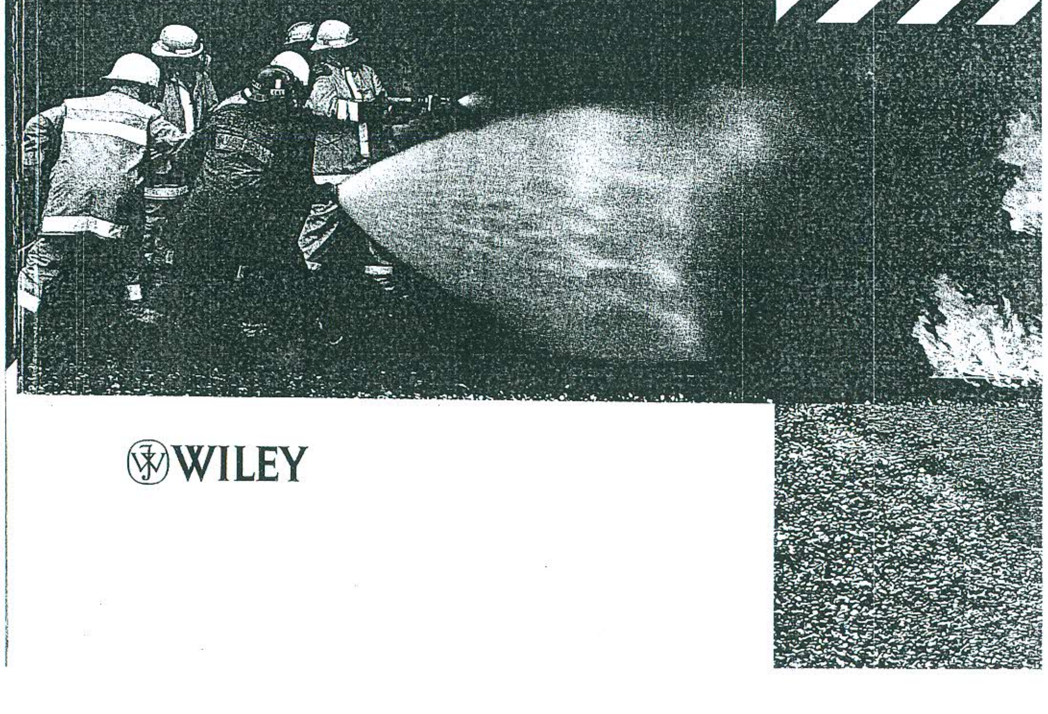
EVALUATION OF FIRE SAFETY

D. J. RASBASH G. RAMACHANDRAN B. KANDOLA J. M. WATTS M. LAW



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3 REVIEW OF SOME MAJOR FIRE & EXPLOSION DISASTERS

3.1 Introduction

Fire and explosion disasters and the concern and investigation that follow them probably provide the major input into requirements for fire safety. In this chapter, a number of disasters that have occurred in the last three decades will be reviewed, with particular emphasis on important lessons that have been learned that are currently being incorporated into fire precautions. A common feature in a number of disasters in buildings is a sudden spread of fire from an apparently small and limited fire to one that is highly threatening and disastrous. There have been fires in which the rapid spread of smoke was the main cause of the disaster. A major feature of disasters, particularly in industrial and transport processes, has been an explosion, which was either solely responsible for the disaster or worsened the fire situation greatly. Special consideration is given here to disasters with these features.

3.2 Major disasters in buildings involving sudden rapid spread of fire

3.2.1 SUMMERLAND LEISURE CENTRE, ISLE OF MAN, 1973

A picture of the Summerland complex is shown in Figure 3.1, and a diagram of a part of the premises called the *Main Solarium Level* is shown in Figure 3.2 (Government Office, 1974). This level was the one at which people entered the premises. It contained a solarium in which shows were given, an amusement arcade 32 m long by 17 m wide and 4 m high that opened to the solarium, and a restaurant. Above the latter two areas there were three further stories in which various activities were carried out and which overlooked the solarium. There was also an open-air public area called *novelty golf* outside the amusement arcade and solarium.

Three extensive areas of flammable surfaces were incorporated into the building and played a major part in the fire disaster. Firstly, the roof and most of the wall, shown in Figure 3.1, were constructed of large panes of Oroglas (poly methyl methacrylate). Those concerned with the design of the building were not fully conversant with the flammability properties of this material. Secondly, abutting onto the Oroglas and stretching upwards from the rear part of the amusement arcade to the top of the building was a wall of Galbestos cladding. This was a steel

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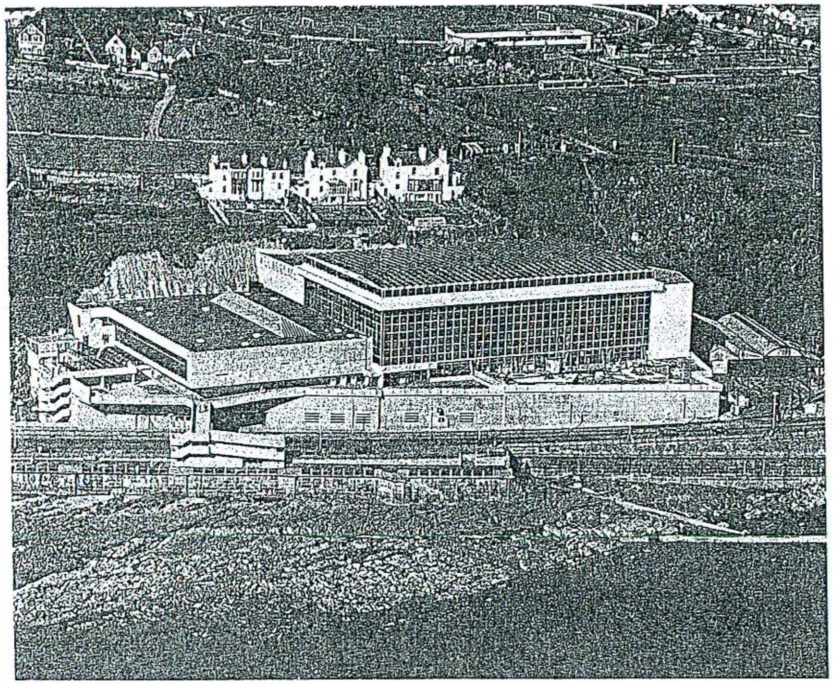


Figure 3.1. External view of the Summerland leisure complex

sheet surfaced on both sides with resin, and it had passed a standard fire test for roofing systems, which exposes specimens to $12\,kW/m^2$ radiation. Thirdly, between the sheet steel outer wall and the amusement arcade there was a cavity 0.3 m wide and 12 m long, the inner wall of which was Decalin, a form of fiberboard (class 4, which is the lowest grading in the BS 476, Part 7 Spread of flame test).

The fire occurred while a concert was in progress in the solarium. Following warning of a fire and signs of smoke at the far end of the amusement arcade, the first rapid spread of fire took place along the length of the amusement arcade. This produced a flame above the front of the arcade that involved the upper stories, and above the side, which involved the Oroglas wall. The fire then spread rapidly to the whole of the wall and the roof. Figure 3.3 shows a picture of the fire at this stage.

The cause of the fire was a plastic booth that had been set on fire by children at point X (see Figure 3.2). This ignited the resin on the sheet steel and the flame soon spread to the resin within the cavity and to the fiberboard material and supporting wooden struts on the other side. The fire on the outside wall of the building was controlled by extinguishers. Within the confines of the cavity, to which air had limited access, the fire persisted and a fuel-rich fire developed over a period of about 20 min before the fiberboard wall burned through. The place of access of the air to the cavity was at the corner of the building where there was an incomplete seal and the point of breakthrough into the amusement arcade was near this point at the closed end of the arcade. At this point, flame and fuel-rich gas was ejected into the arcade, followed by a continuous flame

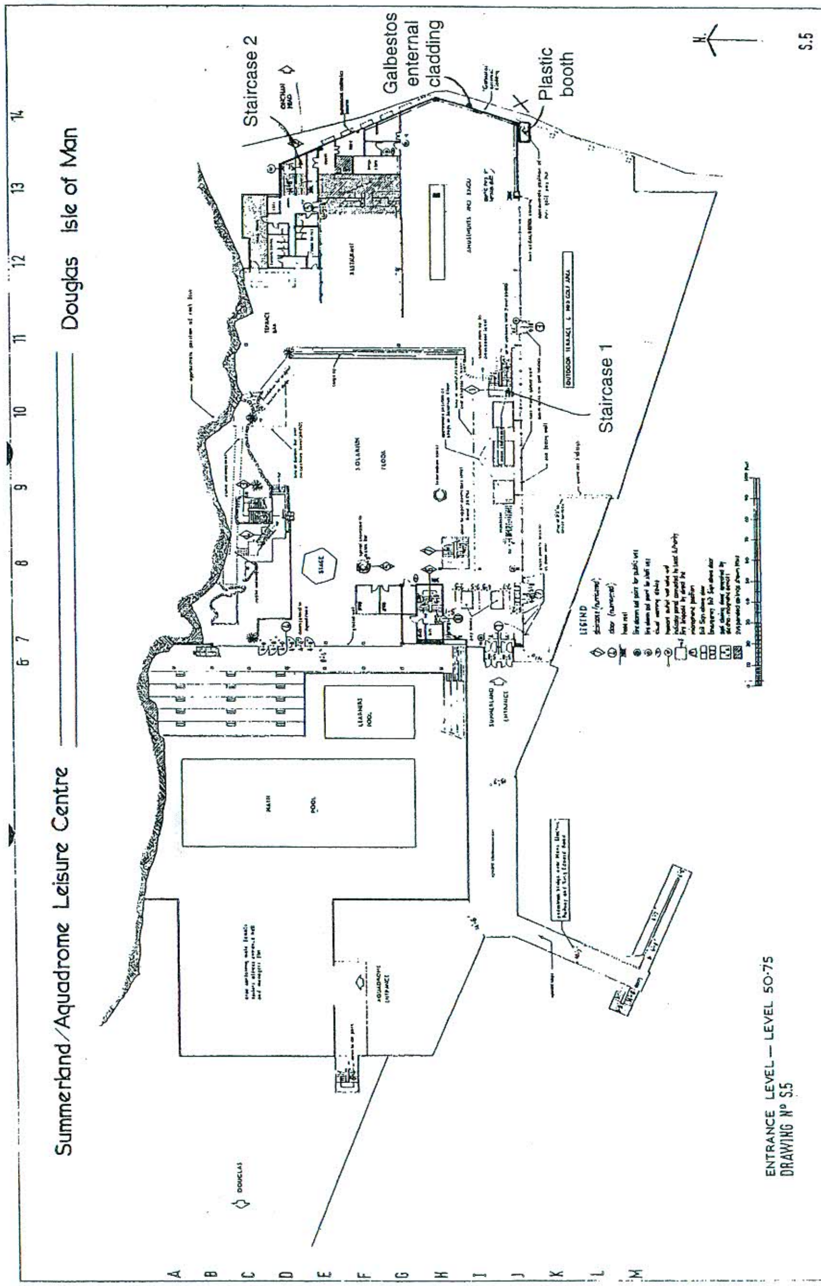


Figure 3.2. Main solarium level, Summerland

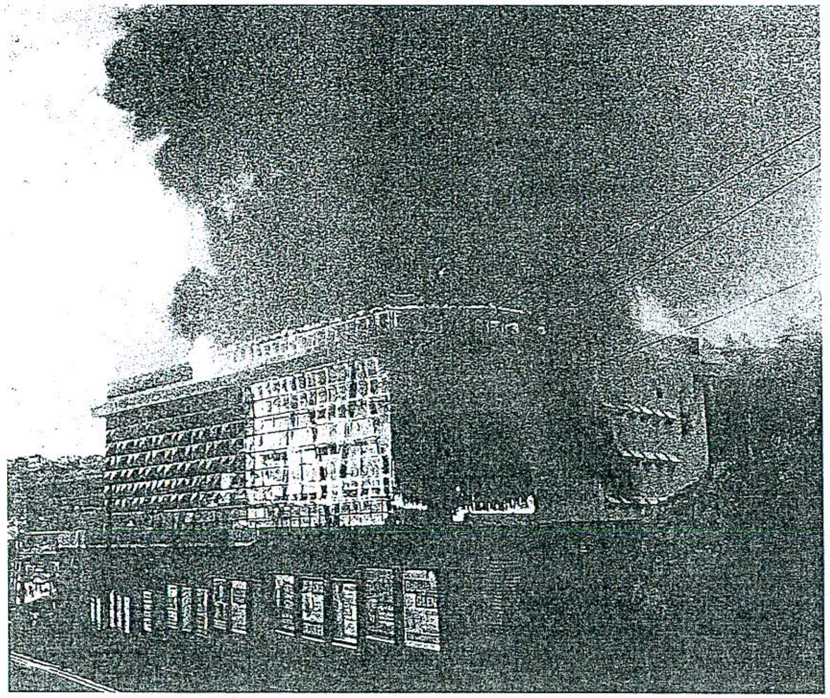


Figure 3.3. Fire spread involving the Oroglas wall and roof of Summerland

from inside the cavity. This could have acted as a powerful ignition source for the combustible wall surfaces that were present in the arcade. The flames spread along the length of the arcade in 1 to 2 min.

There were 3000 people in the building at the time, of whom 50 persons – men, women, and children – perished in the fire. They were found in different parts of the premises. Many people died on an open staircase (staircase 1 in Figure 3.2) that people were using to escape from the upper floors. It was fully exposed to the flames that poured out from the open end of the amusement arcade, and to flames from the nearby fire on the Oroglas wall. A number of bodies were also found on stairway 2. This was intended to be a protected stairway but it served also as a service stairway and a permanent opening was made between one of the floors and the stairway through which much smoke must have passed during the fire. A number of exit doors from the main solarium level were locked at the time of the fire and there was no disciplined evacuation procedure. One reason for delay was the need for parents to look for their children who were in different parts of the leisure center.

3.2.2 THE STARDUST DANCE CLUB FIRE, DUBLIN, 1981

Forty-eight young people died in this incident. There were about 800 people in the dance hall when the fire occurred (Keane, 1982). In the early stages, the fire involved the West Alcove (Figure 3.4), measuring 17 m by 10 m, with a floor that sloped upward toward the back where the

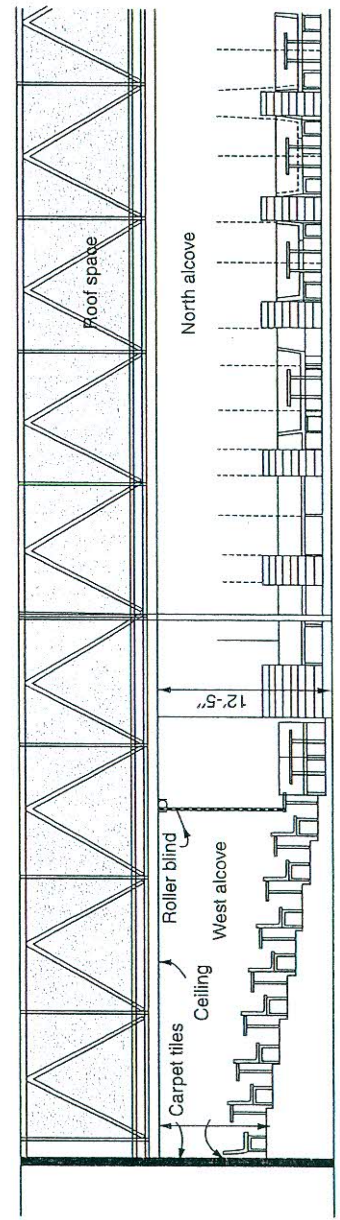


Figure 3.4. Stardust club interior (section) showing west alcove

height was 2.4 m. The alcove, which was empty and partially cut off from the main body of the dance hall by a roller blind (Figure 3.5), had rows of seats each measuring 0.9 m long with 4-cm-thick PVC covered polyurethane foam seating and backrests. The back row was installed against the back wall, which was lined with carpet tiles; these gave a class 3 to 4 performance in the standard spread of flame test. Mineral fiber insulating tiles, which were almost noncombustible, formed the ceiling of the alcove above which there was a roof space. Some mechanism caused the ignition on the back row of seats so that a line fire developed. The people in the hall were aware of there being a small fire in this area for some 6 to 7 min, during which time the roller blind was raised. The flame impinged on the carpet tiles and the back wall rapidly became involved. Then, within tens of seconds, all the seats in the alcove began to burn, and flames and smoke spread very quickly to the main body of the ballroom.

Experiments carried out during the investigation showed that when one of the 0.9-m seats was ignited along its whole length it could produce a heat transfer of 100 kW/m^2, on the back wall. The combination of burning seats plus carpet tiles produced a burning rate at the back of the alcove of about 800 kW/m run, sufficient to produce extensive flaming under the ceiling and high levels of radiation down on the seats in front. Full-scale tests showed that the heat transfer from the flames just ahead of the back wall rose rapidly to a peak of 250 kW/m^2. The result was that the tops of the seats well ahead of the back wall were exposed to a heat transfer in excess of 60 kW/m^2, sufficient to produce spontaneous ignition in a few seconds. The array of seats below the ceiling acted as an extensive surface that could respond to the very high heat transfer rates.

A noteworthy point is that a part of the ceiling in the alcove collapsed, which led to the shattering of the roof and the venting of some of the heat and smoke. Had venting not occurred, it is likely that many more of the 800 people in the hall would have been killed.

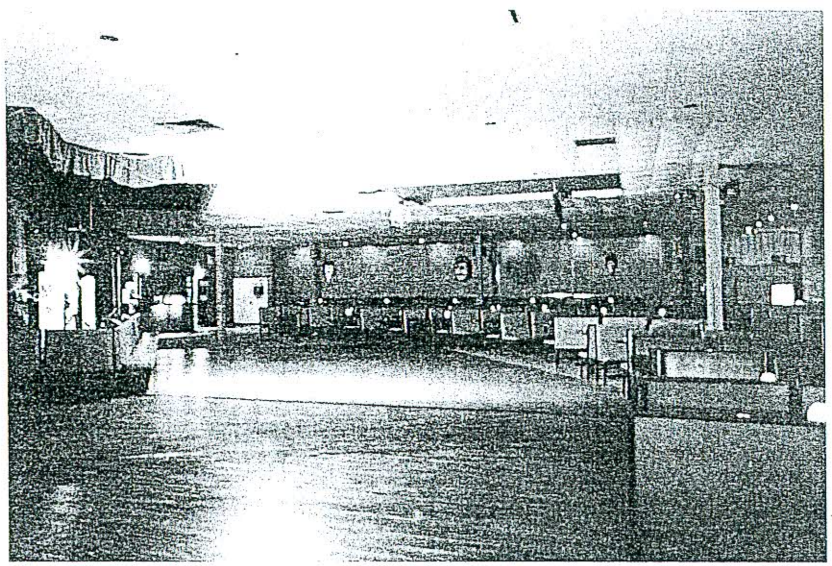


Figure 3.5. Stardust club interior – alcove behind roller blind

3.2.3 KING'S CROSS UNDERGROUND STATION, LONDON, 1987

The fire at King's Cross caused the deaths of 31 people. The origin of the fire was a wooden escalator about 40 m long leading from railway platforms to the booking hall (subsurface). It was the left-hand escalator of a group of three running in a semicircular shaft 8 m in diameter. The side balustrade and handrail of this escalator was separated from the wall and ceiling of the escalator shaft by a combustible horizontal surface 0.3 m in width. Surfaces on the escalator were class 3 or 4 spread of flame; these included the risers and treads of the steps, the balustrade, and probably also the laminated surfaces separating escalators from each other and the wall. In addition, the first meter of the wall and ceiling was covered by an advertising hoarding, which, because of the presence of varnish and plastic covered advertisements, was the most flammable item associated with the escalator shaft. There was also evidence that the ceiling had been recently painted in such a way that if it had been subjected to the spread of flame test, it would probably have given a class 3 or 4 performance. When a sample that included the plaster and concrete base was exposed to a heat transfer rate of 75 kW/m^2 in a cone calorimeter, a number of the layers of the paint delaminated in 2 to 3 s, ignited in 5 s and produced a heat output of between 200 and 450 kW/m^2, with much smoke, for about 20 s.

The Inquiry (Fennell, 1988) found that the fire was ignited by a lighted match falling through a gap at the edge of the escalator into residues of lubricating grease that had been allowed to collect beneath the escalator. This led to what appeared as a comparatively small fire in the middle of the escalator. Suddenly, after a period of about 15 min, fire shot up the escalator and quickly involved the upper part of the escalator shaft as well as the combustible material in the booking hall above. People in the booking hall were confronted with a wall of flame and black smoke moving rapidly toward them.

During the inquiry, different opinions were expressed concerning the mechanism of sudden rapid flame spread, including a mechanism that involved delamination of the thick paint on the ceiling. A field modeling study carried out at Harwell, which was reported late in the investigation, indicated that flames within the trench of the escalator did not move vertically upwards, as had been assumed up to that time. It was likely that the flames were confined to the trench itself for a significant time, thus promoting flame spread along the escalator. Tests on a one-third-scale escalator system, carried out by the Health and Safety Executive, showed that this could indeed have happened. Heat transfer rates within the escalator trench of about 150 kW/m^2 were measured, and were found to be predominantly convective rather than radiative. It was decided by the Inquiry that this was the mechanism of rapid fire spread.

However, the opinion was also expressed (Rasbash, 1991) that the spread of fire out of the trench on to the advertising hoarding, which was also observed, might have rapidly produced a line source heat transfer to the ceiling of the order of 100 kW/m^2. A consequent spread up the hoarding/ceiling combination and under the ceiling to the booking hall could take about 20 s. There could thus have been a double blow awaiting those in the ticket hall. Most of the people who were killed were in the ticket hall and many had been sent there from the underground station through a separate escalator as a way of escaping the fire.

3.2.4 BRADFORD CITY FOOTBALL GROUND, 1985

At about 15.40 on 11 May, 1985, during a football match, a fire started in the main stand of the Bradford City Football Ground. The stand was some 90 m long, and within 7 min of the first sign of fire the stand was completely alight. Fifty-six people lost their lives. A full report is given by Popplewell (1985).

The stand was set on the side of a hill. It was divided into two approximately equal longitudinal sections by a wooden fence 1.5 m high. Above the fence, spectators were provided with timber seats affixed to timber frame; below the fence there were polypropylene seats fixed to concrete. Access to and from the seating sections was from a long corridor extending along the length of the back of the stand. The corridor was located at the highest point of the stand, next to the perimeter wall that contained exit doors and turnstiles leading to and from the outside road.

Because of the natural slope of the hill, there was a void underneath the wooden floor of the stand, which varied in depth from 0.21 to 0.75 m. There were gaps in the flooring and between the seats through which, over the years, combustible rubbish had been allowed to fall and which had accumulated to a depth of about 0.2 m. There was also a close-boarded roof to the stand that was covered throughout its length with roofing felt.

The fire started at 15.40 in the void beneath the wooden seats just above the wooden fence, near one end of the stand. People nearby felt heat and looking down through a gap, could see flames. Figure 3.6 shows a photograph taken early in the fire indicating smoke coming up through the gaps in the floor and with flame underneath seat J141. Flames spread upward through the void under the floor and appeared through gaps above the floor at 15.43. Within a minute, the area of the fire visible above the floor was several square meters in extent and increased to about 10 m^2 in a further minute, at which time the flame height extended to the roof. By 15.46, there was a serious spread of fire involving the roof, and by 15.47 the whole of the stand, roof, and seats were completely alight as shown in Figure 3.7.

Most of the people who died were trying to escape through the back corridor. In the first few minutes of the fire, there was no major effort on the part of spectators to escape, as the fire did not appear to be threatening. However, once the fire covered several meters above the floor, then a rush to escape started, particularly upwards to the corridor at the back of the seats. It was likely that at this time the corridor was beginning to become smoke logged. Although there were exits from the corridor onto the street, most were closed and a number of them, particularly the turnstiles, were locked. The exits could not accommodate the number of people attempting

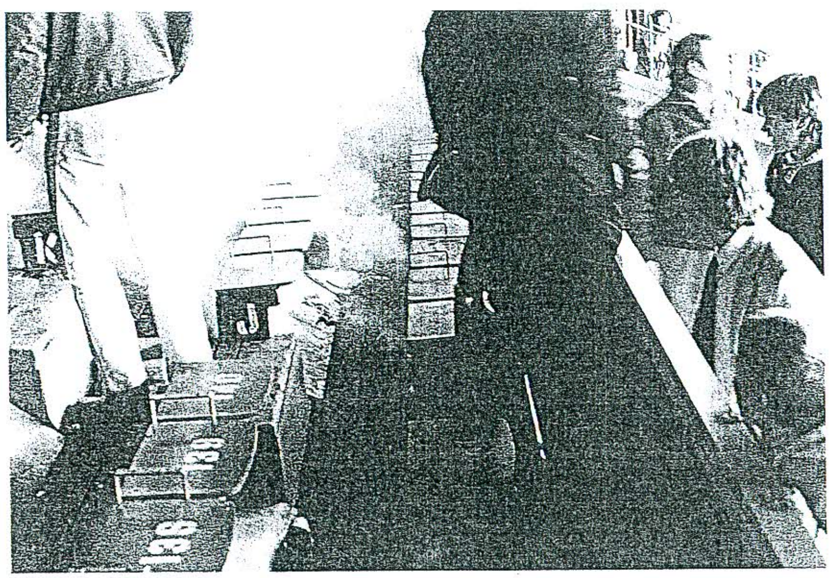


Figure 3.6. Early stage: fire under the seating, Bradford City

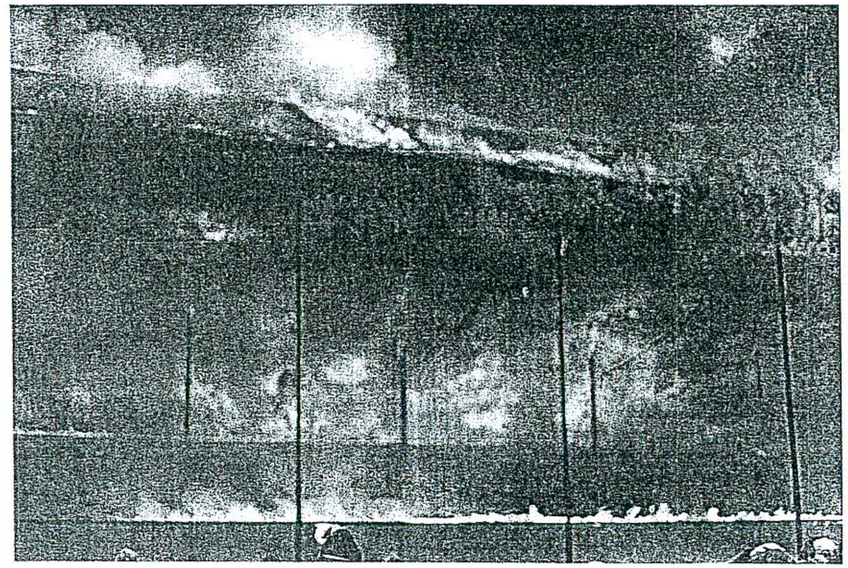


Figure 3.7. Complete involvement of roof and stand, Bradford City

to use them in the minute or two that was available for escape and the majority of people who died did so near exits at the center of the corridor and toward the end of the corridor where the fire started.

3.2.5 INTERSTATE BANK, LOS ANGELES, 1988

On Wednesday, 4 May and continuing into 5 May, 1988, fire spread from floor to floor through exterior openings of this 62-story tower building in downtown Los Angeles. The fire destroyed four floors and damaged a fifth. It claimed one life, injured approximately 35 occupants and 14 fire personnel, and resulted in a property loss of over $200 million. Details of the building and the fire are given in reports by Routley (1989) and Klem (1989).

Built in 1973, the building contains approximately 1625 m^2 net area of office space per floor, built round a central core (see Figure 3.8). Below the ground there is a basement accommodation, a garage, and a pedestrian tunnel. Approximately 4000 people work in the building. They are mainly staff of the banking corporation, but tenants occupy several floors. The tower contains four main stairways. The two northern stairs are enclosed within a common shaft while the southeastern stair has a pressurized vestibule separating each floor area from the stair shaft. The building has a structural steel frame, protected by a sprayed-on fire protective coating, with steel floor pans and lightweight concrete decking. The exterior curtain walls are glass and aluminum.

There were extensive smoke detector installations including detectors connected to magnetic hold-opens for doors at each end of the elevator lobby to the 12th floor (G + 11), which was the floor of fire origin. However, it was reported that these detectors were not connected to the fire alarm system. A sprinkler system was being installed and was virtually complete, but the valves between the standpipe riser and the system on each floor were not yet open.

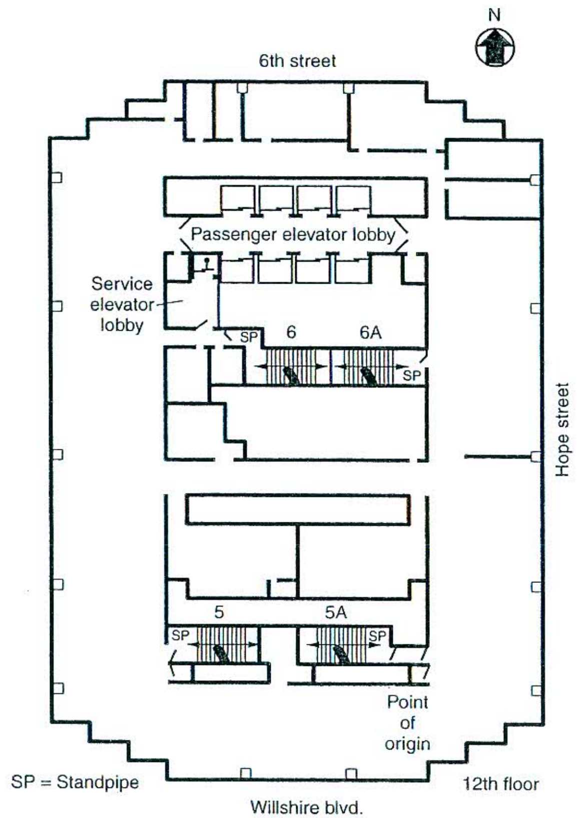


Figure 3.8. Typical floor area in Interstate Bank building (Nelson, 1987)

At approximately 10.25 p.m. on the night of the fire, employees of the sprinkler system contractor heard glass falling and saw smoke at the ceiling level on the fifth floor (G + 4). A manual alarm was pulled but sounded for only a few seconds. It is believed that security personnel on the ground floor silenced the alarm. The fire originated in an open-plan office area in the southeast quadrant of the 12th floor (see Figure 3.8). The area of origin contained modular furniture with numerous personal computers and terminals. The cause is thought to be electrical in origin, but the precise source was not determined. The fire extended to the entire open area and several office enclosures to fully involve the 12th floor, except for the passenger elevator lobby, which was protected by the automatically closing fire doors.

Fire also extended to floors above, primarily via the outer walls of the building. Windows broke and released large flames. Flames also penetrated through gaps between the curtain wall panels and the ends of the floor slab. The curtain wall construction was such that it did not butt the edge of the slab. The external flames gave heavy exposure to the windows on successive floors as the fire extended upward from the 12th to the 16th (G + 15) floor. The flames were estimated to be lapping 9 m up the face of the building. The curtain walls on these floors, including windows,

spandrel panels, and mullion, were almost completely destroyed by the fire. The fire extended at a rate estimated at 45 min per floor and burned intensely for approximately 90 min on each level. This resulted in at least two floors being heavily involved during most of the fire. Fire fighting prevented extension beyond the 16th floor.

Firefighters faced unusual challenges. The steel structural frame interfered with radio communications. Access to upper floors was by stairwells that were filled with heat, smoke going up, and waters cascading down. Two "airborne engine companies" were deployed via helicopter. Problems were encountered with pressure reducing valves on standpipes and overpressure caused several hose ruptures and made hand lines difficult to control. The heat of the fire caused several aluminum alloy valves in the occupant hose cabinets to fail creating high-pressure water leaks. These leaks took water from the supply that was available for hand lines and caused additional water damage on floors below the fire. Thirty-two attack companies used approximately 20 hand lines on the fire floors. The estimated water flow through hand lines at the height of the fire was 150 L/s (2400 US gallons per minute).

The floors below the fire received massive water damage. Those above were heavily damaged by heat and smoke. In spite of the total burnout of four-and-a-half floors, there was no damage to the main structural members, and only minor damage to one secondary beam and a small number of floor pans. Although there was concern for structural integrity during the incident, postfire analysis indicated that there was no danger of major or minor structural collapse. It was noticed that quality control in the application of the sprayed-on fire protection was unusually good.

The bank's disaster plan went into effect immediately and proved to be well worth the many person-hours of planning. If this fire had occurred during normal working hours, many more lives would have been at risk. However, with people occupying the 12th floor, there could have been earlier alarm and possibly first aid fire fighting. The barrier weakness at the junctions of curtain walls and floor slabs is now well recognized and easily remedied. If the automatic sprinkler system had been in operation, the risk to both life and property would have been significantly reduced.

Nelson (1989) was able to reconstruct important aspects of the fire growth and behavior, by making an engineering analysis of the fire. One of the models used in his analysis was an early version of FPETOOL (Nelson, 1990) that included ASET (Available Safe Egress Time). The rate of heat release curve used to simulate the burning of the initial fire was based on measurements for similar computer workstations. It is shown in Figure 3.9. The calculated growth before flashover is shown in Figure 3.10 and is compared with the fast and moderate fire growth curves of NFPA 72E (1990). Nelson (1989) extended the study to examine the potential for flashover. Figure 3.11 shows how ceiling height and floor area affect the rate of heat release needed to produce flashover. (The three curves represent different ceiling heights – 1.8, 2.7, 3.7 m. The abscissa is floor area, ranging from 50 to 1400 m^2, and the ordinate is the rate of heat release. Triangles indicate floor area dividing points below which smoke temperatures cannot exceed 600 °C because of insufficient oxygen.)

3.2.6 DUPONT PLAZA HOTEL, PUERTO RICO, 1986

On 31 December, 1986, a mid-afternoon fire at the Dupont Plaza Hotel and Casino in San Juan, Puerto Rico, resulted in 97 fatalities, over 140 injuries, and property losses involving millions of dollars. The fire department arrived approximately 5 min after notification of the fire, but it took nearly five hours to achieve final extinction because of the severity and magnitude of the fire that confronted them and the complexity of the rescue problems. Reports by USFA and Polaris Research Development (1987) and Klem (1987) give comprehensive descriptions of the fire.

Built in the early 1960s, the 22-story hotel was L-shaped on plan, with the main entrance at one story above grade, accessed by a large ramp. There was a ballroom at ground level, the Casino

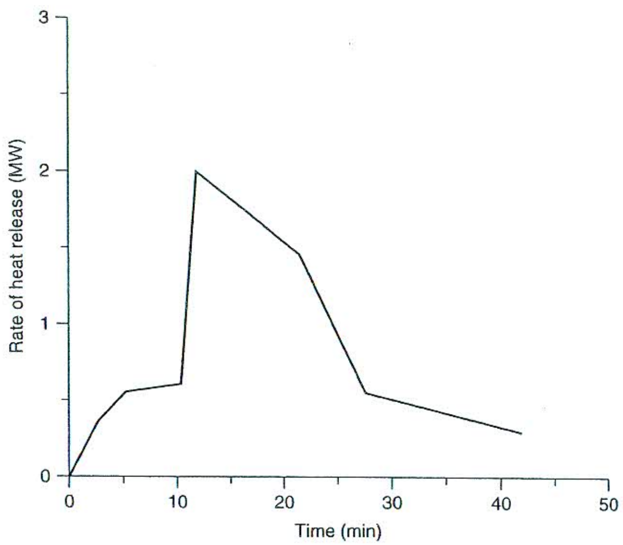


Figure 3.9. Rate of heat release for typical computer work station (Nelson, 1987)

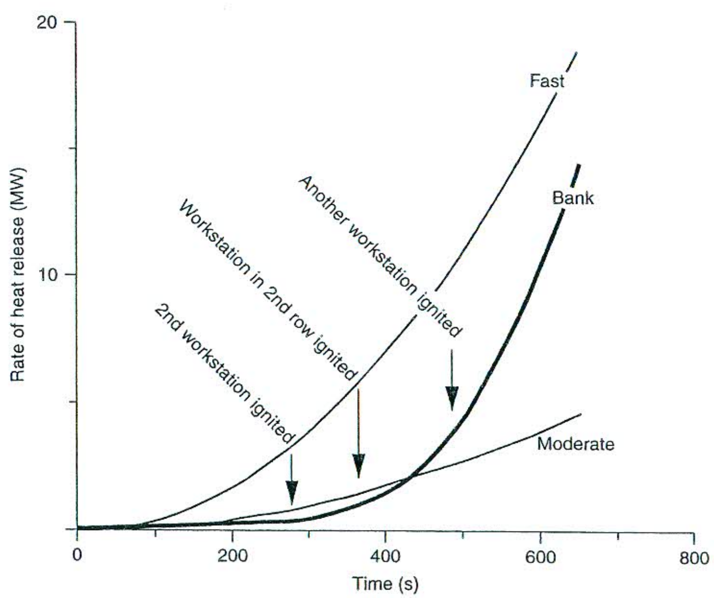


Figure 3.10. Estimated rate of heat release on 12th floor of Interstate Bank building (Nelson, 1987)

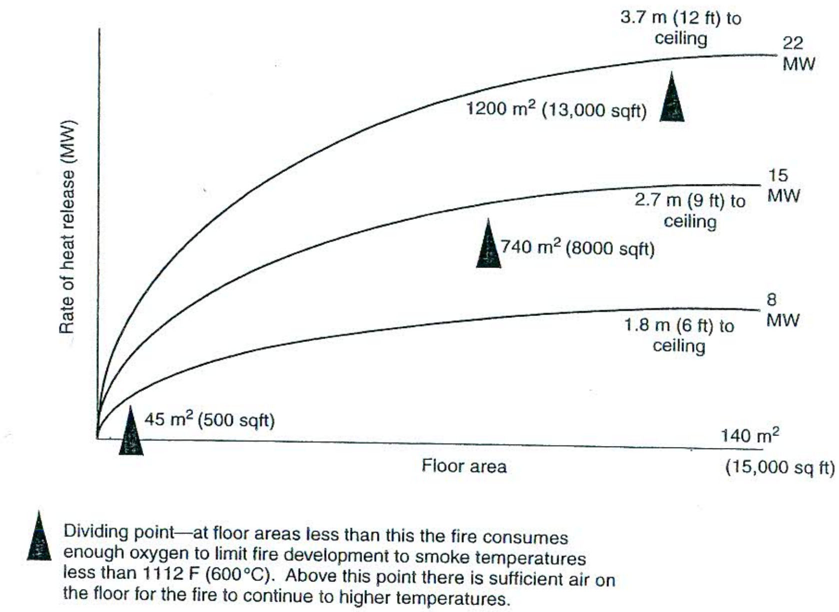


Figure 3.11. Maximum fire size in a closed space as a function of floor area and distance from fire to ceiling (Nelson, 1987)

at entrance level, and there were various shops, restaurants, and conference rooms surmounted by a 17-story tower with 423 guestrooms.

The construction in the ballroom area included unprotected noncombustible and some combustible material. The casino, lobby area, and the high-rise tower contained fire-resistive construction. The ballroom can best be described as a general-function, conference-type room, which could be divided by single free-hanging panels. A portion of the ballroom was being used for storage at the time of the fire. Both the casino and the ballroom had suspended ceilings, creating large voids below the structural ceiling. Three sides of the casino had floor-to-ceiling windows, as did the atrium that connected the ballroom and casino. The casino had two means of egress (exit ways): on the ballroom side there was a pair of free-swinging tempered glass doors, and at the opposite end there was a solid-core inward-opening wood door.

There were no automatic detection and alarm systems. There was a local-only, manual fire evacuation alarm system installed in the high-rise tower. There were no sprinklers. There was a standpipe and hose system in the tower.

The fire was discovered at approximately 3.22 p.m. in the south part of the ballroom, which was unoccupied. The fire department was notified at about 3.45 p.m. The authorities later determined that the fire was deliberately set in a large stack of recently delivered guestroom furniture, temporarily stored in the ballroom. Subsequent spread of the fire is shown in Figure 3.12. The fire developed quickly after ignition. It involved the stored materials, the combustible interior – including cardboard and wood packing – the carpeted walls, stacked chairs, and a combustible, removable partition that separated the south ballroom, where the fire started, from the adjoining north ballroom. While the south ballroom was approaching full involvement, the fire

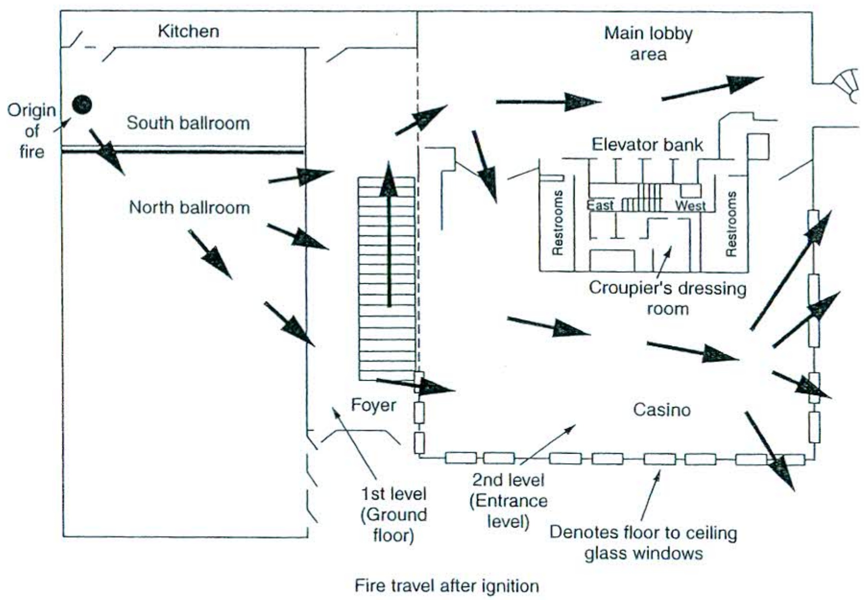


Figure 3.12. Fire travel in the Dupont Plaza Hotel (Nelson, 1989)

penetrated the combustible partition, spreading products of combustion to the north ballroom and to a foyer connecting the ballroom level (ground floor) to the entrance level directly above. There was limited extent of fire growth and damage in the north ballroom, but it is believed that fire reentered the upper portion of the north ballroom at some time after 10 min, probably upon breakage of the glass partitions at the lobby level of the foyer. This would explain the damage found in the balcony area and on the ballroom ceiling.

Witness accounts indicate that smoke emerged into the foyer from an open door of the north ballroom at approximately seven minutes. This was the first time that smoke entered the view of the general public, and initially it was cool and thin. The foyer contained the main staircase to the lobby. Flashover occurred in the south ballroom at about 10 min after established burning. It involved large portions of combustible wall material, and ignited portions of the partition between north and south, significant parts of the wood flooring, and the stacked chairs. Intense heat from the flashover broke the glazed partition between the south ballroom and the foyer so that a massive quantity of smoke and flames was released into the foyer.

Once the fire had reached casino level, smoke spread to the high-rise tower by several means, including service and passenger elevators, the hotel's HVAC system, toilet exhausts for guestrooms, the exterior of the building, and through stairways connecting the casino level to each guest room floor. Occupants of the high-rise became aware of the fire and many moved to the roof of the building and waited for helicopter rescue, while others stood on guestroom balconies awaiting rescue.

Between 200 and 250 people were estimated to have been in the casino at the time of the fire. They began to leave the casino once smoke was spotted through the glass walls overlooking the atrium and ballroom. Most of them moved towards the west portion of the casino, which led to the main hotel lobby and to an exterior spiral stairway leading to ground. Not all of them

were able to safely reach this exit before the flame front vented through the lobby and out of the opening to the spiral stairway. When this occurred, the main exit path for the remaining occupants of the casino became blocked. As the fire grew in intensity and as more people became aware of the fire, they rushed to the only available exit – the wooden door at the far end of the casino. Because two simultaneous actions were needed to unlatch and open the door, which unfortunately opened inward as well, it was difficult in the crowded conditions to exit by this route and people began looking for alternative means of escape. Some people began to break the exterior glass walls at the rear of the casino, and then jumped to the ground 5 m below.

Ninety-three victims were found dead at the scene and four died later in hospital. Fatalities were mainly clustered near the west exit of the casino. Other fatalities were located in the lobby area, in a passenger elevator, and one fatality was found in a guestroom on the fourth floor (G + 3). All but eight of the fatalities at the hotel were burned beyond recognition. Analysis of blood samples indicated that carbon monoxide alone or combined with hydrogen cyanide played a major role in the deaths of the nonburned victims but was probably not significant for those who were burned (Clark *et al.*, 1990).

Table 3.1. Fire characteristics calculated in engineering analysis of Dupont Plaza Hotel fire (Nelson, 1987)

Mass burning rates

- Preflashover (free) burning of initially ignited fuel package
- Postflashover burning of materials in the south ballroom
- Burning of foyer ceiling after flashover of south ballroom but prior to entry of fire into casino

Rates of heat release

- Preflashover (free) burning of initially ignited fuel package
- Rate of energy flow from south ballroom to north ballroom prior to flashover in south ballroom
- Rate of energy flow from north ballroom to foyer prior to flashover in south ballroom
- Postflashover energy flow from south ballroom
- Energy release from the foyer ceiling after flashover of south ballroom but prior to entry into casino

Smoke temperatures

- South ballroom
- North ballroom
- Foyer prior to flashover in the south ballroom
- Foyer following flashover in the south ballroom

Other fire characteristics

- Smoke layer depth
- Velocity of smoke/fire front
- Mass product in smoke layer
- Oxygen concentration in smoke layer
- Visibility in smoke layer
- Flame length (extension)
- Flame spread
- Potential response of sprinklers
- Potential response of smoke detectors
- Fire duration

Nelson (1987) conducted an engineering analysis of the development and growth of the fire and its effects that led to a description of the course of this fire, fitting the available information. For example, he concluded that approximately 40 s after flashover in the south ballroom, a deep, hot, toxic smoke front traversed the lobby, forcing the occupants to flee and blocking the exits from the casino to the lobby. Additionally, a wall of flame lapped out of the ballroom up to the wooden ceiling of the foyer and across a major portion of that ceiling. Very quickly, this added fuel to the fire. At about 2 min after the flashover, most of the glazing surrounding the foyer had failed and a sudden flow of hot gases and unburned fuel traversed from the foyer into the casino. It quickly changed to a flame front that swept the length of the casino in about 20 s. A large body of flame then broke through the windows of the west wall of the casino. Table 3.1 lists the specific fire characteristics described in the analysis. Figure 3.13 shows predicted smoke layer temperature in the north and south ballrooms and in the foyer. These are consistent with the patterns of damage observed after the fire. Nelson's report illustrates the value of analytical, engineering methods, and how they should be used to evaluate not only potential fire hazards but also the impact of different circumstances and different fire protection measures on the course of a fire.

It was believed that the fire was set intentionally because of labor dissatisfaction. Inevitably, the extensive litigation that ensued included much independent analysis to determine behavior, response, and performance of any materials or structural assemblies that might have contributed to the resulting fatalities. Owing to the adversarial nature of litigation, most of this work was cloistered until the time of legal disclosure. A panel was convened nine years after the fire to discuss some of the research outcomes from the diverse analyses of this fire (Lund, 1995). The

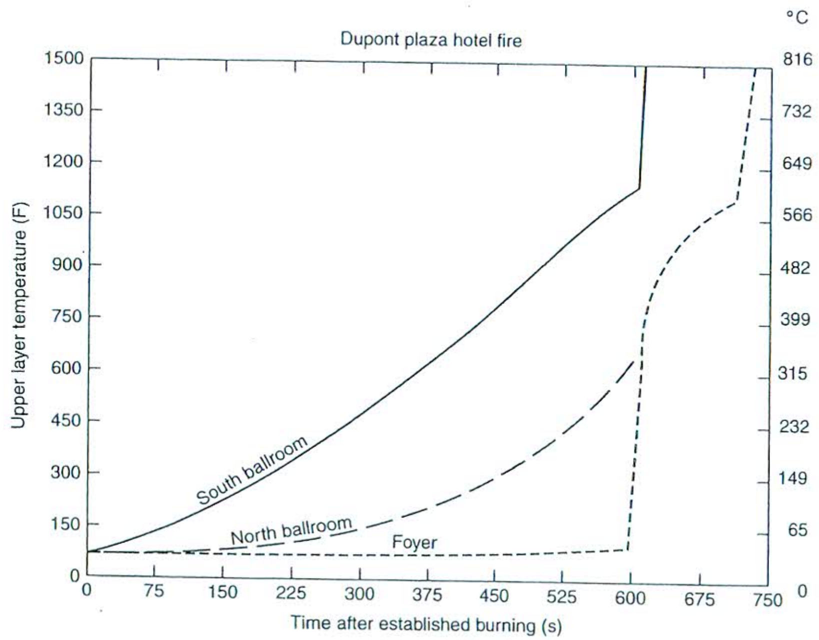


Figure 3.13. Estimated average temperature in smoke layer at Dupont Plaza Hotel fire (Nelson, 1989)

reported accomplishments included a new intermediate scale calorimeter, more advanced models of glass breakage in fires, further development of scale modeling of smoke flow in buildings, and enhanced integration of Computational Fluid Dynamics (CFD) models with computer animation.

3.3 Fires in which extensive spread of smoke was a major factor

3.3.1 BEVERLY HILLS SUPPER CLUB, KENTUCKY, 1977

Around 8.45 p.m. on the evening of 28 May, 1977, a fire occurred at the Beverly Hills Supper Club at Southgate, Kentucky. In addition to the total destruction of the Club, the fire resulted in the death of 164 persons. Best (1978) and Lawson (1984) give detailed information about this tragic fire.

The Club had dining facilities, a nightclub with live entertainment, lounges, and a number of rooms used for private parties. A rebuilt club was opened in 1972, but there had been numerous addition and alterations since then, the latest being in 1976. The total floor area had become approximately 5000 m^2 by the time of the fire (see Figure 3.14).

The building was mainly unprotected, noncombustible construction. The ground floor of a small two-story front section contained the main entrance, foyer, main dining room, main bar area, the Zebra Room, office areas, coat-check room, and part of the Viennese Room. The upper story contained a number of small party rooms, lavatories, and dressing rooms. The remainder of the building was single story. It contained the other part of the Viennese Room, the kitchen, various utility and storage areas, the Cabaret Room, the Empire Room, and the Garden Rooms.

The interior finishes were primarily wood or dense fiberboard panels on the walls and carpet on the floors. There were suspended ceiling assemblies with noncombustible ceiling tiles, which supported recessed lighting fixtures. In the oldest part of the building where the fire started, evidence was found of combustible tiles in ceiling assemblies installed earlier and left in place when the noncombustible assembly was installed beneath. Furnishings consisted of tables, tablecloths, and other dining and entertainment accessories including padded, vinyl-clad chairs throughout the various rooms.

There were ten exits from the building, including an employee exit from the kitchen. A main corridor connected all ground floor dining areas and entertainment areas to the main entrance. This corridor had no smoke or fire partitions. There were no internal fire division walls anywhere in the building, no smoke or fire detectors, no fire alarm system, and no automatic sprinkler system.

When the fire occurred, there were about 3500 patrons and 250 employees in the club. All the major rooms and most of the smaller rooms were occupied. Investigation established that the fire started in the unoccupied Zebra Room, at the front of the building (Figure 3.14). The most probable cause was electrical and combustibles located there, which would have fed the fire. The concealed combustible tiles and wooden supports provided fuel for continued fire spread in the concealed spaces. Evidence indicated that the fire burned for a considerable time prior to its discovery at 8.45 p.m. The county police-fire communications center received notice of the fire at 9.01 p.m. Despite attempts at extinction, flashover occurred in the Zebra room. The fire subsequently broke out of the room through the double doors at the north end and then spread rapidly throughout the building.

The biggest crowd, about 1000 persons, was in the Cabaret Room, some 45 m away from the room of origin, down the main corridor (Figure 3.14). Most of the victims were occupants of the Cabaret Room. After a bus boy warned patrons in the room that there was a fire and indicated the emergency exits, some exiting began. Soon after, smoke came into the Cabaret Room through its main entrance (from the main corridor). This main entrance provided the exit used normally by patrons (in nonfire conditions). Two other exits were available. One, at the northwest corner, led

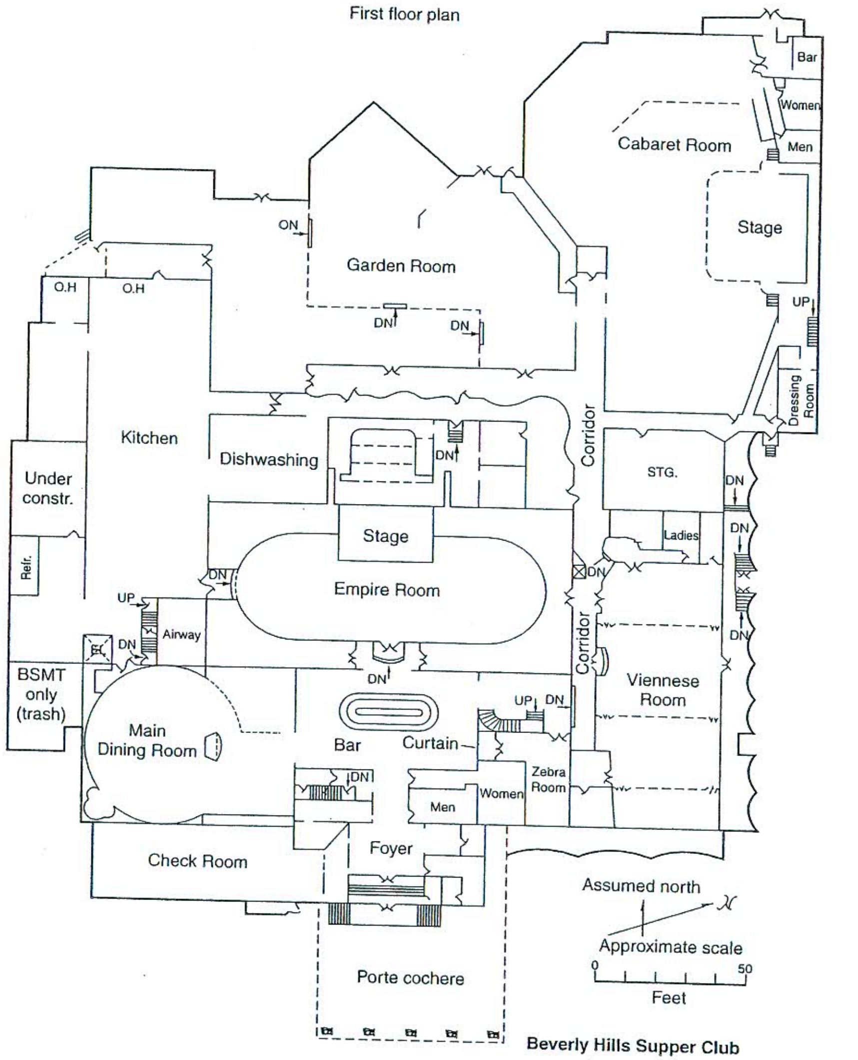


Figure 3.14. Floor plan of Beverly Hills Supper Club (Emmons, 1983)

through double doors to a service bar area and then to another set of double doors to the outside. The other, at the northeast corner, led through a door and across a short corridor to a single door to the outside.

Bright (1977) undertook a qualitative analysis of fire spread from the Zebra Room to the Cabaret Room. He concluded that the rapidity of the spread down the main corridor, somewhere between 2 and 5 min was undoubtedly a factor in the large loss of life in the Cabaret Room.

The corridor had combustible wall linings and a combustible carpet assembly on the floor, which would have assisted rapid spread. Emmons (1983) applied principles of fluid dynamics to derive numerical estimates that would explain the fire behavior. There was an apparent discontinuity, because the rate of fire and smoke spread was minimal for about 15 min after discovery and then it suddenly increased in the long corridor, extending about 45 m in less than 5 min. He hypothesized that smoke migration was minimal initially because with all doors closed there was no significant force to move it. There was a strong movement of smoke in a northerly direction once the doors in the Garden Room were opened, which is consistent with reports that the prevailing wind was from the south. Emmons estimated a rate of smoke travel, and Figure 3.15 shows a plot of smoke volume against time. This was based on principles of conservation of energy and mass in a fluid network, supplemented by eyewitness information. He also developed an estimate of the rate at which the flame spread down the north–south corridor and he concluded that there would have been rapid spread regardless of the combustibility of the linings.

3.3.2 FAIRFIELD HOME, NOTTINGHAMSHIRE, 1974

In December 1974, a fire took place at the Fairfield Home, Edwalton, Nottinghamshire, UK, in which 19 people died. There was a Committee of Inquiry that reported it in July 1975. (DHSS, 1975). This fire was of importance, in that it was one of those that had taken place in a CLASP building, and there had been concern about these buildings for some five years.

CLASP means Consortium of Local Authorities Special Programme. This organization had brought together a method of construction that was a light pin-jointed steel frame on a thin slab

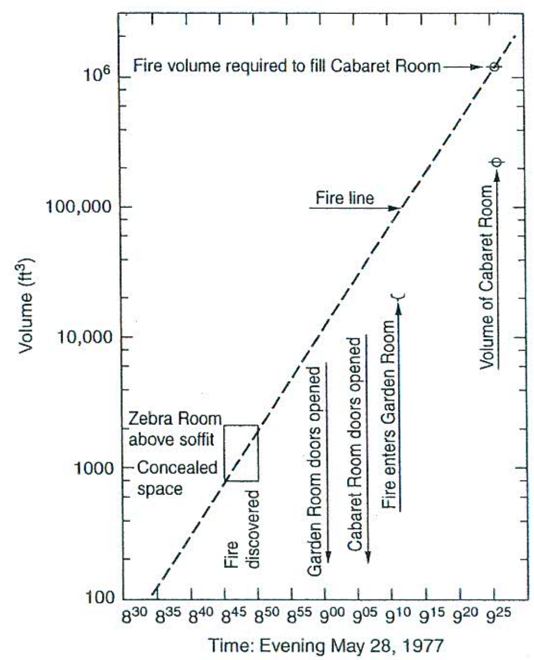


Figure 3.15. Fire growth in the Beverly Hills Supper Club (Emmons, 1983)

foundation having structural floor and roof diaphragms. The building was designed to be used in areas where there might be subsidence and where it could give in in various directions and not crack. The design, however, involved the use of a large void or cavity in which the pin structure was erected. This cavity extended across the whole area of the building with the ceiling of the lower floor as the lower surface of the cavity and the floor of the upper floor, or the roof, as the upper surface. The structure could be a number of stories high and in these buildings it was postulated when they were designed first that the ceiling and floor acted as a membrane protection to the steel frame, thus giving it the necessary measure of fire resistance between the floors.

The dominant factor in this type of property was the presence of voids that could cause both the spread of smoke and the spread of fire. In many instances, the upper surface of the void was of combustible materials, usually timber but occasionally plywood; the lower surface of the void might have been constructed from fiber insulating board or perforated board. Voids extended horizontally across the whole level of the building.

The Fairfield Home was a single story building made up of a central area and five outlying dormitory houses, all connected to the central area by corridors. A single undivided roof covered the whole building from end to end. The fire occurred at about 2 a.m. in a bedroom in house no. 1 and probably burned for some time before effective action was taken. The Committee of Inquiry decided that it was substantially the early travel of smoke through the voids that caused many of the fatalities. Nine people died in house no. 1 in which the fire started. In addition, smoke traveled through the void into house no. 2 and in this way was thought to bypass fire doors and lobbies leading to the corridor between the two houses. Nine people died in house no. 2, most of them in bedrooms with the bedroom door shut. Also the fire traveled to many other parts of the building, particularly house no. 5, which was substantially destroyed. The ceiling of the building was plasterboard, 3/8 inch thick, dropped into aluminum tees that were supported by mild steel straps. A glass fiber insulating quilt was laid on the ceiling but did not cover it all directly. The ceiling in the area where the fire started was found to be much distorted and disturbed. The underside of the roof was wood but there was bitumen in the roof structure as well. In certain areas of the communicating corridors, the plasterboard suspended ceiling was perforated. The door of the bedroom in which the fire started was open so there was a plentiful supply of air for fire development there, and smoke evolved could either leak through into the void directly or pass into a corridor where perforations conducted the smoke into the void. Smoke could also pass into closed bedrooms by penetrating the ceiling at the outer edges.

The dominating factor in this incident was the deep inadequacy of fire safety in the building itself due to the presence of the extensive void. The building was of a popular design, and a large number of such buildings had been built before sufficient experience was accumulated to appreciate the hazard. In this way, it has similarities with other manufactured or built items, which have a design fault that does not show up until an extensive amount of capital has been invested. This left a major problem of what one did to improve the safety of the many other CLASP buildings so that at least the hazard could be lived with even though it was impossible to eliminate. The judicious combination of fire detection, fire stopping, and subdivision of the voids served to reduce the risk to a tolerable level.

3.4 Fires associated with explosions

3.4.1 MV BETELGEUSE, IRELAND, 1979

MV Betelgeuse was a tanker of 61,776 gross registered tonnage, carrying a cargo of 75,000 tonnes of Arabian heavy crude and 40,000 tons of Arabian light as well. It was off-loading at a jetty about 400 m off Whiddy Island in Bantry Bay, Ireland, when the first of several explosions

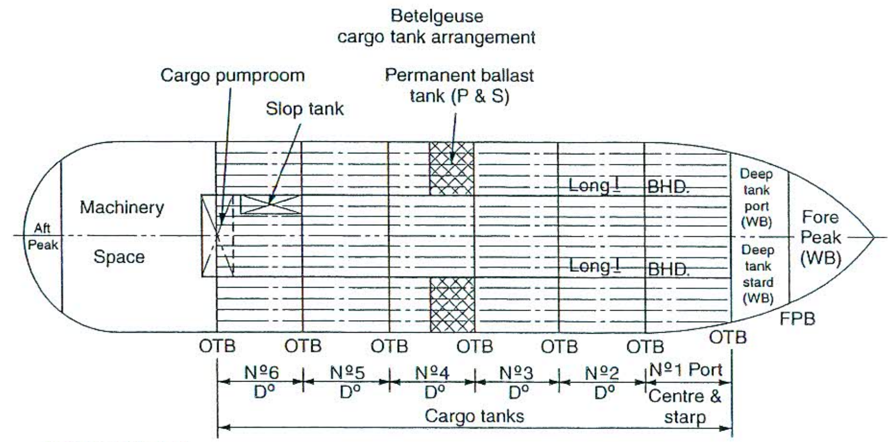


Figure 3.16. MV Betelgeuse as tied up at the jetty

occurred. An account is given in Costello (1980). Figure 3.16 is a diagram of the ship as it was tied up at the jetty showing the arrangements of the main tanks of the ship. There were 18 tanks in 6 groups of 3, each group of 3 consisting of a center tank, and port and starboard wing tanks. Number 4 wing tanks were further divided to provide two ballasting tanks 4(a), 4(b).

At about 00.30 on 8 January, it had already off-loaded its heavy crude from number 1 and 6 tanks and the central tanks, prior to off-loading the light crude from wing tanks 2, 3, 4(b), and 5. Certain water ballasting activities were being carried out, mainly involving the 2 to 5 center tanks that had discharged cargo. A muffled explosion took place in tanks 4(a) that were very near the center of the ship. This broke the back of the ship just aft of number 3 tanks and caused a release of light crude from wing tanks 3. A fire was started near the center of the ship, but as crude oil was released the fire soon found its way around the side of the ship. At 1.06 a violent explosion occurred in the rear part of the ship in all three number 6 tanks and in the center tank of number 5. The back of the ship was further broken and there was a further major release of light crude and an intensification of the fire. There was no connecting passageway from the jetty to the island, and 50 people who were on the ship and the jetty died as a result of the fire. Figure 3.17 shows the ship broken into three parts (central part under water) some 12 h later.

Evidence given at the public inquiry indicated that the primary cause of the disaster was the failure of the structure of the ship as a result of the stresses caused by the discharging and ballasting operations. Parts of the ship from which the cargo had been discharged were subject to an upward force, and parts in which cargo or ballast was present were subject to a downward force. Over the period of operation of the tanker there had been substantial corrosion on the structural members of the ship leading to wastage of these members. Calculations based on the load ballast conditions of the ship at the time of the disaster showed that the longitudinal structural members near the deck of number 4 ballast tanks would have buckled under the strain. There was strong evidence that this buckling took place and that it occurred prior to the explosions in the 4(a) tanks. It was postulated that this buckling caused structural failure between the vapor space of

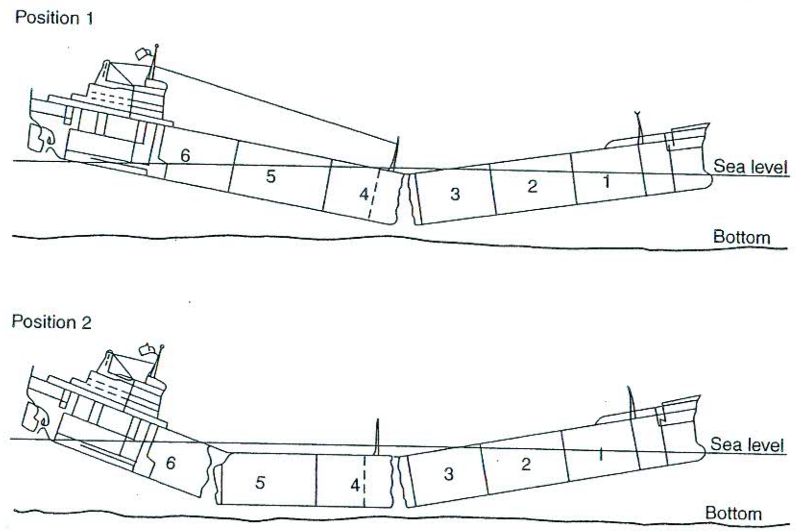


Figure 3.17. MV Betelgeuse some 12 hours after the explosion

the number 3 wing tanks containing light crude and the number 4 ballast tanks, allowing vapor to enter and an explosive mixture to develop within the latter. Moreover, rubbing or impact between steel parts caused by the buckling process could have established sparks sufficiently incendiary to ignite the gas mixture. The resulting explosion in the ballast tanks caused the bottom plates of the ship to fracture. This would have resulted in a massive release of light crude on both sides of the ship.

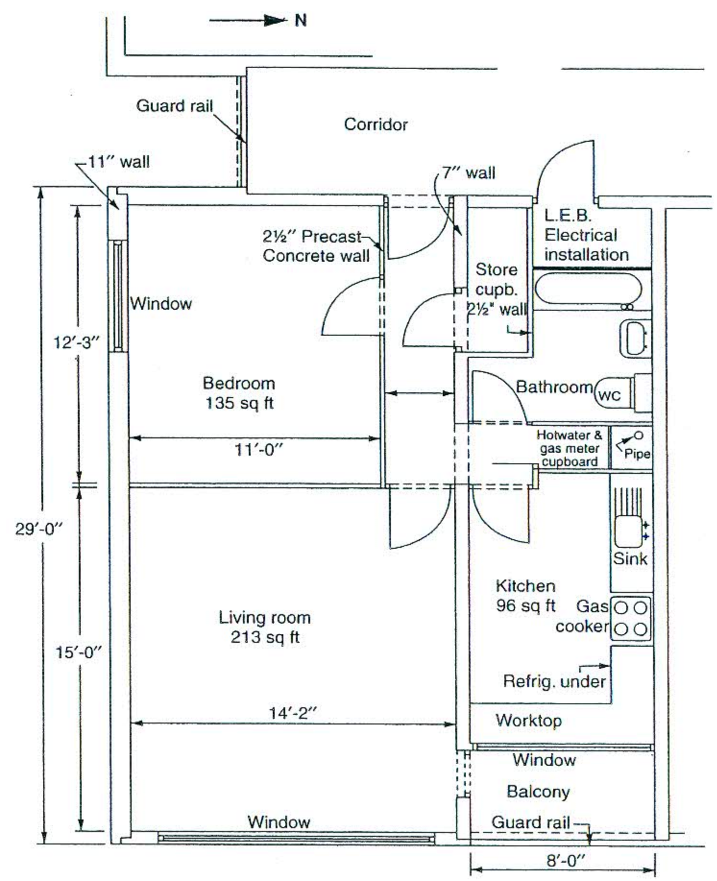
Among a number of recommendations, the tribunal strongly supported the use of inert gas to displace air in spaces above tanks and to replace discharged cargo. Also closer supervision of structural stresses during discharging and ballasting operations and efficient measures to monitor and counteract corrosion in tanks were called for.

3.4.2 RONAN POINT, LONDON, 1968

Ronan Point was a 22-story block of flats, with 5 flats per floor, on a concrete podium containing garages and a car deck. It was built using the Larsen Nielsen system, an industrialized method chosen to save using skilled labor. At about 05.45 on 16 May, 1968 there was an explosion in Flat 90, at one corner of the eighteenth floor (see Figure 3.18). There was the same layout in the flats above and below Flat 90. A full account of the incident is given in the Ministry of Housing and Local Government (1968).

The explosion blew out the non–load-bearing face walls of the kitchen and living room and also the external load-bearing flank wall of the living room and bedroom of the flat, thus removing the corner floor slabs of the floor above, which then collapsed (see Figure 3.19). The flank walls and floor above this collapsed in turn, and the weight and impact of the wall and floor slabs falling on the floors below caused progressive collapse of the floor and wall panels right down to the level of the podium (see Figure 3.20).

The first Fire Brigade officer to enter the remains of Flat 90 found that a fire had good hold on the contents of the kitchen and bathroom and part of the entrance hall, being fed by ignited town



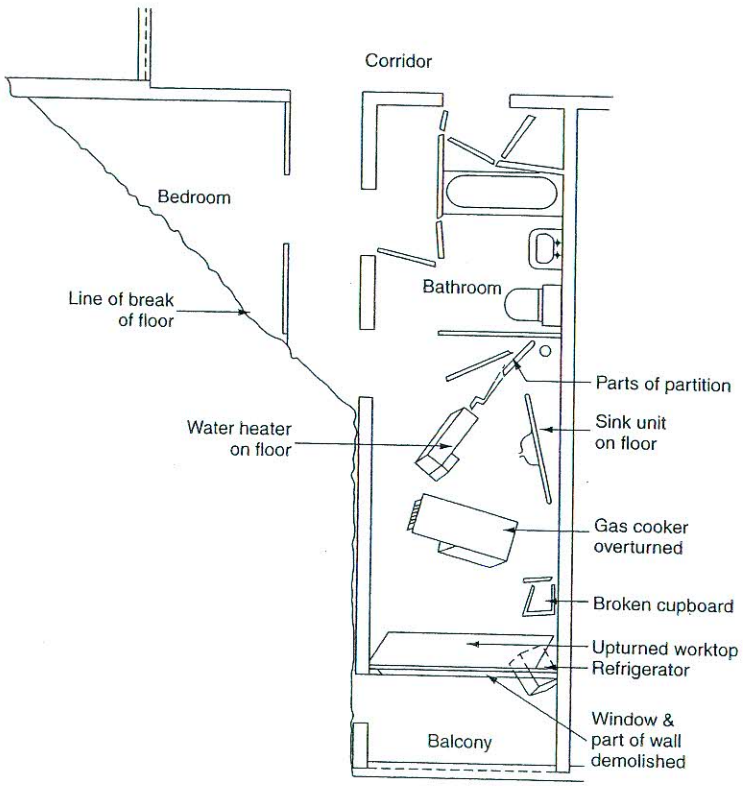
Plan (b) *Layout of Flat 90*

Figure 3.18. Plan of Flat 90, Ronan Point, before the explosion

gas that was escaping from a supply pipe in the kitchen. One jet of water quickly brought the fire under control, and when the main gas cock was turned off, the burning gas was immediately extinguished.

There were four deaths due to multiple crushing injuries, two being on the 19th and two on the 17th floor. Seventeen people were injured, one dying later from an unrelated cause and the others suffering no permanent injury or disfigurement. The person in whose flat the explosion occurred found herself lying on the floor when she recovered consciousness, made her own way out and suffered from minor shock and burns.

All the living rooms at the corner were almost completely destroyed on each floor, as were the bedrooms on the upper floors, down to the sixteenth floor. Below this, the bedroom floors held and damage was not extensive (see Figure 3.20). There was a main load-bearing cross wall



Plan (c) *The extent of the damage to Flat 90*

Figure 3.19. Plan of Flat 90, Ronan Point, after the explosion

between the living room and the kitchen and it did not fail. Except for damage to the kitchen of flat 90 caused by the explosion, the kitchens were relatively unaffected. Apart from the one corner, the block was very little affected either by the explosion or the subsequent collapse. The flat immediately opposite Flat 90 suffered from blast, as did the fire doors and lift doors on that floor. There was virtually no blast damage elsewhere and no visible damage.

The Inquiry by the Ministry of Housing and Local Government (1968) stated that the cause of the disaster was a town gas explosion in Flat 90. The gas had escaped into the flat due to the failure of a substandard brass nut joining the flexible connection from the gas cooker to the gas supply pipe, and the explosion occurred when the tenant struck a match to light her cooker. It was concluded that the explosion was not of exceptional violence, being approximately 83 kPa (12 lb/in^2) in the hall and probably not more than 70 kPa (10 lb/in^2) in the kitchen. This was within the "normal" range of domestic gas explosions. It was estimated from fire brigade reports of 1966 that the frequency of gas explosions involving town gas in premises supplied with gas was approximately 8 per million dwellings, of which 3.5 per million were of sufficient violence

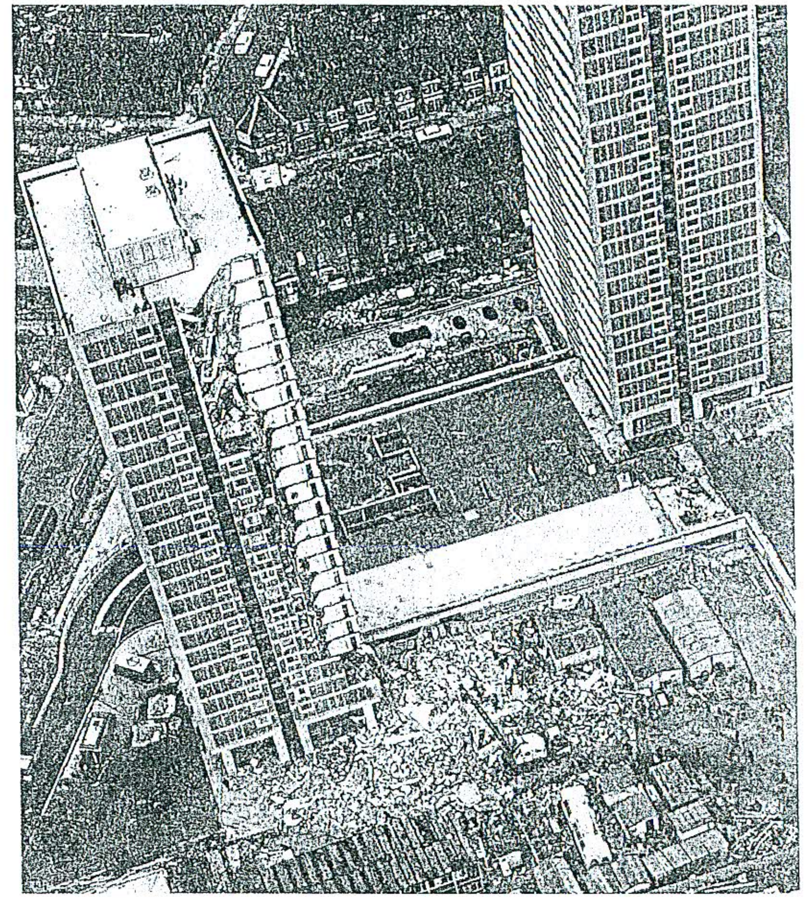


Figure 3.20. Aerial view showing Ronan Point and Merritt Point

to cause structural damage. In the light of these figures, the Inquiry accepted that town gas was a safe and acceptable domestic fuel, but the nature of the risk per dwelling in high blocks is transformed if progressive collapse can occur as the result of an explosion in one flat. It was noted that when structural damage was involved, the cause was far more likely to be faulty equipment than a fault on the part of the user.

There were three possible ways of dealing with the hazard: preventing an explosion by disconnecting gas supplies from tall blocks; preventing the load-bearing walls being pushed out by using ventilation, explosion relief and strengthening; preventing progressive collapse by providing alternative load paths.

The Inquiry rejected the first method, on the grounds that gas was justifiably regarded as a safe and acceptable fuel in domestic premises and was likely to become even more popular when supplies from the North Sea came on line. Furthermore, there remained the possibility of explosions from other substances than town gas, as well as other forms of accidental damage. However, a statutory requirement for inspection of gas installations was recommended. The Inquiry concluded that if the windows had been open in Flat 90 then the explosion would not have occurred, and recommended that consideration should be given to improving ventilation in flats in high blocks. Finally, the Inquiry recommended new provisions in the Building Regulations to deal with progressive collapse, taking into account wind, fire, and explosion.

3.4.3 PIPER ALPHA PLATFORM, NORTH SEA, 1988

The Piper Alpha Platform came on stream in 1976 (Drysdale and Sylvester-Evans, 1998). At the time of the disaster it was producing some 125,000 barrels of oil per day, one third of its total capacity. At about 2200 on 6 July, 1988, an explosion occurred at the Production Level, followed swiftly by a major fire. The platform was destroyed and evidence from the survivors was thus critical at the Cullen Inquiry (1990). The east elevation of the Platform before the explosion is shown in Figure 3.21.

The Production Level was divided into four modules

A – the well heads
B – separation of oil
C – gas compression with gas condensate collected in a drum beneath this module
D – control room, workshops, switch gear, electrical power generator, diesel power generator

The accommodation modules were located above Module D, including the east replacement quarters (ERQ), which was a four-story building used as the main muster area. Firewalls separated the modules – 4.5 h rated between A/B and B/C, and 6 h rated between C/D – but they were not rated for explosion overpressure.

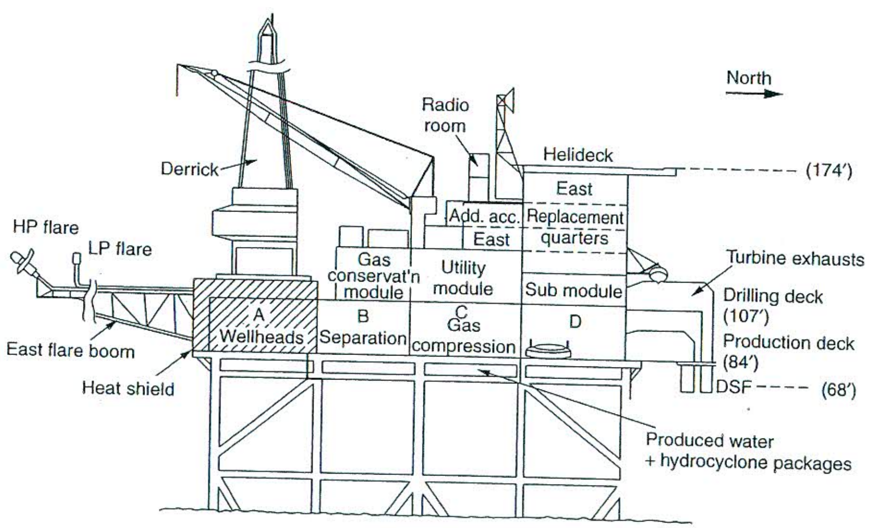


Figure 3.21. Piper Alpha platform: east elevation

The Cullen Inquiry concluded that the initial explosion was in module C, fueled by a release of condensate from a blind flange that had not been fitted securely. The ignition source was not established. The overpressure from the explosion caused failure and breakup of B/C and C/D firewalls. Ejection of wall panels caused a rupture of pipe work in module B – thus releasing crude oil – and also failure of a condensate pipeline passing from C to B, which created a fireball some 28 m in diameter. Unburned fuel-rich gases from the fire in module B, and residual fuel from module C flowed towards module D to produce a fire beneath the ERQ. A crude-oil fire developed in module B and continued until at least 2250. A riser failed catastrophically at 2220 resulting in a massive fireball and leaving a torch flame to develop beneath the whole platform, at which time the atmosphere in the ERQ had already deteriorated badly. A second riser failed at 2250 and a major fireball developed. Between 2300 and 2330, the two other risers failed, the derrick collapsed and the center of the platform sagged. Shortly thereafter, the ERQ toppled into the sea.

There were 61 survivors out of 226. After the explosion occurred, the smoke plume prevented access to either modules B or C, but personnel were able to move through module A and then make their escape at a lower level. Of the 135 bodies recovered (79 being from the ERQ), only 4 indicated death from burning. Most died from inhalation of smoke and gas. Smoke prevented access to lifeboats and helicopter access to the helideck was not possible. Areas of refuge were not effectively sealed from smoke.

As a result of the disaster, much effort has been expended worldwide in the mitigation of effects from explosions and fires. It is possible to estimate overpressures using various empirical relationships. Blast walls and relief panels have been installed accordingly. Pipeline inventories have been isolated from fixed installations. Emergency shut down valves have been increased in number and installed in protected locations. The importance of preventing hydrocarbon leaks has been recognized. Nevertheless, over a two-year period up to October 1994 some 523 releases were reported to the UK Health and Safety Executive, 70% of which involved more than 10 kg of hydrocarbon. Fortunately, the frequency of ignition was only 3% (HSE, 1996). Efforts to mitigate the effects of smoke include pressurization of secure areas, air locks, barriers, water spray, sealing of wall penetrations.

The above measures, together with new lifetime management systems, have made considerable improvements, leading Drysdale and Sylvester-Evans (1998) to suggest that the risk of a major disaster offshore may have been reduced by about 90%.

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4 REQUIREMENTS FROM PUBLIC AND PRIVATE AUTHORITIES FOR FIRE SAFETY

4.1 Introduction

Fire safety has been a concern of mankind for centuries, even millennia. It has been expressed in edicts usually following major fire or explosion disasters and guided by such understanding of fire and explosion as was available at the time. In the wealthier countries of the world, the present generation has inherited a large swath of legal and other requirements and associated advice. The legal requirements emanate from many government departments since they tend to gravitate to the department concerned with the risk or hazard rather than the phenomena of fire and explosion as such. In addition, local authorities, insurance companies, standards bodies, and professional organizations are concerned with setting requirements for fire safety. There is also a major international element concerned with transport fire hazards and the requirements of international trade. Most of the requirements of the relevant legal instruments are prescriptive in nature. However in recent years, particularly as more is understood of the nature of fire hazard, a functional and more open approach to fire safety legislation has been developing.

The first task for the engineer designing fire safety for a specific hazard area is to become acquainted with the legal requirements concerning the safety for this area and the relevant advice that exists on how to fulfill these requirements. In this chapter, a summary is given of legal and other requirements for fire safety in the United States (Sections 4.2 to 4.6), Canada (Section 4.7), and the United Kingdom (Section 4.8), which may be regarded as examples of countries where extensive fire safety requirements exist.

Legal requirements for fire safety change frequently and do not endure in the same way as scientific relationships. In the narrow sense, much of this chapter is already out of date. However, many of the past requirements embody ideas that were considered to be a good practice at the time and they rightly command respect. Knowledge of these requirements is an aid to judgment, which is a vital part of the evaluation of fire safety. Fire safety engineers need to know what the law currently requires of their project, but they should also understand how these requirements have been developed.

4.2 US regulatory environment

Over the years, most US jurisdictions have developed building regulations designed to provide for public safety. Building codes and similar instruments are adopted sets of rules designed to

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8 LIFE LOSS

8.1 Introduction

It is necessary to understand the characteristics of fire casualties, factors affecting life risk, and the behavior of building occupants at the time of a fire in order to incorporate appropriate life-safety measures into fire regulations, codes, and standards. A fair deal of information on these aspects can be obtained by analyzing the fire statistics that are available in many countries, particularly the United Kingdom, United States, and Japan. These statistics reveal some general trends and patterns as described briefly in this chapter.

Fire statistics show that loss of life due to the structural instability or collapse of a building involved in fire is a rare occurrence. Risk to life in a fire is mainly due to exposure to heat, smoke, and toxic gases produced by burning materials or products such as upholstered furniture. Smoke particles when dispersed in the air reduce visibility and can also lead to sensory irritation. Inhalation of heated air, whilst not instantly fatal, can lead to death in a short time if the temperature exceeds a certain level. Exposure of a person to a large dose of a toxic gas can cause incapacitation and eventual death.

The rates at which fatal and nonfatal casualties occur in fires are quantitative indicators of life risk consistent with the form in which statistics are available at present. Fatality rate per fire is a particularly useful measurement, especially if it can be related to the time factor and its components involved in the evacuation of a building. This problem is discussed with the aid of an exponential distribution applied to data available from UK fire statistics. This distribution arises from a Poisson probability model that can also provide an estimate of the multiple-fatality rate as a function of evacuation time. This rate provides an appropriate yardstick for measuring the life risk posed by fire, particularly in a building occupied by a large number of people.

Fatal Accident Frequency Rate (FAFR) is another measurement of life risk, which is generally taken into account for industrial buildings and plants. The FAFR due to fire in different risk areas is compared with other sources of death. The rate of death per person, per fire, or per annum is another useful indicator if data are available on the number of persons at risk in different types of buildings.

The last section of this chapter is concerned with a fire risk assessment method that was recently developed in the United States. This method is useful for analyzing the impact of changes made

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to a combustible product on its life-safety risk. The basic features of this method are discussed together with the results obtained for upholstered furniture, which was the product investigated in one of the case studies.

8.2 Characteristics of fire casualties

A proper perspective of the risk to life in fires can be obtained by analyzing the statistical data on fire casualties. Information on fire casualties, particularly deaths in the United Kingdom, was analyzed by Chandler during the 1960s and 1970s in a series of interesting research notes and reports (see, for example, Chandler (1971, 1972)). According to these studies, smokers' materials have been the main known cause of fire fatalities, especially among the elderly. In the United States, the National Fire Protection Association (NFPA) publishes every year in its journal an analysis of fire deaths including incidents involving multiple deaths. Sekizawa (1988, 1991) and Hall (1990) have investigated the reasons for the differences in fire death rates between United States and Japan. They have drawn some useful conclusions, a summary of which is as follows.

Japan's overall fire death rates per million population are far lower than those in the United States; fire death rates in the United States are two and a half times the corresponding rates in Japan (excluding incendiary suicides). However, the gap has closed to some extent in the past decade due to the fact that US fire death rates declined substantially prior to 1982 while rates in Japan declined very little. Deaths due to incendiary suicides have been increasing in Japan, partly offsetting the decline in fire deaths due to all other causes.

Sekizawa (1991) has identified two typical fire death patterns in residences in Japan – "Disaster-Vulnerable People and Daytime Fire" and "Nondisaster-Vulnerable People and Nighttime Fire." The former pattern can be described as the case in which a person who needs help to move encountered a fire and failed to escape when he/she was alone during daytime. The latter pattern involves a person capable of normal physical function getting killed in a fire mainly because of the delay in detection while asleep or in a drunken state during the nighttime. The majority of people in the disaster-vulnerable group are aged 65 and over, so that the fire death rate is much higher than that for the other group. Older adults are a high-risk group in the United Kingdom and United States as well. Fire death rates in Japan are nearly equal to the US rates for ages 71 to 80 and one-fourth higher for ages 81 and above.

For adults from 31 to 50 years of age, nearly two-thirds of all Japanese fire deaths are incendiary suicides. Without this uniquely Japanese problem, the US rates are more than triple the Japanese rate for this age group. In Japan, only children and older adults (age 61 and above) have most of their fatal fires from accidental causes. Similar fire death patterns in homes in the United States have been identified by Karter (1986).

In the United States, as in the United Kingdom, preschool children (ages 0–5) are a high-risk group, with a fire death rate nearly twice the average for all ages. In Japan, preschool children have a higher fire death rate than older children but about the same risk as the overall average if incendiary suicides are excluded. One reason for this difference is probably a higher incidence of single-parent families in the United States and a generally larger incidence of gaps in child supervision (Fahy, 1986). This factor together with proportion of children-in-care, perhaps, reflects family instability identified by Chandler (1979) as a social indicator strongly correlated with fire incidence. Preschool children in Japan also are more likely to sleep in their parents' rooms, which may give them an advantage in responding to fires. US preschoolers have a fire death rate four times the rate of their Japanese counterparts.

Most of the fire deaths occur in dwellings. In the United Kingdom and United States, the majority of deaths in accidental fires in dwellings were attributed to a relatively small number of specific causes such as careless disposal of smokers' materials, incidents with space heaters – mainly misuse or placing articles too close to them, ignition of matches mostly by children playing with them and misuse of cooking appliances. Electricity is the major fuel where deaths are caused by the misuse of space heaters or cooking appliances. As mentioned in Section 7.8, a contributory factor for an increase in fire deaths during severe winter is the use of portable heating appliances to supplement central heating.

In the United States, heating appliance deaths are mainly caused by portable heaters and space heaters, especially in poor and rural areas. Japan also has proportionally more trouble with heating equipments. The high risk of fire deaths among older adults in Japan may be partly due to the use of older types of portable heaters such as kerosene heaters that can cause serious fires when placed too close to combustibles in the small rooms typical of Japanese homes.

The pattern of nonfatal casualties from accidental dwelling fires in the United Kingdom is generally similar to that of fires caused by the misuse of cooking appliances, mostly electric or and the remainder gas. The next most common specific cause is the careless disposal of smokers' materials, followed by electric and gas space heating appliances, electrical wiring, electric blanket, and bed warmer. Television sets, washing machines, and dishwashers are other minor causes of nonfatal casualties. There is a falling trend in nonfatal casualties, where the source of ignition is an electric blanket or bed warmer. The characteristics of nonfatal casualties mentioned above are generally true for the United States and Japan.

8.3 Location of casualties

According to Table 8.1 based on the UK Fire Statistics for the period 1978 to 1991, half of the casualties in single-occupancy dwellings were found in the room of fire origin. Most of the remaining casualties were found elsewhere on the floor of origin or floors above the floor of origin. A comparatively smaller number of casualties was found in the floors below the floor of fire origin. Location of casualties in multiple-occupancy dwellings had a similar pattern except that an almost equal number of nonfatal casualties were found in the room and floor of fire origin.

It is understandable that occupants in the floors above the floor of fire origin have greater risk than those in the floors below. Fire, smoke, and toxic gases generally spread upwards and are more likely to be encountered by the people in upper floors whether they remain in their places of occupation or attempt to escape to safer places in or outside the building involved in fire. People in lower floors have a greater chance of avoiding combustible products and escaping safely.

It is apparent that while fire is a major threat to the occupants in its immediate vicinity, it is generally smoke and toxic gases that pose a greater threat than flame (heat) to the occupants who are remote from the fire. Smoke and fumes travel faster than fire to the occupied areas and escape routes. Even a small fire can generate considerable amounts of smoke and other combustible products and threaten a greater number of occupants outside the room of origin. Most building fires spread beyond the room by convection (advance of flame, smoke, and hot gases) rather than by the destruction of the structural boundaries (Harmathy and Mehaffey, 1985). A majority of fires in dwellings, where most of the casualties occur, are confined to the room of origin (see Table 8.2 based on the UK Fire Statistics).

Table 8.1. Location of casualties – single- and multiple-occupancy dwellings

Whereabouts of casualty and occupancy type	Number of persons	
	Fatal	Nonfatal
Single-occupancy dwellings		
Room of origin of fire	3539 (58.2)	26,259 (44.6)
Elsewhere on the floor of origin	1216 (20.0)	15,500 (26.3)
Floors above the floor of origin of fire	1267 (20.8)	14,835 (25.2)
Floors below the floor of origin of fire	54 (1.0)	2330 (3.9)
Total	6076 (100.0)	58,924 (100.0)
Multiple-occupancy dwellings		
Room of origin of fire	2347 (66.8)	15,353 (35.0)
Elsewhere on the floor of origin	823 (23.4)	18,245 (41.6)
Floors above the floor of origin of fire	330 (9.4)	9066 (20.6)
Floors below the floor of origin of fire	16 (0.4)	1233 (2.8)
Total	3516 (100.0)	43,897 (100.0)

Note: The numbers within brackets denote the percentage number of casualties.
Source: Fire Statistics, United Kingdom, 1978–1991.

Table 8.2. Spread of fire in dwellings (Fires starting in rooms or compartments within buildings)

Extent of spread	Number of fires	Percentage of fires
Confined to the item ignited first	308,844	40.2
Spread beyond the item but confined to the room contents only	184,020	24.0
Structure involved	215,464	28.1
Spread beyond the room but confined to the floor	25,540	3.3
Spread beyond the floor	33,527	4.4
Total	767,395	100.0

Note: Spread of fire only, not heat, smoke, and so on.
Source: Fire Statistics, United Kingdom 1978–1991.

8.4 Nature of injuries

Consistent with the location of casualties (Table 8.1), burns cause the highest percentage of fatalities in the room of fire origin. Elsewhere, gas or smoke is the major cause and accounts for more than 50% of the fatalities in the dwellings overall (see Table 8.3). Statistical studies and surveys (Bowes, 1974) carried out in the United Kingdom in the 1970s revealed that not only was

Table 8.3. Fatal casualties in dwellings by whereabouts of casualties and cause of death

Whereabouts of casualty and occupancy type	Number of persons		
	Cause of death		
	Overcome by gas or smoke[a]	Burns or scalds	Other or unknown causes
Single occupancy			
Room of origin of fire	1653	953	328
Floor of origin of fire	731	133	116
Elsewhere	868	130	118
Total	3252	1216	562
Multiple occupancy			
Room of origin of fire	1217	510	200
Floor of origin of fire	504	66	67
Elsewhere	217	37	40
Total	1938	613	307

[a]Including cases where "burns" and "overcome by gas or smoke" were joint causes of death.
Source: Fire Statistics, United Kingdom, 1978–1988.
A breakdown of figures for causes of death as in the table has not been published for the years 1989 to 1991.

a large proportion of fatal and nonfatal fire casualties being reported in the category "overcome by smoke and toxic gases" rather than heat and burns but also that there was a fourfold increase in the former category between 1955 and 1971. In the United States, in the absence of detailed national fire statistics during the 1970s, victims in a number of large fire disasters were reported, in newspapers and fire journals to have died from exposure to toxic smoke products.

It is an accepted fact that toxic products of combustion are the major causes of incapacitation and death in fires (Berl and Halpin, 1976, Harland and Woolley, 1979). In many fires, death or injury is not due to the immediate toxic effects of exposure to these products but results from the victim being prevented from escaping due to irritation and visual obscuration caused by dense smoke or to incapacitation caused by narcotic gases. Consequently, the victim remains in the fire and sustains fatal or nonfatal injury due to a high dose of toxic products inhaled during the prolonged exposure or due to burns. According to UK fire statistics, more than 50% of fatalities and more than 30% of nonfatal casualties are trapped by smoke or fire, because they either were unaware (asleep etc.) of fire or because of other reasons. Survivors from fires may also experience pulmonary complications and burn injuries that can lead to delayed death.

Increasing fire risk due to smoke and other combustion products led to the commencement of intensive research on combustion toxicology (Purser, 1988) during the 1970s. These studies have ranged from fundamental laboratory-based thermal decomposition experiments to large-scale fires with comprehensive gas analysis, bioassay, and detailed pathology of fire victims. Two types of models have been developed – the "mass loss" model and the "fractional effective dose" model. Both the models require as inputs the rates of generation of life-threatening combustion products and the estimate of the times when tenability limits are exceeded, resulting in incapacitation or death. For calculating these limits two major computer packages are available – ASKFRS (Chitty and Cox, 1988) developed by the Fire Research Station, UK and TENAB which is part of HAZARD developed by the Centre for Fire Research, National Institute of Standards and Technology, USA

8.5 Materials first ignited

Fires in the United Kingdom during the past few years when food fat was the material first ignited have risen steadily, but account for only a small number of deaths. The group of materials next most frequently first ignited was textiles, upholstery, and furnishings, accounting for more than 20% of dwelling fires and also for a large number of deaths. Within this group the major items were bedding, upholstery, or covers and clothing. Other individual items first ignited in a large number of fires in dwellings were electrical insulation and paper or cardboard.

The observations mentioned above were more or less true even 20 years ago. An analysis of UK fire statistics for 1970 showed that the chance of fatality in fire involving furniture and furnishings was twice that of other fires in houses (see Chandler and Baldwin (1976)). The majority of these fires involved upholstery and bedding and over 90% were caused by smokers' materials, electric blankets, space heating or the activities of children, and suspected arsonists. Nearly all fatalities were found in the fire room, overcome by smoke or toxic gases and the great majority were young or elderly (over 65). The main hazard appeared to be to people in armchairs and beds, using potential sources of ignition (smoking, space heating etc.), failing to respond to a fire in their vicinity through being asleep or otherwise incapacitated, and then being overcome by smoke or toxic gases. According to a study carried out by Clarke and Ottoson (1976), more than one-fourth of all US residential fire deaths resulted from upholstered furniture fires. Smouldering cigarettes inadvertently dropped on furniture were a common cause of these fires.

One possible reason for the increase in smoke-related casualties in homes during 1970s was the increased use of modern synthetic materials in furnishings and upholstered furniture. Cellulosic materials were replaced by thermoplastic fibers and urethane foam cushioning materials. The increase may not be directly related to modern materials but to the changes in living styles, which have led to more furnishings and upholstery material being used in homes. The introduction of synthetic upholstery fabrics has offered enormous scope to furniture designers where fashion appeal, color, durability, stain resistance, and so on are required and these fabrics have virtually replaced the traditional covers.

There is little doubt that the gradual change from natural to synthetic materials has brought certain benefits in fire performance. Natural materials tend to be prone to smouldering from small ignition sources, particularly when in contact with a lighted cigarette, whereas synthetic materials tend to be more resistant to this type of ignition. However, the synthetic fabrics are mainly thermoplastics and when subjected to a flame can burn rapidly with the fabric "melting" to expose the flammable infill fibers and foams. Natural fabrics (wool, cotton etc.) tend to form carbonaceous chars during flame exposure, which can act as an effective barrier to the penetration of fire. The results of a series of experiments (Woolley *et al.*, 1978) illustrated the ease of ignition of modern upholstery materials even with small ignition sources.

8.6 Casualty rate per fire

A simple yardstick for measuring life risk due to fires in any type of building is the ratio between number of fatal or nonfatal casualties and number of fires. Global trends in the risk can be observed by calculating the annual casualty rates per fire as shown in Tables 8.4 and 8.5. These figures have been extracted from Fire Statistics, United Kingdom published annually by the Home Office. (There is generally a delay of about two years for the publication of statistics for any year.) The figures for any other type of building can be obtained from the Home Office on payment of charges covering mostly the cost of computer time.

According to figures in Tables 8.4 and 8.5, both the fatal and nonfatal casualty rates do not vary significantly from year to year. In fact, there is some indication that the rates are gradually declining

Table 8.4. Fatality rate per fire

Year	Single-occupancy dwellings			Multiple-occupancy dwellings		
	Number of deaths	Number of fires	Fatality rate per fire	Number of deaths	Number of fires	Fatality rate per fire
1978	473	35,049	0.0135	251	15,830	0.0159
1979	575	38,629	0.0149	282	17,223	0.0164
1980	533	33,886	0.0157	268	15,683	0.0171
1981	496	35,230	0.0141	279	18,274	0.0153
1982	457	34,994	0.0131	257	18,826	0.0137
1983	432	34,667	0.0125	274	20,195	0.0136
1984	436	34,972	0.0125	250	21,020	0.0119
1985	438	36,905	0.0119	255	22,468	0.0113
1986	462	37,313	0.0124	283	22,389	0.0126
1987	441	36,669	0.0120	267	23,286	0.0115
1988	445	36,251	0.0123	269	24,331	0.0111
1989	394	34,947	0.0113	234	25,514	0.0092
1990	372	33,535	0.0111	246	25,328	0.0097
1991	382	33,876	0.0113	208	25,632	0.0081
Overall	6336	496,923	0.0128	3623	295,999	0.0122

Source: Fire Statistics, United Kingdom.

Table 8.5. Nonfatal casualty rate per fire

Year	Single-occupancy dwellings			Multiple-occupancy dwellings		
	Number of casualties	Number of fires	Casualty rate per fire	Number of casualties	Number of fires	Casualty rate per fire
1978	3503	35,049	0.0999	1835	15,830	0.1159
1979	3712	38,629	0.0961	2265	17,223	0.1315
1980	3463	33,886	0.1022	2017	15,683	0.1286
1981	3755	35,230	0.1066	2471	18,274	0.1352
1982	3966	34,994	0.1133	2605	18,826	0.1384
1983	4239	34,667	0.1223	2809	20,195	0.1391
1984	4546	34,972	0.1300	3112	21,020	0.1480
1985	4836	36,905	0.1310	3506	22,468	0.1560
1986	5459	37,313	0.1463	3736	22,389	0.1669
1987	5362	36,669	0.1462	3932	23,286	0.1689
1988	5590	36,251	0.1542	4399	24,331	0.1808
1989	5594	34,947	0.1601	4607	25,514	0.1806
1990	5233	33,535	0.1560	4647	25,328	0.1835
1991	5676	33,876	0.1676	4976	25,632	0.1941
Overall	64,934	496,923	0.1307	46,917	295,999	0.1585

Source: Fire Statistics, United Kingdom.

over the years. This trend is generally true for fires in the United States and Japan. An increase in the number of fires appears to be a major factor affecting an increase in the number of casualties. The results mentioned above, perhaps, indicate the fact that fire fighting and protection strategies including fire safety codes are performing effectively in the United Kingdom, United States, and Japan, while fire prevention activities aimed at reducing the frequency of fires need to be stepped up.

According to the figures quoted by Hall (1990), the overall civilian death rate per fire in 1987 was 0.0025 for the United States and 0.0316 for Japan. Excluding incendiary suicides the fatality rate for Japan was 0.0185. According to fire statistics for the years 1981 to 1991, the overall fatality rates for United Kingdom are 0.0026 for all fires and 0.0075 for occupied buildings. For United Kingdom, the overall rates for nonfatal casualties are 0.0346 for all fires and 0.1062 for occupied buildings compared to 0.0121 for United States and 0.1306 for Japan. The UK rates for both the fatal and nonfatal casualties are considerably higher than the corresponding rates for United States but lower than those for Japan. One reason for the differences in the rates for the three countries may be differences in the methods of classifying and estimating fire casualties data; there may be other reasons also. Any comparison of fire casualty rates between countries ought to be made with caution.

8.7 The time factor

In the event of a fire in a building, the casualty rate, fatal or nonfatal, would increase with the time (t) spent by the occupants under untenable conditions caused by combustion products. As a first approximation, the increase in the casualty rate per unit time, say, a minute, may be assumed to be a constant λ. The parameter λ can be estimated by relating the overall casualty rate discussed in the previous section to the average value of the variable t but sufficient data are not available at present for estimating this average time.

However, an approximate value for λ for any type of building can be obtained by relating casualty rates to delays in discovering fires with the aid of statistics published by the Home Office, UK. For example, based on these statistics for the 14-year period 1978 to 1991, total figures for the number of fires and fire deaths are given in Table 8.6 for two types of dwellings – single-occupancy and multiple-occupancy dwellings. The fatality rates estimated by these figures are also shown. Table 8.6 has been reproduced from a study on early detection of fire and life risk carried out by Ramachandran (1993a), which contains a similar analysis for nonfatal injuries.

The fatality rates for fires discovered at ignition are high apparently due to the fact that, as discussed in Section 8.3 a high percentage of fatal casualties were found in the room of fire origin. The figures in Table 8.6 for the other three categories of discovery time provide some indication of the reduction in fatality rate due to early discovery of fire. The discovery time for the last category, more than 30 min after ignition, can vary significantly within a wide range although an average time of 45 min has been suggested in Section 7.6.

For the reasons mentioned above, a reasonably good estimate of λ can be obtained by considering only the second and third categories – discovered under 5 min and discovered between 5 and 30 min. With average discovery times of 2 and 17 min, the increase in the fatality rate for these two categories divided by 15 provides an estimate of λ measuring the increase per minute as shown in Table 8.6. This method based only on discovery time is similar to "longitudinal analysis" adopted by Maclean (1979) for evaluating the relationship between fire brigade attendance time and fire loss.

Using the estimated value of λ, the linear relationship between fatality rate and discovery time of fires is depicted in Figure 8.1. For any discovery time D, the fatality rate per fire is given by $\lambda . D$ plus a constant K (Table 8.6) estimated by the intercept on the vertical axis. The parameter K, as discussed in the next section, denotes the overall and joint contribution to the fatality rate arising from other time periods involved in the evacuation process (Ramachandran, 1990). These periods are considerably short in relation to the total duration and hence K is only a small percentage of the overall fatality rate. The parameters λ and K are generally applicable to fires not discovered at ignition ($D > 0$). Figure 8.1 provides realistic estimates of the fatality rate for discovery times up to 40 min; extrapolation beyond 40 min would be somewhat unrealistic.

Table 8.6. Discovery time and fatal casualties

Discovery time and occupancy type	Number of deaths	Number of fires	Fatality rate (per fire)
Single-occupancy dwellings			
Discovered at ignition	445	76,243	0.005837
Discovered under 5 min after ignition	686	212,519	0.003228
Discovered between 5 and 30 min after ignition	2156	141,462	0.015241
Discovered more than 30 min after ignition	2766	53,677	0.051530
Total	6053	483,901	0.012509
Multiple-occupancy dwellings			
Discovered at ignition	204	27,805	0.007337
Discovered under 5 min after ignition	334	123,648	0.002701
Discovered between 5 and 30 min after ignition	1281	110,078	0.011637
Discovered more than 30 min after ignition	1703	28,125	0.060551
Total	3522	289,656	0.012,159

Note: Single-occupancy dwelling: $\lambda = 0.000801$
$K = 0.001,626$
Multiple-occupancy dwelling $\lambda = 0.000596$
$K = 0.001509$
Source: Fire Statistics, United Kingdom 1978–1991.

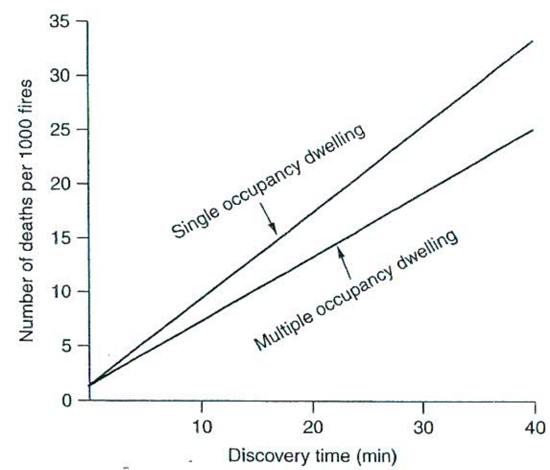

Figure 8.1. Discovery time and fatality rate (current risk level)

For fires that are not immediately discovered, automatic detection systems could reduce the fatality rate if it is assumed that these devices reduce the discovery time. The operation time of detectors depends on several factors such as their type (heat, smoke etc.), the location of the seat of the fire and the rates of development of heat and smoke. Assuming that the reduced discovery time is one minute on average, the reduced fatality rate would be $(\lambda + K)$, that is, 0.0024 for single-occupancy dwellings and 0.0021 for multiple-occupancy dwellings (see Ramachandran

(1993a)). It would be useful to mention in this connection that, (overall) fatality rates per fire of 0.0043 with detectors and 0.0085 without detectors have been estimated for single- and two-family dwellings in the United States (Bukowski *et al.*, 1987).

8.8 Evacuation model

Following the notation adopted by Ramachandran (1990), the discovery period, D, is a major component of the total time (H) taken by an occupant to evacuate a building in the event of a fire. This is the first among three main periods occurring sequentially in time since the start of the fire. The second period, B, is referred to as *recognition time* or *gathering phase* in human behavior studies (Canter, 1985). The third period, E, relates to the elapsed time since the commencement of the actual movement of an occupant until a safe place is reached inside a building, for example, entrance to a protected staircase or outside the building. Although commonly known as *evacuation time*, the period E really refers to an emergency or nonfire situation. Means of escape facilities such as maximum travel distance and number and widths of staircases should be designed according to the total evacuation time $H(= D + B + E)$ but only the subperiod E is generally considered explicitly in fire safety regulations, codes, and standards.

A combustion product such as smoke takes a time, F, to travel from the place of fire origin and produce untenable conditions on an escape route. If the total time H taken by an occupant to get through this route exceeds F, he/she is likely to sustain a fatal or nonfatal injury depending on the level of severity associated with F. For a safe evacuation, the condition $H \leq F$ should be satisfied, which is the objective of designing escape route facilities, smoke control systems, and emergency lighting. This model proposed by Marchant (1980) in terms of the ratio (H/F) has been modified by several authors to include additional periods in the total evacuation time H (see Sime (1986) for a review of these studies).

The evacuation time E and, hence, the total time H are affected by several factors governing the behavior of occupants at the time of a fire (see Canter (1985)). Depending on these factors some occupants may decide to evacuate while some may ignore the fire alarm and remain in their rooms. Some occupants who recognize the existence of the fire may help the group attempting to fight the fire by first-aid means such as portable fire extinguishers. Some occupants may be trapped in their rooms because of their physical conditions (bed ridden, etc.) or mental capability limitations or due to a temporary reduction in their ability because of sleep, drugs or alcohol. Some of the occupants, for example, patients in a hospital involved in evacuation may require assistance in preparing for escape and during escape.

Depending on their location relative to the place of fire origin and other factors mentioned above, some occupants of a building may "succeed" in fulfilling the condition $H \leq F$, while others may "fail" and consequently sustain fatal or nonfatal injuries. As discussed in the last section the casualty rate would increase with the duration of exposure to untenable conditions. This period denoted by t can be expressed as

$$t = H - F \qquad [8.1]$$

An estimate of the increase in the fatality rate per minute of exposure for all the occupants in a building is provided by the parameter λ in Table 8.6 although it is only based on the discovery time. The value of λ is generally small since it is related to the occurrence of a rare event. It is, therefore, an approximation for the parameter p given by the exponential function

$$p = 1 - \exp(-\lambda) \qquad [8.2]$$

The probability of no deaths during any period t since the onset of untenable conditions at time F is given by $\exp(-\lambda t)$ and the probability of one or more deaths by

$$p_d(t) = 1 - \exp(-\lambda t) \qquad [8.3]$$

Again, for values of t encountered in most of the fires λt would be small such that it is an approximation for $p(t)$. In terms of the discovery time D, from equations [8.1] and [8.3], the fatality rate per fire is given by

$$\begin{aligned} p_d(t) &= 1 - W\exp(-\lambda D) \\ &= 1 - W(1 - \lambda D) \\ &= K + W\lambda D \qquad [8.4] \end{aligned}$$

approximately where

$$\begin{aligned} K &= 1 - W \\ W &= \exp[-\lambda(B + E - F)] \\ &= 1 - \lambda(B + E - F) \qquad [8.5] \end{aligned}$$

The values of the parameter K for the two occupancy types considered are given in Table 8.6. In Figure 8.1, W has been amalgamated with λ since it is almost equal to unity.

A model similar to equations [8.4] and [8.5] was suggested by Ramachandran (1990) but with a different weight (not λ) for the time periods B, E, and F. It may be seen (Ramachandran, 1993a) that

$$K = \lambda(B + E - F) \qquad [8.6]$$

Based on equation [8.6], it may be seen that $(B + E - F)$ on average, has the values of 2.0 min for single-occupancy dwellings, and 2.5 min for multiple-occupancy dwellings. The values of B, E, and F for any occupant would vary depending on the location of the occupant with reference to the place of fire origin, mobility of the occupant, and on the decision of the occupant to evacuate or not. From equations [8.4] and [8.6], with $W = 1$,

$$p_d(t) = \lambda(H - F) \qquad [8.7]$$

approximately.

Considering multiple-occupancy dwellings as an example, in the absence of automatic detection systems, the overall fatality rate per fire is 0.0122 as shown in Table 8.4 or 8.6. This rate is consistent with an average discovery time of 18 min such that $t = 20.5$ min from equation [8.1]. In other words, the fatality rate of 0.0122 is the result of exposure to untenable conditions for a period of 20.5 min. Accordingly, $B + E - F$ is 2.5 min such that, from equation [8.6], $K = 0.0015$ as given in Table 8.6.

Installation of automatic detectors in multiple-occupancy dwellings would reduce the detection time to one minute and the fatality rate to 0.0021 as discussed earlier. In this case, the period of exposure to severe untenable conditions, $(H - F)$, is drastically reduced to 3.5 min. In the case of sprinklers, 3 min may be assumed for detection time. Sprinklers, if they operate satisfactorily, will reduce the fire severity and the rate of growth of fire and smoke; they also have a high probability of extinguishing the fire. This performance will increase the time (F) for the commencement of untenable conditions, by say, 4 min. Calculations would show that, if sprinklers are installed in multioccupancy dwellings, $B + E - F = -1.5$ and $H - F = 1.5$ such that the fatality rate is reduced to 0.0009 approximately (see Ramachandran (1993a)). A combination of detectors and sprinklers would reduce the fatality rate to almost zero. The results mentioned above may be adjusted by assigning appropriate probabilities for the nonoperation of detectors and sprinklers.

It may be seen that, for evacuating a multiple-occupancy dwelling, occupants will have, on average, an extra time of 17 min if only detectors are installed, 19 min if only sprinklers are installed and 21 min if the building is equipped with both the systems. In these three cases, there is a clear justification for allowing an increase in the design evacuation time E beyond the level for E specified for a building without these active fire protection devices. For office buildings in the United Kingdom, a design evacuation time of 2.5 min has been recommended in British Standard BS5588.

Depending on the reliability of active fire protection devices and factors such as physical or mental ability of escaping occupants, the increase in E can be up to a limit such that an acceptable level specified for fatality rate per fire is not exceeded. If this level is 0.005, for example, $t(= H - F)$ should not exceed 8.4 min. This level for t can only be achieved if the average discovery time, D, is less than 5.9 min in the absence of automatic fire detection systems; $(B + E - F) = 2.5$ min in this case as discussed earlier. With automatic detectors, $D = 1$ such that $(B + E - F)$ can be increased to 7.4 min. In this case, the design evacuation time, E, can be increased by 4.9 min if B and F are assumed as constants. Hence, E can be increased to 7.4 min for a building with detectors if it is 2.5 min for a building without detectors. Similar calculations would show that the design evacuation time should not exceed 9.4 min if only sprinklers are installed and 11.4 min if the building is equipped with both the systems. A relaxation (increase) in the design evacuation time (E) for a building equipped with fire protection systems would allow for an increase in the maximum travel distance specified in fire safety codes or standards.

The method described in this section is a simple technique based on a regression analysis for estimating approximately the correlation between the fatality rate and the time $t(= H - F)$ measuring the duration of exposure to untenable conditions. The method restricts the variable t to positive values and does not take into account the uncertainties (standard deviations) associated with the random variables H and F. If sufficient data are available for establishing the probability distributions of H and F, a more complex probabilistic method suggested by Ramachandran (1993b) can be applied to estimate the design evacuation time.

8.9 Multiple-Death fires

Fires can not only cause direct damage to human life in terms of fatal and nonfatal casualties but also indirect losses, for example, distress and financial loss to the families of the victims and to the society at large. The aggregate disutility or consequences due to fire deaths would be generally low for single-death fires and high for multiple-death incidents (Ramachandran, 1988). The disutility associated with a single fire with, say, ten deaths is greater than the total disutility caused by ten fires each with a single-death. Catastrophies have serious social and political consequences.

For the reasons mentioned above, it is necessary to analyze specially the characteristics of multiple-death fires and the trends in the rates of occurrence of these large incidents. Such studies are periodically carried out by the NFPA, United States, which publishes its findings in its journal. According to its recent report by Miller and Tremblay (1992), 52 catastrophic multiple-death fires in United States during 1991 claimed 342 lives. Just over half of these fires occurred in residential structures. The remaining 25 included 15 nonresidential structure fires, 9 vehicle fires and a wild fire. Nearly half of all deaths – 160 – occurred in residential structures, 92 in nonresidential buildings and 90 in fires outside of structures.

As revealed in the study mentioned above and earlier reports of the NFPA, the tragedies could have been prevented by adherence to NFPA codes and standards and basic fire safety principles.

Some of the recurring factors in multiple-death fires included the absence of operating smoke detectors and sprinklers, delays in fire department notification, and blocked or locked exits. Other major factors were inoperative or poorly functioning central heating systems, electrical code violations, and lack of escape planning, apart from socioeconomic factors such as poverty and homelessness.

In the United Kingdom, case studies of multiple-death fires have occasionally appeared in fire journals such as the one published by the Fire Protection Association. Only more than 20 years ago a detailed analysis of the characteristics of multiple-death fires was carried out by Chandler (1969). This report showed that during 1960 to 1966, about three-quarters of the multiple-death fires in buildings were in dwellings and most of these were in houses rather than flats. It is probable that most of these fires were in multiple occupancies, where more people were exposed to fires than in single occupancies. Among other occupancies, 10 people were killed in a department store fire, 19 in a fire in a club above an industrial building and 5 in living accommodation above a launderette. A third of the outdoor multiple-death fires were in vehicles and about a quarter in caravans. The winter months accounted for about two-thirds of the multiple-death fires.

According to Chandler (1969) the most prominent of the known sources of ignition in multiple-death fires were smoking materials, oil heaters, children playing with fire, and vehicle crashes. Furniture or furnishings were the leading materials first ignited among known cases. Compared with fatal fires as a whole, a much higher proportion of multiple-death fires involved young children, whereas the proportion of old people was lower. Only 21% of these large life loss fires were confined to the room of origin and 11% spread beyond the building of origin. Provision of self-closing doors at the entrances to stairways in multiple occupancies and improvement of housing conditions were suggested by Chandler as measures likely to reduce the frequency of multiple-death fires.

The annual booklet on fire statistics published by the Home Office, UK, includes a table showing the breakdown of the total number of deaths according to four categories – one death, 2 to 4 deaths, 5 to 9 deaths and 10 or more deaths. This information is given for each year for a 11 year period up to the year to which the publication relates; fires in the last category are listed. According to the list in 1991 statistics, there were 5 fires involving 10 or more deaths during the period 1981 to 1991. These included a 13-death fire in a house in Deptford (1981), a 16-death fire at Abbeystead Waterworks (1984), a 55-death fire at Manchester airport (1985), a 56-death fire at Bradford City football ground (1985), and a 31-death fire at Kings Cross underground railway station (1987).

The annual publication of the Home Office, UK also contains a table on fire fatalities showing the breakdown of the number of fires according to six categories – no death, one death, two deaths, three deaths, four deaths, and five or more deaths. The total figures based on these data for the period 1978 to 1991 are given in Table 8.7 for single- and multiple-occupancy dwellings. A discrete (discontinuous) distribution applicable to a random variable with integer values may be fitted to these data for estimating the probability of occurrence of a given number of deaths in a fire. Poisson is one such distribution that has been widely used in the statistical literature for modeling the occurrences of rare events. Adopting an extended form of this distribution (Beard *et al.*, 1969)

$$p(x, t) = \exp(-\lambda t)(\lambda t)x/x! \qquad [8.8]$$

where

$$x! = x(x-1)(x-2)\cdots\cdots\cdots 2\cdot 1$$

and $p(x, t)$ is the probability of exactly x deaths occurring in a fire due to exposure to untenable conditions caused by combustion products for a period of t minutes.

Table 8.7. Frequency distribution of number of deaths

Number of deaths	Single-occupancy dwellings		Multiple-occupancy dwellings	
	Number of fires	Percentage of fires	Number of fires	Percentage of fires
0	491,532	98.9151	292,747	98.9014
1	4794	0.9648	3002	1.0142
2	421	0.0847	194	0.0655
3	110	0.0221	40	0.0135
4	45	0.0091	10	0.0034
5 or more	21	0.0042	6	0.0020
Total	496,923	100.0000	295,999	100.0000

Note: Single-occupancy dwellings.
Average number of deaths per fire ($\lambda\bar{t}$) = 0.012705
$\lambda = 0.000801$
$\bar{t} = 15.9$ min
Multiple-occupancy dwellings
Average number of deaths per fire ($\lambda\bar{t}$) = 0.012153
$\lambda = 0.000596$
$\bar{t} = 20.4$ min
Source: Fire Statistics, United Kingdom, 1978–1991.

The parameter λ in equation [8.8], as defined in Section 8.7, is the fatality rate or probability of one or more deaths during a unit period of one minute. It is an approximation for the exponential function defined in equation [8.2]. Also, $p(o, t)[= \exp(-\lambda t)]$ is the probability of no death during a period of t minutes such that $[1 - p(o, t)]$ is the probability of one or more deaths during this period as defined in equation [8.3].

For a population of fires, the variable t has an average $\bar{t}$. According to a property of the Poisson distribution, an estimate of $\lambda\bar{t}$ is provided by the overall average number of deaths per fire based on frequency distribution such as in Table 8.7. Assuming an average of, say, 8 deaths for the category 5 or more, calculations would show that $\lambda\bar{t}$ is approximately equal to 0.0127 for single-occupancy dwellings and 0.0122 for multiple-occupancy dwellings. Using the figures for λ given in Table 8.6 approximate values for $\bar{t}$ are 15.9 and 20.4 min, respectively, for these buildings. Figures in Table 8.7 include scenarios in which sudden exposure to risk conditions could have been quickly fatal.

For multiple-occupancy dwellings, if an average of 15 deaths is assumed for the category 5 or more deaths, $\lambda\bar{t}$ would only increase marginally to 0.0123 and $\bar{t}$ to 20.6 min. The values of $\lambda\bar{t}$ and $\bar{t}$ can be thus adjusted, if necessary, to take account of any reasonable average value for the maximum number of deaths. This maximum would depend on the average number, $\overline{N}$, of people at risk in the type of building for which $\lambda\bar{t}$ is estimated from data such as in Table 8.7. If $\bar{t}$ can be estimated from experimental and scientific investigations, the value of λ can be adjusted accordingly for any value of $\overline{N}$.

The average (fractional) number of deaths per fire, $\lambda\bar{t}$, estimated as described above, is simply the ratio between total number of deaths and total number of fires. This parameter is the same as the overall fatality rate per fire given in Table 8.6. The overall rates in Tables 8.6 and 8.7 differ slightly since Table 8.6 does not include some fires for which information on discovery time was not available.

In equation [8.8], both λ and t have been assumed as constants although they may be functions of x. An increase in the number of deaths may be the result of exposure to untenable conditions for a longer duration such that t would increase with x. If equation [8.8] is modified to take

account of variations in λ and t, it would lead to a complex Poisson model, an application of which is beyond the scope of this book. Therefore, the simple model in equation [8.8] may be applied to practical problems in which λ and t can be assumed to be constants.

It may be required, for example, to estimate the probability of r or more deaths occurring in a fire if a group of occupants are exposed to untenable conditions for a specified period of t minutes. This probability based on equation [8.8] is given by

$$q_r(x, t) = 1 - p_r(x, t) \qquad [8.9]$$

where

$$p_r(x, t) = \sum_{x=0}^{r-1} p(x, t)$$

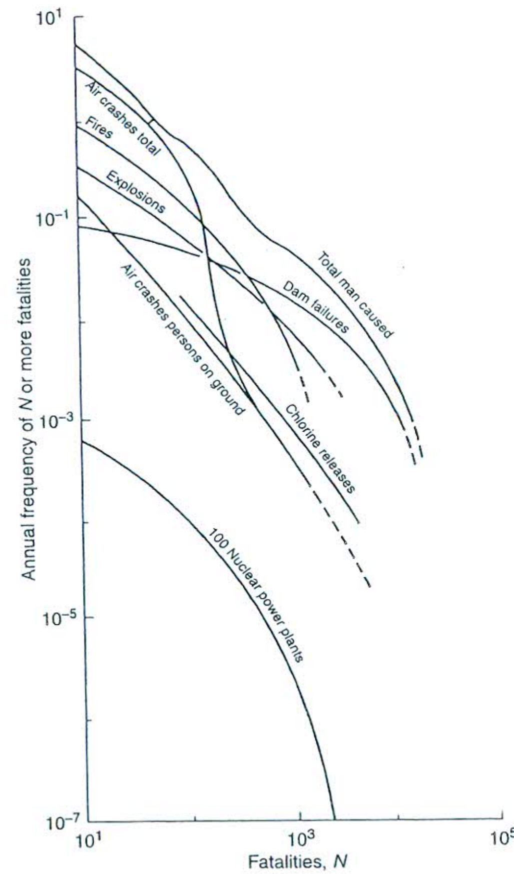

Figure 8.2. Frequency of man caused events in the United States

As one might expect, $q_r(x,t)$ would increase with the duration of exposure denoted by t. In multiple-occupancy dwellings, for example, calculations would show that the probability of 2 or more deaths would increase from 0.00020 for 30 min of exposure to 0.00044 and 0.00060 for exposure of 50 and 60 min respectively.

With $r \geq 2$, an appropriate value of t corresponding to an acceptable level for $q_r(x,t)$ may be selected for designing a large building according to the risk of multiple deaths occurring in a fire. This design value for t will in turn provide the design value for the evacuation time (E) as discussed in the previous section. Subject to the limit imposed on t, the magnitude of E may be adjusted to take account of the presence or absence of fire protection measures such as sprinklers, detectors, and smoke control systems.

In statistical literature $q_r(x,t)$ is known as the *survivor* or *tail* function, which is the complement of the cumulative distribution function $p_r(x,t)$. Rasmussen (1975) used this function, referred to later by Fryer and Griffiths (1979) as $f(N)$ lines, to compare multiple fatalities expected in various types of manmade hazards with hazards of pressurized water reactors in the United States. The figure reproduced in Figure 8.2 has been widely quoted in the subject of quantification of risk. The $f(N)$ relationship has been put forward by several authors for investigating risks due to various types of hazards. Rasbash (1984) has discussed these studies in order to define target probabilities for premises of different sizes (see Table 2.7).

8.10 Other measurements of life risk

The overall fatality rates, single or multiple, given in Tables 8.6 and 8.7 indicate current levels of life risk due to fires on a per fire basis. They denote the probabilities of one or more people dying in the event of a fire occurring in a building of the type considered. These probabilities can be expressed on an annual basis if they are multiplied by the probability of a fire occurring in a building in a year. The occurrence probability per year has been discussed in detail in Chapter 7. This probability would vary depending on the size and type of building as discussed with reference to Table 7.2.

Another factor affecting life risk is the number of occupants (N) in a building. The probability (rate) of death per, say, hundred people would be a useful measurement of life risk particularly for a large building. For any occupancy type, this parameter can be estimated by dividing the fatality rate per fire by the average number ($\overline{N}$) of people in a building. Special surveys may have to be carried out for obtaining information on $\overline{N}$. The fatality rate per person per fire can be expressed on an annual basis by multiplying it by the annual probability of fire occurrence.

Fatal Accident Frequency Rate (FAFR) is another measurement of life risk, which is the number of fatalities that occur during a hundred million man-hours of exposure to an occupation or activity. FAFR has been calculated for various industrial occupations such as nuclear and chemical industries and nonindustrial activities such as traveling by bus, train, car or air, canoeing, and rock climbing. For example, the FAFR for fire safety in the chemical industry as a whole has been estimated to be 4. On this basis, it has been arbitrarily decided in at least part of a major chemical firm that no single activity which any person is carrying out should contribute more than 10% to the FAFR, that is, 0.4 (Kletz, 1976).

As mentioned in Section 7.8, North (1973) has calculated rough values of FAFR for many occupancies in the United Kingdom. These only covered the years 1967 to 1969 and in cases in which deaths were infrequent the estimates had wide confidence limits. For fire deaths in a dwelling, the FAFR was 0.19 and in hotels 3.6. The latter figure was probably distorted by some serious multiple-fatality fires that happened during 1967 to 1969.

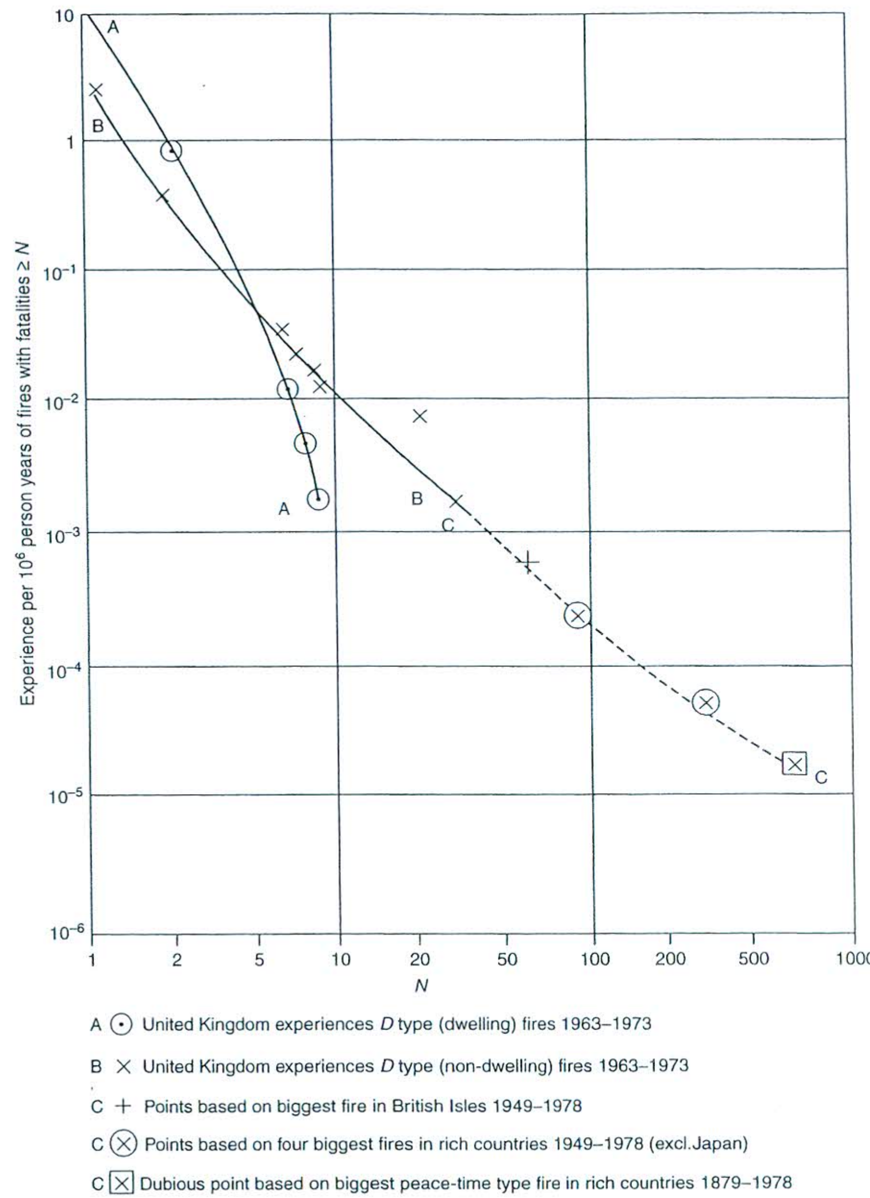

Figure 8.3. Experience per 10^6 person years of fires with N or more fatalities.

An American report (Balanoff, 1976) allowed estimates to be obtained for FAFR for firemen on or following activities at the fireground. The report indicated 86 deaths per 100,000 firemen per annum and provided an estimate of 42 for FAFR. About half of the deaths were due to heart failure and 10% each due to building collapse, burns, and smoke inhalation. From these figures, assuming that only 5% of firemen's time was actually spent fire fighting, the FAFR for this activity was about 800 (Rasbash, 1978). Firemen might be expected to endure a substantially high risk during the small fraction of their working time in which they are engaged in the highly risky activity of fighting fires.

Another method of measuring life risk is based on the relationship between the records of actual fire disasters and the population experiencing them. The level of safety that this method reveals has not occurred by chance. It is the result of a continuing process of interaction between the social and technical development of the environment on the one hand and the legislative and regulatory process that has taken place over the years on the other hand. Figure 8.3 produced by Rasbash (1984) is an example of this method, quantifying the measure of safety from multiple-death and catastrophic fires to which people have become accustomed in everyday life under peacetime conditions.

Figure 8.3 omits fires not attended by fire brigades, particularly mine fires and offshore ship fires. It uses information from outside the United Kingdom based on countries with a similar background, particularly Western Europe, North America, and Australia, to extrapolate the UK experience to obtaining estimates of the probability of disasters, of 100 and even 1000 deaths. This extrapolation is rather more speculative but is reasonable because it is a simple extrapolation of the trend already established.

8.11 Impact of product choices on life risk – US method

In the United States, a fire risk assessment method has been recently developed to analyze the impact of changes made to a combustible product on its life-safety risk (see Bukowski *et al.*, (1990)). The method has been designed to calculate the expected severity (in deaths per fire) and the relative likelihood (as fire probability) of each of a large number of fire scenarios that may involve the product as the first item ignited or as a secondary contributor. Briefly, fire risk is measured in terms of both the probability of an event (fire) and the consequence of that event (e.g. deaths resulting from a fire). The problem is to predict how a change in the fire properties of a product (ignitability, heat release rate, toxic potency, etc.) will change the life-safety risk in a given occupancy.

The fire risk assessment method mentioned above combines the likelihood of a fire, based upon fire incident databases, with the expected consequences or severity of a fire, predicted by a computer based hazard calculation method, HAZARD 1, developed at the Centre for Fire Research, National Institute of Standards and Technology, USA. The method thus uses simulation models based on known laws of physics of fire, in combination with information on the behavior of people confronted with fire and the effects of heat and smoke on people, to estimate the severity of a specified fire. The method provides an organized structure for a large series of fire scenarios constructed to represent all the possible ways that a fire might involve the product considered.

A scenario is defined as a detailed description of a specific fire incident related to a building, a fire involving specific items in that building, and the persons occupying the building at the time of the fire. These details are drawn from a review of fire incident data from the national databases, focusing on – buildings and rooms where fires originate, combustible contents of the room, heat sources igniting the first item (flaming or smouldering), final extent of flame damage, factors

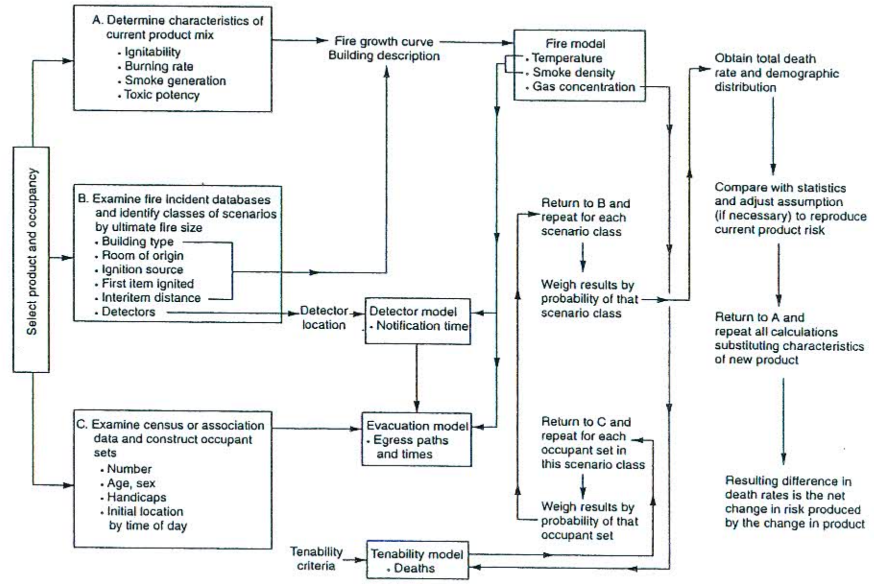

Figure 8.4. Modeling sequence to compute fire risk

contributing to fire spread, and location of any fatalities relative to the fire. Also considered are more specific building characteristics – numbers, types, and layouts of rooms and floors, dimensions of rooms, and the sizes of the openings connecting them.

Figure 8.4 illustrates the sequence of modeling activities used in the risk assessment process. As mentioned earlier, the universe of possible fires is divided into a set of well-defined scenarios. Thereafter, for each scenario, the method follows the sequence described in Figure 8.4 for each occupant set. The deaths-per-fire results for the scenario selected are estimated using the probability for each occupant set. Using the fire scenario probability and the total number of fires, one obtains the number of fires for that scenario. This is combined with the deaths-per-fire estimate for the scenario to obtain the number of deaths. These results are combined with similar results for all other scenarios to produce a sum that gives the estimated risk.

The procedure described above is conducted twice. The first computation is to produce a base line of fire risk associated with the mix of versions of the product in use. This is done either using the product's average characteristics, or, if possible, by conducting runs for the versions of the product in use and weighting the results by the share of product in use. The second computation is done using the characteristics of the new product – its peak rate of heat release, its relative ignitability and so on. A comparison of these two computations then produces a measure of the change in risk achievable by changing to the new product. This process has been demonstrated for each of four case studies – upholstered furniture in residences, carpet in offices, concealed combustibles in hotels, and interior finish in restaurants.

Consider, as an example, the case study (July, 1990), concerned with fires involving upholstered furniture in homes. The output of the method consisted of a series of tables giving fire death rates

Table 8.8. Upholstered furniture in residences – Output from US risk model deaths per 100 fires

	With smoke detectors			Without smoke detectors		
	Day	Evening	Night	Day	Evening	Night
All causes	2.73	1.50	1.00	2.73	1.50	29.74
Causes						
O_2[a]	0.00	0.00	0.00	0.00	0.00	0.00
CT[b]	0.00	0.00	0.00	0.00	0.00	0.00
Convect. heat	2.73	1.50	1.00	2.73	1.50	29.74
Occupants						
Adults	0.13	0.17	0.00	0.13	0.17	0.19
Elderly	0.00	0.00	0.00	0.00	0.00	0.00
Child, 12–18	0.00	0.00	0.00	0.00	0.00	0.00
Child, 3–12	0.00	0.00	0.00	0.00	0.00	0.00
Child, 0–3	0.13	0.17	0.01	0.13	0.17	28.18
Impaired	2.47	1.16	0.99	2.47	1.16	1.08
Drunk	0.00	0.00	0.00	0.00	0.00	0.00

[a]Oxygen deprivation
[b]Concentration–Time product.

in various categories such as age or sex of victim, time of day, type of building, and room of origin. Results were obtained for the class of fire scenarios sharing common characteristics: for example, upholstered furniture first item ignited, ignition sources other than smoking materials, starting in the living room of a ranch house and spreading beyond the living room with bedroom doors open. Table 8.8 is an example for the scenario mentioned above extracted from the report showing a summary of expected deaths per 100 fires with and without smoke detectors for day, evening, and night. These results relate to convected heat as the cause. Oxygen deprivation and toxicity of smoke (measured by the concentration–time product) were the other two causes considered for which the deaths per 100 fires were estimated to be zero. Table 8.8 details how the death per fire numbers are divided among the occupant types. A total of 155 deaths were estimated for this scenario. For the "base" case consisting of living room and bedroom fires, a total of 624 deaths was predicted by considering several scenarios.

Selected studies were conducted to test the sensitivity of the results to changes in key assumptions. These studies covered three input categories – occupant, fire modeling, and building size (volume). The occupant variables examined focused on assumptions related to escape through windows and rescue by persons outside the residence, smoke awareness at night, and location of occupants impaired by alcohol at night. Fire modeling variables included the extent of the smouldering period for upholstered furniture and the impact of breaking of a window in the fire room at flashover, providing an additional source of oxygen.

The "new" upholstered furniture selected had the same fire properties as the "base" case discussed above. However, the materials used in the "new" product would generate smoke with a tenfold increase in toxic potency over the "base" case. Consequently, a comparison of the results indicated a 46% predicted increase from 624 to 909 deaths. Smouldering fire scenarios contributed three-fourths of the increase while flaming scenarios contributed the remaining one-fourth. For the "basic" case, the cause of death was always convected heat. However, for the "new" product, toxicity was the causal factor in 96% of deaths.

Symbols

B	recognition period; gathering phase
D	discovery period
E	elapsed time since the commencement of movement until a safe place is reached inside the building
F	time for a combustion product to attain untenable conditions
FAFR	Fatal Accident Frequency Rate
H	$= (D + B + E)$
K	$= (1 - W)$
N	number of people at risk
p	$= 1 - \exp(-\lambda) \cong \lambda$
$p_d(t)$	probability of one or more deaths during period $t = 1 - \exp(-\lambda t) \cong \lambda t$
$p(x, t)$	probability of exactly x deaths in a fire due to exposure to untenable conditions for t minutes
$p_r(x, t)$	cumulative probability from $x = 0$ to $(r - 1)$ of the extended Poisson distribution $= 1 - \exp(-\lambda t) \cong \lambda t$
$q_r(x, t)$	probability of r or more deaths $= 1 - p_r(x, t)$
r	number of deaths occurring in a fire in the equations for $p_r(x, t)$ and $q_r(x, t)$
t	period spent under untenable conditions $= H - F$
W	$= \exp[-\lambda(B + E - F)] \cong 1 - \lambda(B + E = F)$
x	number of deaths in a fire in the equation for $p(x, t)$
λ	increase in casualty rate per unit time

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9 PROPERTY DAMAGE

9.1 Introduction

As defined in Section 7.2, fire risk in a building is the product of two components – probability of fire starting and probable damage in a fire. Damage to life has been discussed in Chapter 8, while this chapter is concerned with direct material damage to a building and its contents. Note that a fire can also cause indirect/consequential losses (see Ramachandran (1995)). Direct damage can be measured in terms of area damaged, spatial extent of spread, and duration of burning or financial loss. Expected values of these four random variables and their correlations can be estimated approximately by applying the statistical models described in Sections 7.4 to 7.6. A better description of the random variation (uncertainties) governing area damage or financial loss is provided by a probability distribution, with nature and uses in fire protection problems that are discussed in the next section.

Fire losses occurring every year in buildings of any type can be regarded as a sample of observations from a "parent" probability distribution with large losses constituting the "tail" of this distribution. The behavior of the "tail" over a period of years (samples) can be studied with the aid of extreme value distributions (Section 9.3) that have found practical applications in many engineering problems. In the absence of information on small losses, extreme value models can be applied to large losses in order to estimate the average loss in all fires, large and small, in a particular building or group of buildings.

The relative effects of several factors and their interactions considered as "independent" variables can be evaluated simultaneously (not individually) by performing a multiple regression analysis (Section 9.4) with financial loss, or area damaged, as the "dependent" variable. The probability of loss or damage exceeding a specified level or probability of fire spreading beyond, say, the room of origin can also be used as a dependent variable. In such a case, the "logit" transformation is usually applied to the probability to satisfy certain statistical assumptions.

9.2 Probability distribution

Many factors affect the spread of fire in a building and hence the level of damage sustained in a fire is a random variable with a probability distribution. This distribution expresses mathematically the probabilities with which the damage in a fire could reach various amounts. The shape of this

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