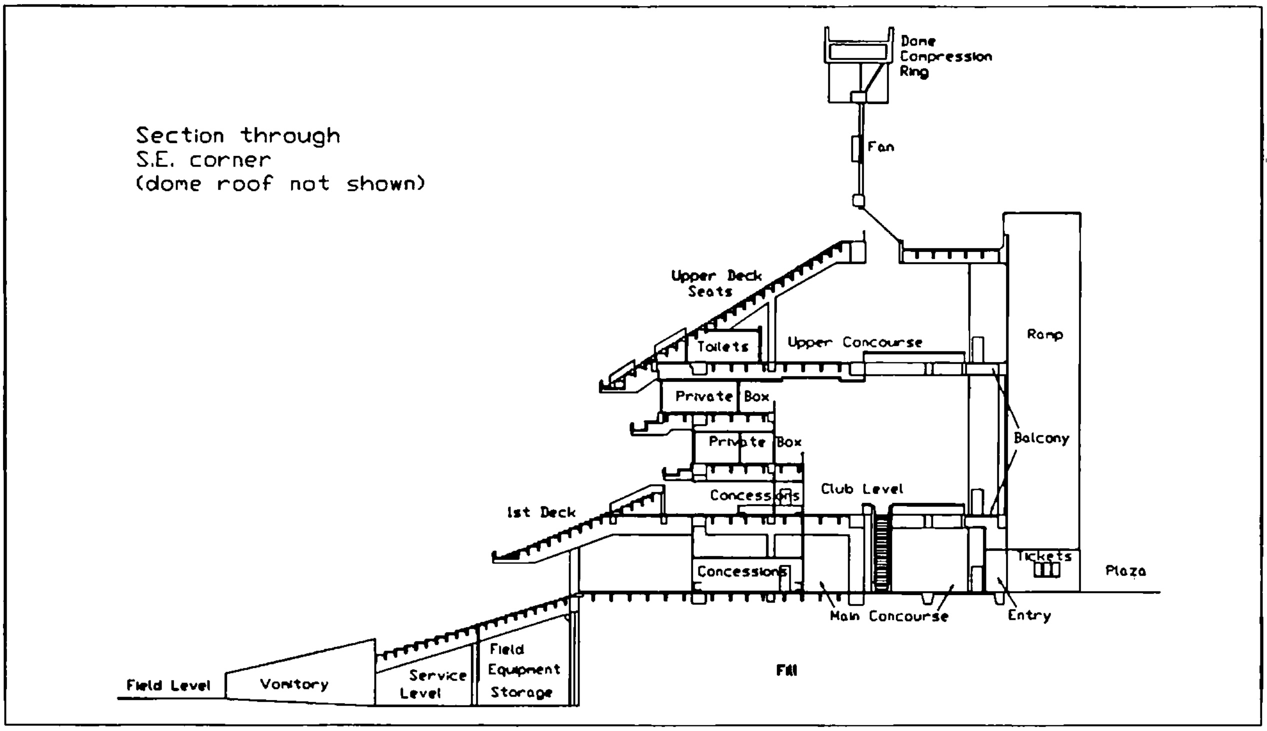

Figure 1 — Cross section through the S-E corner of a large stadium. The dome, a thin, semi-rigid membrane, is not included. The massive structure at the top of the wall is the "compression ring" which supports and takes the outward thrust of the dome.

outer wall. Figure 1 appears to show the concourse atrium cut off by two floors. However, these had large balustraded openings: on the "Club Level" to the right and below the word "Level" and on the Upper Concourse below the word "Concourse". At the ends of the Figure 1 building, the intermediate concourse levels became three levels of corridors connecting the two sides. Overall, the building measured 195 m (640 ft) by 250.5 m (822 ft). This stadium seated about 80,000 fans.

The second example discussed is a medium size stadium seating about 35,000 fans in main and upper deck seats (see Figures 2 and 3). The building is 130 m (425 ft) long by 94 m (310 ft) wide and 34 m (112 ft) high. The roughly 7.9 m deep dome trusses were slightly arched with their bottom chord 26 m (86 ft) above the playing field at their center span. Four smoke exhaust fan rooms were located within the box trusses at their ends. Retractable stands at the base of the main seating could be deployed for events not requiring the full playing field area.

The basic design of each stadium was similar: typically the playing field was surrounded on all sides by tiers of seats. Figure 1 is a cross section of a large stadium*. Smaller examples may lack private boxes and have only a single balcony above the main concourse (see Figures 2 and 3). Access to the playing field was via "vomitories" connecting to circumferential, service level corridors under the lower stands. Team rooms and storage areas opened off these corridors. The lower deck seating extended up from the edge of the field to a main concourse area behind the stands (see also Figure 3). Patrons reached these seats by descending aisles from the concourse. Partially

* Not shown on the drawing is the dome. This was a thin, semi-rigid membrane supported by the massive "compression ring" at the top of the wall. No drawing of the dome was available for use in preparing this figure.

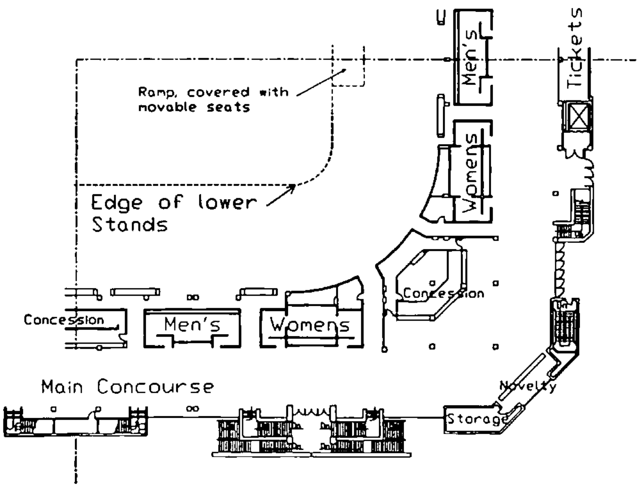

Figure 2 — SE quadrant of the concourse level of a 35,000 seat domed stadium.

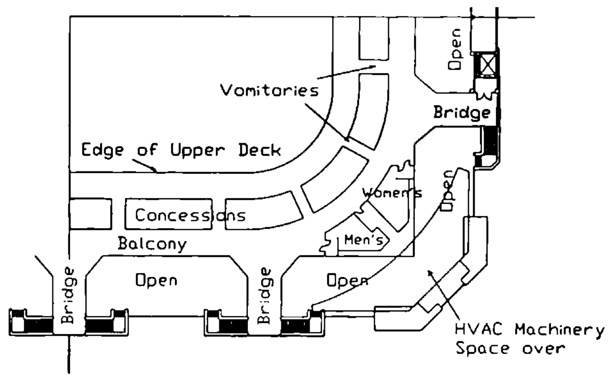

Figure 3 — SE quadrant of the balcony level of the concourse shown in Figure 2.

overlapping this was a second deck of seats. These seats were reached from a balcony above the main concourse ("Club level" of Figure 1; see also Figure 3).

Ramps (vomitories) provided access to the second deck seats. In the largest stadium, there were two levels of private "VIP" boxes above the second deck. These were reached by additional balconies. Upper deck seats overlapped the private boxes and extended up to the outer wall of the stadium. These were served by vomitories connecting to a separate, upper concourse.

One very small case studied was simply a rectangle of temporary stands erected on the floor of a convention center hall. For this, access to the seating was in from the four corners to the front (playing surface) side of the stands and then up aisles to the rows of seats.

The under-stands concourses and balconies included concession stands, toilets, press-rooms, and, in the larger stadia, hospitality suites and restaurants. Below the lower concourse and under the lower deck seating were utility rooms, team rooms, and storage space. In all cases, a shipping/receiving area and truck loading dock were features of the understands facilities. In several, access to the loading dock was circuitous, via a ramp or through a parking garage under a plaza area—under the main concourse (entry) level. Especially in the larger stadia, there was considerable excess space under the stands and at the ends of the building. This was given over to offices. The total office floor space for the largest stadium amounted to a sizable office building by itself. This was physically separated from the stadium proper and was treated separately.

Public entry and exiting was typically by stair towers or ramps outside the main building shell. Elevators and escalators inside the building shell provided additional vertical access. In large stadia, access to the upper deck seating was segregated from the rest of the stands by separate entries and stairs or ramps. Concourses, balconies, and under-the-stands areas circled

† The authors have not found any consensus in the United States for the size of such a residual fire in a sprinklered space. 5 MW is the size specified in Australian codes and is, apparently, also used in other parts of the UK.

**A fire on 20 July 1993 in the Atlanta-Fulton County Stadium fully involved three VIP boxes. They were not sprinklered. This stadium is not domed or covered. It has main and upper deck seating separated by a single row of VIP boxes. The fire vented primarily toward the playing field.

the entire building. Bridges connected balconies with perimeter exits. The space above the main concourse was not unlike the balconied atria found in many hotels. It consisted of a long oval.

Some domes were thin, rigid or semi-rigid membranes supported by poles and wires anchored to a compression ring at their edge. These included minimal additional features attached to the under side of the dome. Other domes were truss structures where the outward thrust of the dome was carried by the lower cords of the trusses. In several cases, the space within box trusses was used for HVAC equipment rooms, providing air exchange with the out-of-doors through louvered openings at the ends of the box truss. The possibility of fire in these equipment rooms, and thus close under the dome, required special consideration.

Two fire scenarios were considered. One involved the maximum size fire contemplated. It related to special structures and/or facilities on the playing field or open assembly area. In the case of a trade show set-up on the field, an exhibit, or block of exhibits, were imagined to have caught fire. For a dramatic production or concert, the temporary stage and scenery would be the fuel source. In other cases, temporary stands were considered the fuel source. These fires were on the playing field in front of the stands. Design fire sizes varied with the expected fuel load, but fires as large 12 m x 25 m (40 ft x 80 ft) consisting of two adjacent mobile homes and developing 50 MW, were considered. The fire plume extended up toward the dome, possibly stratifying before reaching its underside.

The second fire scenario was a fire in a concession stand or restaurant kitchen, which would have maximum impact on exiting occupants. Typically these spaces were sprinklered. It was assumed that the sprinklers would control, but not extinguish the fire. With the sprinklers still operating, a residual, 5 MW fire was assumed.† Smoke exited the concession into the concourse atrium and was assumed to move up to its ceiling. Whether smoke from a 5 MW residual fire in a sprinklered room would have sufficient buoyancy to do this is questionable. In both cases the smoke control problem was keeping the vomitories, concourses and bridges smoke free until complete evacuation by occupants to the perimeter stairs or ramps could be effected.** In the case of the playing field fire, smoke trapped under the dome should not accumulate to a depth were the smoke layer would impinge on patrons in the upper deck seating. Once the patrons had evacuated, the smoke layer could fill to below this level. The model parameters used allowed this to happen. Thus the smoke filling and evacuation envelopes set the smoke control parameters.

Fire on the Playing Field

Zone fire models of stadia required 20 to 50 or more total rooms. Of these, the space over the playing field or assembly area was usually treated as a single large "room." (However, in one case not discussed here, asymmetry of the proposed ventilation scheme precluded so simple a treatment.) The domes were ventilated and air conditioned. Because of the stage in the building design during which the smoke control studies were done, firm information on the HVAC system was not always available. In particular, the location of inlets and returns, the amount of thermal stratification expected and other design parameters would depend on the smoke control modeling results and had not yet been set. After preliminary smoke control modeling and discussions with the building design

†† The McCaffrey plume typically entrains more than the Cetegen plume. Thus temperatures calculated using the McCaffrey plume will be lower than for Cetegen's. If failure of the smoke to penetrate a pre-existing stratification and reach the top of the dome is an issue, it is conservative to use the algorithm giving the lower temperature.

team's HVAC specialists, vertical temperature profiles were picked and the plume rise calculated. In some cases the fire plume could not be expected to reach the top of the dome, or the top of the under-stands atrium, until after the fire had been detected and the ventilation system re-configured for smoke control. In the smoke control mode, enough gas was extracted from the upper part of the space to draw the smoke up and out. With the larger stadia, the height of the plume meant that a very large volume of air would be entrained. The diluted and cooled smoke had to be exhausted if the smoke layer height was to be controlled. Often dilution so reduced the smoke concentration and temperature that the "hot, smoky upper layer" of a two-layer zone fire simulation was neither hot nor smoky. Where upper layer smoke densities were as low as 5%/m (1.5%/ft), it seemed no threat. How to proceed in these cases needed discussion with the Authority Having Jurisdiction.

In several cases, major changes were needed in the under-stands design to insure that, with the exhaust fans fully on, there would be sufficient fresh air entry to avoid an excessive under-pressure in the stadium and accompanying high roof load.

Air-support domes are used on some large stadia. As yet, the authors have not been asked to study any of these. There are at least two additional constraints on the designer for air-support domes: (1) smoke evacuation must be accompanied by sufficient forced air supply to maintain a positive pressure under the dome and (2) the dome membrane must not be burned through. Usually the dome will be so high above the playing surface that flames even from a very large fire will not reach it and entrainment will have cooled the fire gas so that heat should not be a problem. Of course, these features must be confirmed.

McCaffrey's correlation of experimental data[1] for plume center-line temperature rise is

$$\Delta T = 21.6\,(Z / Q^{2/5})^{-5/3} \qquad (1)$$

where

ΔT = temperature rise along the plume center line [K]

Z = height above the fire base [m]

Q = fire size [KW]

This can be used to estimate whether the plume will penetrate to the top of the dome.†† If the design fire on the playing field is 50 MW, the temperature rise 70 m above the fire is predicted to be 25°C. This is enough to insure plume penetration through any pre-existing stratification so far encountered by the authors. If the fire were only 5 MW, the predicted temperature rise would be 5.3°C. For this size fire and height, penetration to the roof is not a sure thing based on HVAC design estimates for the stadium in question.

To estimate the upward flow induced by the fire plume Cetegen[2] equation 4.17 can be used. After rearranging the terms to simplify its application in the present context, it is

$$m / Q^{1/3} = 0.21\,(\rho_{\infty}^{2} g / C_p T)^{1/3} Z^{5/3} \qquad (2)$$

where

m = mass flow moving up in the plume [Kg/s]

ρ_{∞} = density of ambient air [Kg/m³]

g = acceleration of gravity [m/sec²]

C_p = specific heat of air [KJ/Kg-K]

T = Absolute temperature of ambient air [K]

† Japanese experimental data shows that the Cetegen plume gives better results than the McCaffrey plume for large fires and plumes extending well above the flame tip. However, one must be careful to use the appropriate Q^*.

Z = height above fire base [m]

Q = fire size [KW]

The constant, 0.21, was chosen by Cetegen to agree with his experimental data.‡ Slightly different values (+/- 20%) can be found in the literature. The bracketed quantity on the right hand side is a constant with the value $0.05074^{1/3} = 0.3702$ [Kg/sec-$KW^{1/3}$-$m^{5/3}$]. If Z = 70m the right hand side is 91.195. For a 50,000 KW (50 MW) fire, m = 3,360 Kg/sec or about 2,800 m^3/sec (5,933,000 cfm). Reducing the design fire to 5 MW reduces the flow by a factor of 2.154 (*i.e.*, the plume flow is a weak function of fire size.) But, for the 50 MW fire, the stadium would probably be being used for a trade show. In this case, the upper deck stands would not be occupied. Thus it should suffice to keep the smoke layer above the top of the upper deck vomitories. This would prevent smoke from entering the upper part of the concourse, which might be occupied. For the stadium in question, the top of the vomitories is only 33 m above the field and the plume flow at this height is only 800 m^3/sec (1,700,000 cfm). In order to meet the code requirement for "smoke protected seating," the approving agency required that the smoke be kept at least 6 ft above the top

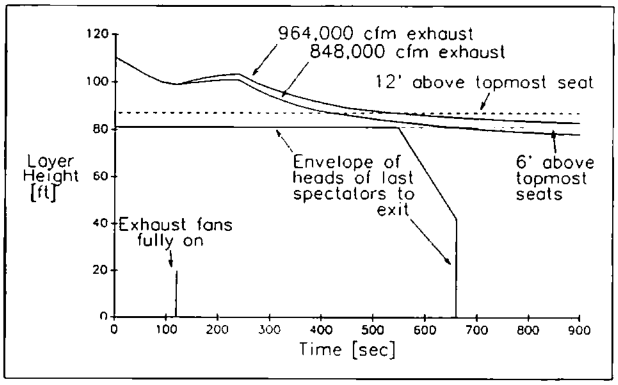

Figure 4 — Layer height versus time for a t^2 fire reaching 20 MW at 660 seconds, Exhaust fans come on at 75 seconds and reach full power at 120 seconds. Also shown is the envelope of the heads of the highest patrons as predicted by EVACNET.

of the upper deck seats until a hypothetical evacuation of the fully occupied stands could be effected. This meant (a) using an evacuation algorithm (EVACNET, [3]) to plot the height of the last exiting patron versus time and (b) keeping the smoke above his head. This translated into keeping the smoke above 47 m for the first 15 minutes of fire. Full simulations, with BRI2, gave the transient descent of the smoke layer for various fan sizes. The resultant fan capacity was slightly larger than would have been needed to keep the smoke out of the upper deck vomitories in steady state.

The required exhaust flows seem very large. However, relative to the volume over the playing field, about 1,750,000 m^3 (60,000,000 ft^3) for the case used in the example of the last paragraph, they amount to less than three air changes per hour. HVAC systems often provide this much flow for a single room. In a stadium, considerably less can usually be provided and still maintain reasonable comfort for the patrons. Supply air entering at the rear of the top of the stands is directed out and down over the seating. Recirculation exhausts through louvered ports at the sides of the playing field. Exhaust from the top of the dome is provided to remove air heated by contact with the sun-warmed dome surface. This dome exhaust is small compared to the smoke control requirements. Smoke extraction is provided by extra roof fans (smaller stadium with box truss supported dome) or perimeter fans above the upper deck seating. (See Figure 1: "Fan" located on the wall below the "Dome Compression Ring." Fans were located at regular intervals all around the perimeter.) The smoke control fans did not, normally, operate as a part of the HVAC system. Extra air supply at the playing field level prevented the smoke control system from pressure loading the dome. This extra supply should not interfere with the HVAC exhaust. A convenient arrangement was to add louvered inlets near the base of the exterior walls and ducts leading to the top surface, rear of the field level vomitories. The needed air then entered the field through these vomitories.

Figure 2 shows combined EVACNET and BRI2 smoke layer modeling results. In this case the fire followed a t^2 growth reaching 20 MW after 660 seconds. The exhaust fans were set (BRI2 program input) to come on 75 seconds after ignition and reach full power at 120 seconds. After the exhaust fans came on, the smoke layer rose for a time. Later it resumed its descent. This was due to the steadily increasing fire size. The fan capacity had been selected to control the smoke from a larger fire than existed when the fans first came on. As the fire grew, it gradually caught up to the fan capacity and the layer descended to a height where the plume entrainment matched the exhaust capacity. The delay time between fire detection and activation of smoke control measures is obviously important. Finding a realistic delay time is not always easy. References to fire experience, as reported in the literature, suggests a very wide range of actual times. It is not always encouraging when compared with estimates proposed by the building's managers and/or the Authority Having Jurisdiction. The run-up time for the fans intended can usually be supplied by the HVAC engineers. These numbers are firm once the fans sizes have been agreed upon.

EVACNET allows estimation of the progress of stadium evacuation. The EVACNET results, a height versus time rectangle with one corner clipped, reflect three evacuation episodes. The exit path for patrons in the upper deck seating is up to the vomitories for those seated toward the lower edge of the stands, and down for those seated towards the top of the stands. The first people to exit will be those closest to the vomitories. Due to crowding of the aisles, those at the top will not be able to move from their queuing location as the aisles will be filled by those below them. (This assumes they will not move down by climbing over the seats to lower rows.) The delay in their movement is represented by the horizontal top of the evacuation rectangle (episode #1). Once the aisles are free, those in the top row of seats can begin to move. Their steady descent is reflected by the clipped corner of the rectangle (episode #2). Finally, when the stands are emptied, there is an abrupt end to this phase of the evacuation (vertical edge of the rectangle at 660 seconds, episode #3).

The single room representing the space above the playing field of the stadium shown in Figure 1 was modeled as eight vertically stacked slabs of varying thickness and cross section area. This allowed better transient representation of the descent of the smoke layer than if the room were considered to have a constant plan area. However, if a simulation program is used which does not allow variable room area with height, good values for the layer descent near one particular height, h, can be obtained, if the ceiling height and volume above the height, h, are correct.

Normal access to the largest stadium considered was via 40 double doors, 10 at each corner of the building (*i.e.* 80 doors in all). With 80,000 people to evacuate, this would average 1,000 people per door. With a desired evacuation time of 10 minutes, this meant 100 people per minute per door or nearly 2 people per second. It is easy to see that areas of refuge within the building would be a desirable feature. The refuge areas were actually the ramps leading down to the exit level. They were provided with emergency doors to the outside at their base. Smaller stadia had similar problems with, generally, similar solutions. (See perimeter stairs of Figures 2 and 3.)

Fire Under The Stands

Modeling a fire under the stands is not as simple as modeling an atrium fire, though there are strong similarities. The principal difference is in the "loop corridor" nature of the stadium concourses. The description which follows focuses on the 35,000 seat stadium. There is significant variation in the architectural treatment of the under-stands concourses of different stadia, requiring different modeling assumptions. Occasional references, below, to the large stadium highlight major differences in the otherwise generally similar smoke control treatment.

Figures 2 and 3 illustrate the under-stands concourse of the medium size stadium. In this case there were only two levels of stands. The concourse atrium was treated as a long corridor-like loop. Considering this as a single room was not satisfactory, as will be discussed below.

Access to the playing field was via four corner vomitories. These connected to corridors leading to offices, locker rooms and loading and storage areas under the lower stands. The under-stands spaces were at main ground level, 9 steps above the playing field. A truck loading dock served receiving and storage space slightly below the level of the field. Material could be moved directly to the field through a wide, upward sloping ramp at one end of the stadium, (See Figure 2). The ramp could be covered by removable (telescoping) stands. Additional temporary stands could be installed to encircle the field for events (such as basketball, ice hockey or concerts) that did not require the full field area.

The main concourse was entered from either end. One entry was "one floor" above grade, reached from a small exterior balcony served by stairs. The other entry was off a large elevated plaza. The plaza connected to other buildings of the total complex. The top of the lower deck seats were at the level of this concourse. From the concourse, patrons reached the lower deck seats via passages between lavatories and concession stands.

Access to the upper deck was via vomitories extending in from a balcony concourse (Figure 3). Bridges connected the balcony to 10 enclosed stair towers outside the main structural wall. These stairs could be used both for normal access and emergency exiting. Openings at the balcony level, between the bridges, made the under-stands area a single oval room 15 m (50 ft) high.

The balcony followed the oval of the field. In each corner roughly triangular lavatory complexes partially filled the space, resulting in a more rectangular plan form for the balcony level. A corridor passed between the lavatories and the rear of the upper stands. Above the lavatories were HVAC equipment rooms. These extended up to the ceiling and out to the exterior walls. Conditioned air supply ducts led off from these and louvered exhausts inlets were found on both sides of these trunks.

In the large stadium, as seen in Figure 1, the under-stands area was better described by two separate atria, one each along the longer sides. Cross corridors at each end connected these. End corridors on three floors, in addition to the main concourse level, were modeled in this case.

As with the larger stadium shown in Figure 1, due to the upward and outward slope of the upper deck stands, the space near the top of the concourse was narrower than at or below the balcony level. In the stadium of Figures 2 and 3, the width of the flat ceiling had shrunk to almost zero as the upper deck stands extended to the exterior wall.

No attempt was made to model the detail of the under-stands space. Gross changes around the concourse and balcony loops, such as the corner HVAC rooms described above, occurred in some stadia and did have to be considered. The challenge was to determine how smoke would spread laterally around the concourse annulus. Therefore, features which would effect the smoke spread had to be included. In addition, a fire room (typically a food concession space) was usually defined separately. The HVAC engineers wanted to be able to use as much of the normal ventilation capacity as possible for smoke control. The question was, could smoke be allowed to spread around the annulus without developing "deep spots". For the stadium of Figures 2 and3, smoke spread under the corner HVAC equipment trunks illustrates this. If smoke could safely be allowed to spread, intakes on both sides of the trunk could be used to exhaust smoke, and possibly exhausts still more remote from the fire could be used. The design criteria were: (1) the smoke layer should not fall below the top of the upper deck vomitories before control had been established; and (2) the lower gas layer should never become smoke contaminated above a low, prescribed level.

If the under-stands concourse is considered as a single room, as is often done with atria, several important aspects of the building design may be lost, but more important, the physics of the modeling process changes. Although the floor plans of Figures 2 and 3 show only one quadrant—implying four-fold symmetry—none of the stadia were strictly symmetric. The differences were usually large enough that they had to be included. In the case of Figures 2 and 3, the constrictions at the corners suggested dividing the concourse annulus into eight rooms: the two sides, the two ends, and the four lower ceilinged corners. In this case, the asymmetry related to the ticketing and entry features and resulted in differences between the two ends.

As soon as the modeling moves from a single room to multiple rooms, even though the rooms may be at the same level, smoke flows change because of inter-layer mixing which occurs at the room-to-room vents. Some single room models, such as FIRST[4,5], include recirculation at the vents, but, where the vent is to an adjacent room—as distinct from the outdoors—the mixing is much more complex. Where it is included, for example in BRI2[6], it is based on physically plausible algorithms which are supported by little experimental data. Most of the data available to check these algorithms shows elevation of the lower layer temperatures above ambient. But lower layer temperature data reflects not only mixing but also (1) radiation heating of the floor and (2) associated convective heating of the lower layer gas and, perhaps more important, (3) radiation absorption by the lower gas layer due to smoke contamination of the layer. Thus the quality of at least three algorithms condition the resultant lower layer temperature prediction. Smoke (opacity) data would be a more straightforward check of the mixing algorithm, but often it is much less detailed than temperature data and proportionately less useful.

The important point is that mixing may sufflciently pollute the lower gas layer that the hot-cool interface height may not be the limiting design criterion. The lower layer smoke density may be the limiting quantity. For this reason, it would be very desirable to have better experimental confirmation of inter-layer mixing algorithms.

Where the prediction shows noticeable pollution of the lower gas layer, a limiting smoke density needs to be agreed upon with the approving authority. A starting point might be somewhere around 0.03-0.07/m (1-2%/ft)—the alarm point of many smoke detectors. Jin[7] provides data suggesting 0.6/m (18%/ft) is the smoke density at which travel speed begins to be influenced. This ten-to-one range provides considerable room for maneuver.

Once the decision has been made to subdivide the concourse level into a number of connecting rooms, the question becomes, how many rooms. Where there are natural "choke points" (such as the combination of corner wash-rooms, concessions and HVAC equipment rooms already mentioned), subdivision at these points is obvious. However, it is not necessary that the choke points be prominent. Typically there are deep beams supporting the seating decks. (Figure l) These may be a significant impediment to gas flow around the concourse annulus and should be accounted for, as should the obstruction to flow of other irregularities of the annulus. Idelchik[8] provides tables and charts useful for determining the effective pipe flow resistance of a wide variety of structural elements. Where the concourse is to be divided into a number of "pseudorooms," the overall resistance to flow around the annulus is calculated. The desired number of rooms is then chosen and the inter-room vents sized so that the pressure drop for uni-directional flow around the loop is that calculated for the equivalent pipe. There is scant experimental data for multi-room fire gas flows. There is almost none against which to test the above subdivision of a long corridor-like room. The authors' experience using this kind of subdivision with BR12[10] is that, if the walls are smooth—plaster board with no beams—there may be numerical difficulties.

On the other hand, if the pseudo-room-to-pseudo-room connections have an effective area times flow coefficient not much larger than the room cross section area times a flow coefficient of 1, the program is numerically stable. When the program is stable, the results of pseudo-room subdivision appear reasonable. Where there are prominent beams, exposed columns and embedded structures, as is typically the case under stadium stands, this proviso is easily met. The number of pseudo-rooms to use depends on the overall complexity of the building. In the case illustrated by Figures 3 and 4, five rooms were used for the sides and three for the ends. Thus twenty rooms represented the entire concourse loop.

Because of the narrowing toward the top of the concourse space, a simulator such as BRI2 is advantageous. Optional features of BRI2 allow expressing the changing room area with height. This better models the descent of the smoke layer in the roughly triangular cross section space at the top of the concourse. Where the narrowing is extreme, it is sometimes useful to use two vents, one above the other, to connect adjacent pieces of the concourses (pseudo rooms). The upper vent is made narrower than the lower one. The combined throttling of the two vents is, of course, adjusted to give the proper overall value. The use of two vertically stacked vents improves the representation of the lateral smoke spread.

Figures 5-7 show the smoke filling of the 20 room simulation of the stadium shown in Figures 3 and 4. Figure 5 is ten minutes after the fire started. The fire room is

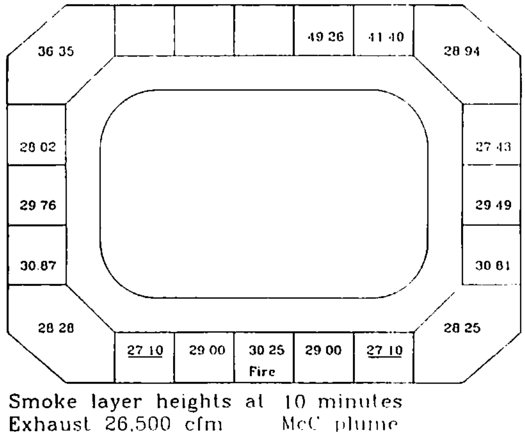

Figure 5 — BR12 simulation of the smoke filling of the concourse shown in Figures 2 and 3. 10 minutes after starting an impulsive, 5 MW fire.

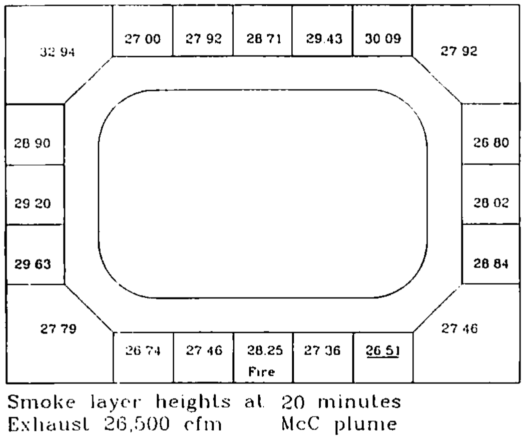

Figure 6 — Same as Figure 5 after 20 minutes.

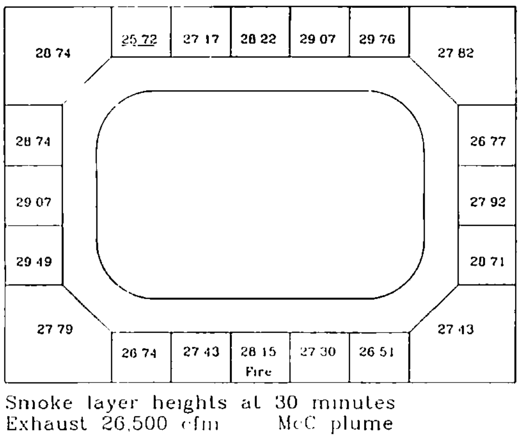

Figure 7 — Same as Figure 5 after 30 minutes.

indicated by "Fire." Smoke layer heights above the concourse floor are given. The underlined number is the lowest smoke layer height. Exhaust is from either side of the four corner rooms. The exhaust vents are not assigned to the corner rooms of the simulation because they are high on the vertical face dividing the corner from the adjacent rooms. They are assigned, one each to the pair of rooms either side of the corner.

Prior to 10 minutes, smoke layers developed in the five rooms closest around the fire. Due to the low ceiling of the corner rooms (under side of the HVAC equipment rooms) smoke could not, at first, pass the corners. When the smoke layers became deep enough, smoke flowed under the two corners into the ends. Because the ends differed, the ends filled at a different rate. Figure 5 shows the situation shortly after smoke had passed the remaining two corners.

The smoke layer over the fire was hot and thin. As the smoke flowed away from the immediate vicinity of the fire it cooled—due to radiation loss and contact with the cool walls. The smoke layer became progressively cooler and thicker as it moved away from the fire. At the corner it spilled under a soffit and there was a higher interface beyond this.

Figures 6 and 7 are similar sketches for 20 and 30 minutes after the fire start. At 30 minutes filling of the entire upper concourse was approaching steady state. The coolest gas and lowest smoke layer were nearly opposite the fire.

SUMMARY

Several aspects of the analysis should be emphasized.

- For fires on the playing field or assembly area, heights and thus plume lengths are large. As a result, smoke reaching the upper part of the stadium may be very dilute and cool—in some cases, so much so as to pose minimal hazard. These cases should be discussed with the Authority Having Jurisdiction before expensive smoke control measures are recommended.
- For fires under the stands—atrium like conditions exist, and engineered smoke control measures successful in atria should be considered. However, open bridges crossing the atrium space to connect the seating with exits set against the exterior walls must be protected.
- Fire originating under the stands may vent into the concourse (for example, food concessions) or may vent into the seating area (fire in a VIP box). Where the fire vents into seating areas, local evacuation may complicate the movement of people out of the stands. Fires which originate in the stands have similar, local effects.
- A two-layer building fire simulation which includes inter-layer mixing may show significant smoke in the lower gas layer for spaces well removed horizontally from the fire. Although inter-layer mixing algorithms may not be quantitatively accurate, the effect will certainly occur and must be considered. How severe the actual problem will be requires engineering judgement as present technology cannot give satisfactory numeric values.
- Close coordination and interaction is required between the HVAC design team, the Authority Having Jurisdiction, and the fire safety modeler to assure an acceptable and economical design.
- More and more multi-purpose, multi-use domed facilities will be constructed in the future. To assure occupant and structure fire safety design objectives, increasing emphasis will be needed on the selection of design fires (type, size, location) for fire safety modeling. In some cases, it may be necessary to stipulate that additional occupancy conditions be met in order for the design to be safe.

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