J. of Fire Prot. Engr., **3** (2), 1991, pp 49-63

THE TECHNICAL INVESTIGATION OF THE FIRE AT LONDON'S KING'S CROSS UNDERGROUND STATION

by

K. Moodie and
S.F. Jagger
Health and Safety Executive,
Research and Laboratory Services Division, Explosion and Flame Laboratory,
Buxton, England

SUMMARY

The behaviour of the fire at London's King's Cross Underground Station on November 18, 1987, was the subject of a prolonged and detailed scientific investigation by the Health and Safety Executive on behalf of the Official Enquiry. In the initial stages of the investigation, a detailed damage survey was made at the site of the fire, and samples of many different materials were collected and subjected to a variety of ignition and flame spread tests. In the course of the investigation, fire growth studies were made on a full-size section of escalator, on scale models of the escalator, shaft and ticket hall, and by numerical modelling.

INTRODUCTION

During the evening of Wednesday, November 18, 1987, a fire occurred at King's Cross Underground Station. The fire and the accompanying smoke involved the Piccadilly Line escalator shaft, the ticket hall, and the passageways leading from the ticket hall, particularly those to the streets and to the main line station concourse above. During the course of the fire, there were 30 fatalities and numerous injuries, some of which were severe burn injuries. One of the severely injured died later in hospital.

The King's Cross Underground Station is the most complex on the London Underground system, serving five lines of the underground system and two mainline stations, King's Cross and St. Pancras. The immediate locus of the fire is shown schematically in Figure 1. It consists of two main escalator tunnels which connect the underground platforms to the station's ticket hall. The longer of these (Piccadilly) was the tunnel in which the fire started. In the centre of the ticket hall there was a ticket office constructed mainly from wood. There were four short staircases leading upwards and out of the ticket hall area, these joined to a roughly semicircular orbital passageway from which there were four passageways leading to the main line stations, Euston Road and other Underground lines. On the right hand side of the ticket hall (when viewed from the top of the escalators) was a wooden partition closing off the first set of exit stairs and behind which refurbishment work was being undertaken.

The total floor area of the ticket hall, excluding the ticket office, was approximately 530 m^2. The height of the ticket hall from the floor to its suspended ceiling was 2.45 m. The Piccadilly line escalator tunnel was approximately 42 m long with an internal diameter of 6.94 m. The escalators descended at an angle of 30 degrees to a

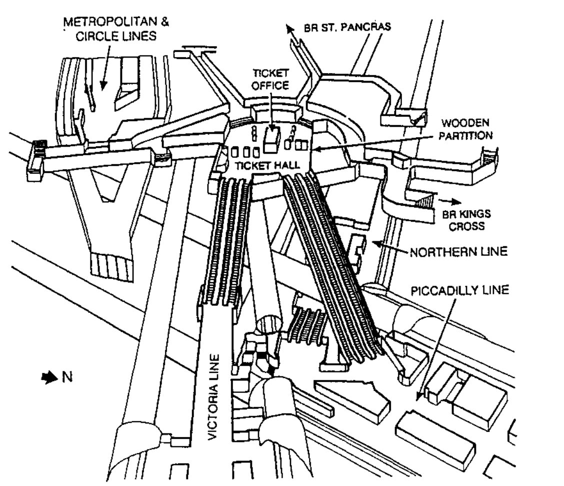

Figure 1. Three-dimensional view of King's Cross underground complex.

floor level 16 m below the ticket hall floor. The Piccadilly line escalator tunnel was divided into two sections (upper and lower) by the escalator staircase, the upper section provided the public with access via the escalators to the Underground system. The lower section served as a machine room and access area to the escalator mechanism.

The treads of the escalator staircase were made from a hardwood ply with oak-wood cleats running along the length. The risers were finished with oak wood panels. The sides of the escalator (balustrades) which were approximately 1 m high were made from hardwood ply backed by a mild steel sheet. The decking between the escalators and the facia panels lining the side walls were also made from the same plywood as the balustrades, but were thinner and were strengthened with an additional mild steel sheet under the top layer of varnished veneer. On the tunnel side walls were plywood advertisement hoardings attached to facia boards with translucent plastic adverts fixed directly to these boards and held in place by aluminium frames. The escalator (or moving staircase) was supported by two sets of nonmetallic wheels attached to either side of the stairs. The staircase was hauled upwards by a sprocket and chain assembly. At the side of the staircase there was a skirting board constructed from a hardwood ply. Its bottom edge was positioned just above the haulage chain.

The tunnel was constructed of metal rings lined with concrete and a plaster skim. The ceiling plaster between the two side facia panels was painted with a modern high build paint system

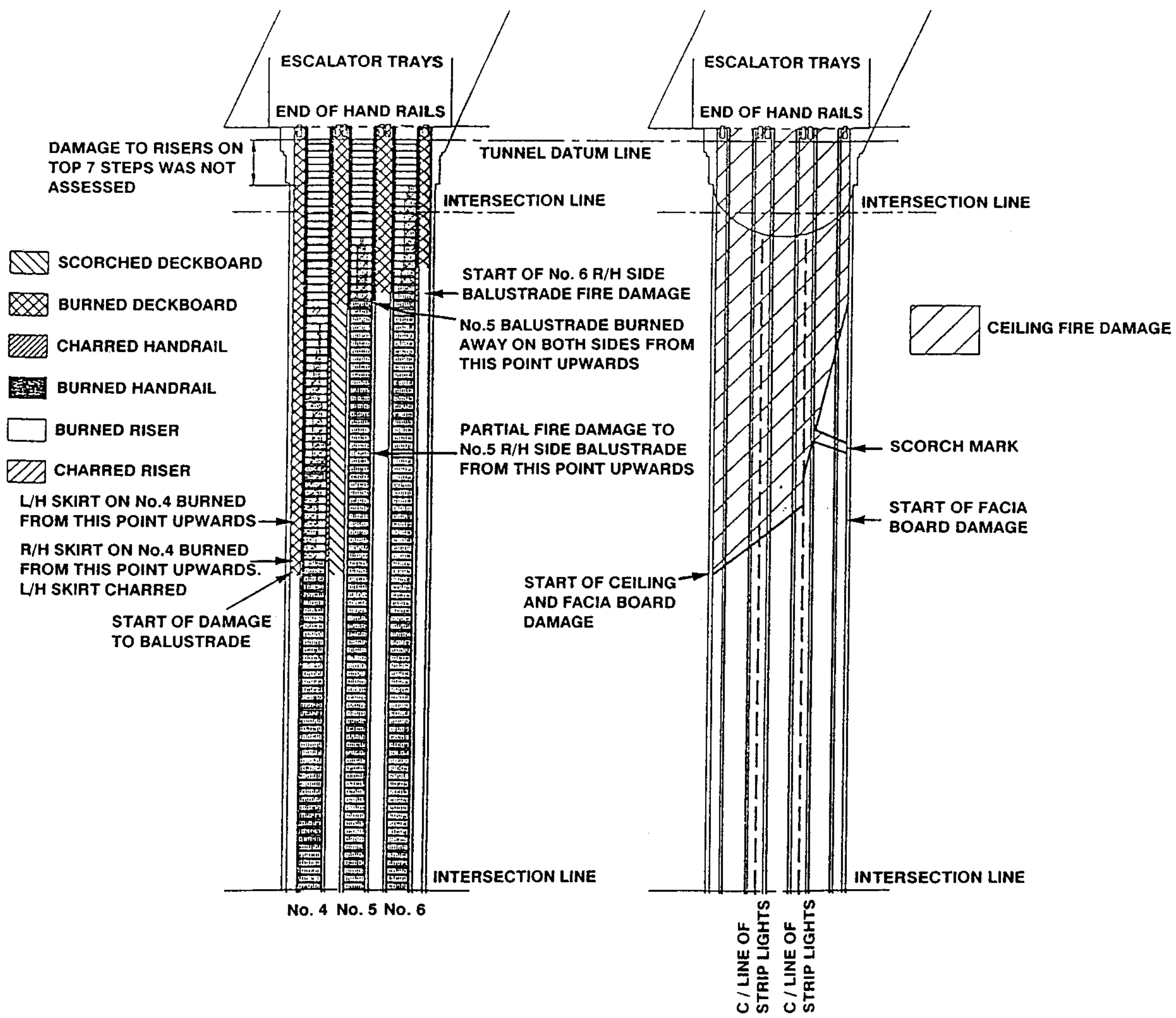

Figure 2. King's Cross Station Piccadilly Line fire damage, plan view.

applied over about 12 coats of old paint.

The ticket hall had a suspended ceiling constructed from fire resistant panels containing some asbestos, many of which had fallen during the fire. This allowed flames to penetrate the cavities behind and burn any combustible material present, such as the runs of electrical wiring.

Observed Fire Damage

General Impressions

The fire damage[1] extended upwards from a point some 22-23 m below the top of the Piccadilly line No. 4 escalator (see Figure 2). It progressively involved more of the available combustible material in the escalator shaft until practically all of the available fuel had been consumed near the top (throat) of the shaft. Also in this region, the fire damage was more extensive on the left hand side (looking up) of the shaft, as illustrated in Figures 3a and 3b, which show respectively the fire damage viewed from below the seat of the fire and the fire damage to the ceiling at the top of the escalator tunnel.

The fire damage continued through the ticket hall as shown in Figures 4a and 4b, where again most of the available fuel had been consumed, although to a lesser degree than in the throat of the tunnel. The fire damage in the passageways leading from the ticket hall became progressively less the greater the distance from the Piccadilly line escalator shaft. They showed the effects of exposure to hot combustion products rather than to either actual flame impingement or to high radiant heat fluxes. This was evidenced by the smoke and soot deposits, the peeling of the ceiling paint and the softening and subsequent distortion of various plastic items.

The general direction of fire spread in the escalator tunnel was upwards, assisted by the 30 degree inclination of the shaft. The picture was consistent with the fire having started in the vicinity of the lowest point of the observed damage on No. 4 escalator, increasing in intensity to a maximum near the throat of the escalator shaft, and then decaying within the outer confines of the ticket hall. It was also consistent with the escape and cooling of hot combustion gases and smoke through the passageways leading from the ticket hall.

Place of Origin of the Fire

The fire most probably started on the right hand side (looking up) of No. 4 escalator some 21 m down from the top of the escalator. This was evidenced by the general pattern of damage, but particularly the charred patterns remaining on the treads and risers in this region which showed that the wood was burnt away to a greater extent on the right hand side of the steps than immediately above or below or on the corresponding left hand side of the escalator. This was consistent with the risers of

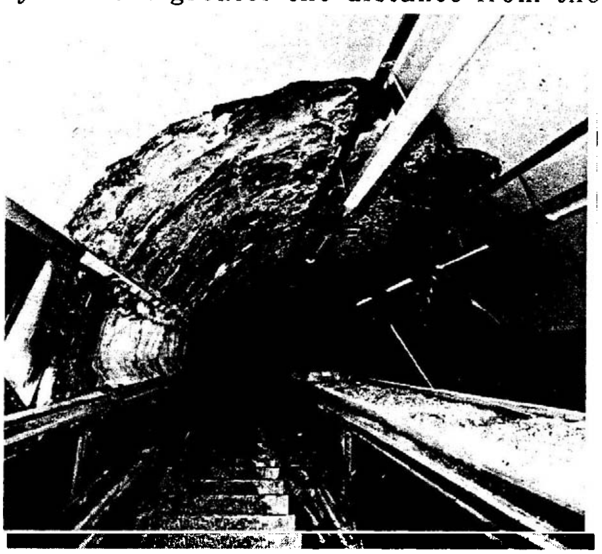

Figure 3a. General view of the damage in the Piccadilly Line escalator tunnel.

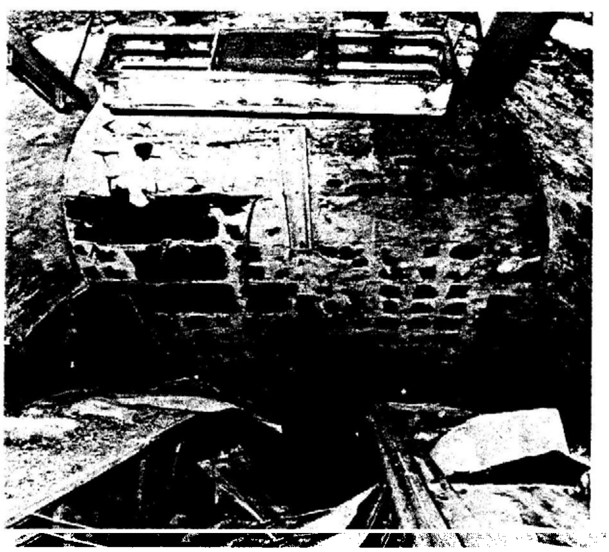

Figure 3b. Fire damage to ceiling in the throat of the escalator tunnel.

Figure 4a. Fire damage at the top of the Piccadilly Line escalators

Figure 4b. Fire damage to the ticket machines in the ticket hall.

these steps having been fire exposed for the longest time.

Fire induced distortion of the right hand wheel retainer track was further supportive evidence that the seat of the fire was located in this region, as was the pattern of fire damage to the right hand side skirting board which was burnt away from below in this region. An examination of the escalator from underneath showed that the fire damage did not extend to those parts of the escalator below the running track supporting the moving staircase.

On the running track of No. 4 escalator, down from the region of fire damage, there was a grease layer of varying depth surmounted with dust and cellulosic deposits which extended across the gap between the tracks of the two sets of running wheels. It was directly below the escalator skirting boards and would not be disturbed by movement of the staircase and its haulage mechanism. A typical example of this layer is shown in Figure 5.

Escalator Tunnel Ceiling Damage

The salient features of the damage to the ceiling and paint are shown in Figures 2 and 3a. Scorching of the paint started abruptly some 22-23 m down the tunnel on the left hand side, with minimum blister damage to the paint below this point. The line of scorching travelled diagonally across the ceiling from the left hand side facia over to the right hand side facia. Towards the top of the tunnel the ceiling damage was more severe, particularly on the left hand side, with most of the paint missing, and in same areas layers of plaster also appeared to have fallen. There were two rows of suspended fluorescent lights along the length of the tunnel ceiling which had suffered minimal fire damage.

Fire Damage to No. 4 Escalator

The No. 4 escalator was severely fire damaged upwards from just below the seat of the fire. Both the right and left hand balustrades were

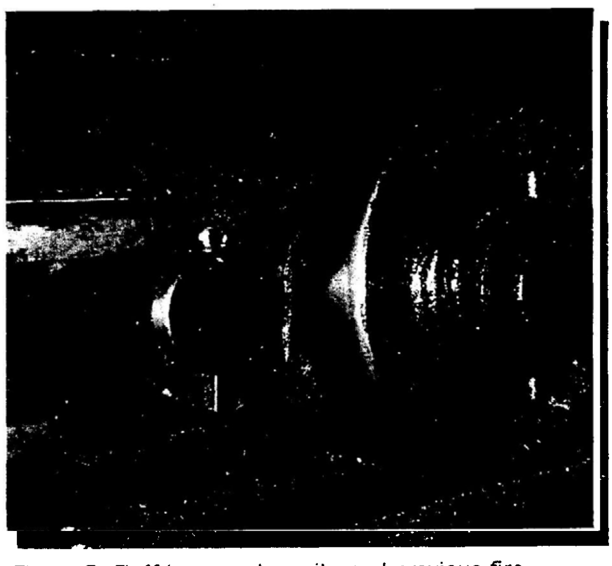

Figure 5. Fluff/grease deposits and previous fire damage to lower part of skirting board, as observed on escalator No. 5.

totally consumed leaving only their steel backing plates. Similarly the skirting boards on the right hand side were completely burnt away. On the left hand side the majority of the skirting board had been consumed. There were some 50 treads and risers on the inclined section of the escalator that were fire damaged. The wooden slats, which formed the treads, and the hardwood riser boards were completely burnt away from above the 13 m mark leaving only the steel backing of the steps. Downwards from this point there were varying quantities of charred wood remaining on the metal steps.

The wood of the deckboards that covered the upward facing surface between the adjacent handrails of escalators Nos. 4 and 5 was burnt away above 9 m leaving only the metal backing sheets. Below this level the deckboards were scorched to a degree that became progressively less towards the start of the fire zone. The deckboard on the left hand side of No. 4 escalator was consumed virtually from the start of the damage. At the top of the escalator the wooden housing for the control equipment was charred but not completely burnt away.

Fire Damage to Other Escalators

Examination of the central escalator revealed that there was no damage to the treads below 9 m; above this point most of the treads were burnt away with no wood remaining on the top five steps. The risers were more damaged on the right hand side than on the left, but in general, fire damage to the stair treads and risers was less than that found at equivalent positions on the No. 4 escalator. Examination of the damage underneath the skirting boards seemed to indicate that the fire attack had been from above, i.e., from the stair treads outward, since there was no evidence for burning underneath the escalator damage marks similar to those recorded on or about the base of the skirting boards on the right hānd side of escalator No. 4 were also found on both sides of escalator No. 5, there were a number of these and they seemed to indicate that there had been previous fire starts. There were also substantial deposits of fluff on a layer of grease on the running wheel track in the vicinity of these damaged areas.

Examination of No. 6 escalator revealed that there was no stair damage below about 8 m. The treads and risers were totally consumed from 6 m upwards. The balustrade had been burnt away on the right hand side for what was presumed to be the same distance as on the left hand side. The deckboards between No. 5 escalator and No. 6 escalator had been consumed completely by the fire for this distance. The skirting boards were completely burnt away from 7-8 m upwards on either side; in both cases burning appeared to have been from the passenger side and not from the bottom of the skirting boards.

Fire Damage in the Ticket Hall

The general pattern of fire damage within the ticket hall became progressively worse towards the ceiling and progressively less the greater the distance from the throat of the escalator shaft. This was consistent with the fire being spread by flames emanating initially from the throat of the Piccadilly shaft.

There was a ticket office in the centre of the ticket hall which was severely fire damaged. It had been constructed from a wooden/steel frame covered in 12 mm plywood finished in melamine. The majority of the fire damage occurred on either side of the ticket office corner nearest the Piccadilly line escalator. Most of the wooden components in this area were either burnt away completely or were more severely damaged than on the rear or other side wall. Most items within the ticket office had suffered some degree of fire damage; for instance, aluminium-based components near the top of the floor-mounted ticket machines had melted, whilst rolls of tickets at the bottom were only scorched. A number of wooden items had been burning and were charred. Wooden drawer fronts were charred, but inside and to the back of the drawers undamaged wood was clearly visible. Items that were near to the floor below the window level appeared to have suffered less damage than those above window level.

There was a temporary wooden partition on the right hand side of the ticket hall (viewed from the escalators) behind which refurbishment work was being undertaken prior to the fire.

This partition ran the full length of the ticket hall and was faced with plywood sheets. Most of this plywood sheeting was burnt away in the upper regions, but in the lower half there were still some charred remains.

Initial Assessment

Observations on-site indicated that the fire had started on escalator No. 4 and suggested that the primary source of fuel was the wood from which the moving staircase of the escalator was mainly constructed. Thus the sequence of events was considered to be the following:

(a) An ignition source developed beneath escalator No. 4 some 21 m down from the top and on the right hand side when looking up. This was probably an extraneous heat source such as a lighted match falling on to the grease/fluff layer on the running track.
(b) The fire on the haulage mechanism developed to ignite the vertical plywood skirting board, and the fire spread from beneath to above the escalator via the skirting board.
(c) Once above the escalator, the fire developed more rapidly and began to involve the plywood balustrades and the stair treads and risers.
(d) The fire spread up the escalator on both balustrades and encompassed the plywood facia and advertisement boards on the left hand side wall of the escalator tunnel. It also involved the deckboards and hand rails.
(e) Flame and hot gases from the escalator shaft passed into the ticket hall and ignited flammable materials therein.
(f) At some stage as the fire continued to develop (i) the paint on the walls and ceiling of the escalator tunnel began to burn and (ii) radiation from both the hot combustion products near the ceiling and the flames from the burning wood caused fire to develop on escalators No. 5 and 6.
(g) A substantial fire developed in the ticket hall, the fumes and hot gases from which spread through the stairways and tunnel system connected to the ticket hall.

Experimental Programme

Experimental work was undertaken specifically to establish the most probable ignition mechanism and to explain the subsequent rapid flashover into the ticket hall which caught people unawares.

Ignition Characteristics of Samples

The ignition characteristics and other properties of a wide variety of samples taken from the vicinity of the escalator (wood, rubber, plastic, grease, etc.) were examined.[2] None of these samples exhibited any unexpected characteristics. The most significant finding was that the grease used to lubricate the escalator, although relatively difficult to ignite when on its own, could easily be ignited by a small flame when mixed with detritus as found beneath the escalator (fluff, tickets, spent matches, etc.); the detritus acted as a wick.

In-situ Fire Test

On the January 8, 1988, a fire initiation test was undertaken at King's Cross Underground Station using the unburnt section of No. 4 escalator. Three attempts to initiate a fire, through the gap at the side of the escalator between the treads and skirting, using a smouldering cigarette failed. However, the first lighted match dropped initiated a fire on the grease/fluff layer present on the running track.

Within 2 min the fire was well established on the grease layer. After 3 min, it had travelled over 1 m and the skirting board immediately above was beginning to burn. After some 6-7 min, the fire was developing rapidly beneath the escalator, and the flames were reaching up to the deckboards, pre-heating the sides of the escalator. However, on the passenger side the flames were only just becoming visible as they started to attack the bottom of the balustrades. The fire was put out after some 9 min for safety reasons.

Full Scale Fire Growth Tests

During late January/early February six full-scale fire growth tests were undertaken on a six-step length of escalator. The tests were conducted in our existing 2.2 m high underground fire gallery at Buxton. The fires were started on a simulant grease layer fixed underneath the test section, and the progress of the fire was observed on video. The fire on the test section was observed to spread slowly across the treads and riser. There was considerable pre-heating of the escalator balustrades due to the fire burning unseen on the grease layer on the running track beneath the escalator. The left hand side of the escalator was also preheated by the fire on the right hand side so that when ignition did occur the fire spread very quickly over it. In the tests, ignition of the left hand side was by piloted ignition. The power output of the fire once established across the escalator was found to be about 1 MW/m length of escalator. The time taken for the fire to encompass or ignite the opposite side was between 11 and 20 min. The results from these tests enabled us to understand better how the fire spread initially, and to make first estimates of the subsequent fire development.

Small Scale Model Tests

Computer simulations of the King's Cross fire, carried out under contract to the Health and Safety Executive by AERE Harwell[3], suggested that the flow in the region of a heat source in the channel of the escalator did not rise vertically upwards, but instead was confined by the updraught in the channel which dominated the flow structure. A parametric study of the escalator duct flow and of the relevant scaling criteria, carried out on our behalf by Cambridge Environmental Research Consultants[4,5], showed that the updraught and the consequent channelling of the flow were aerodynamic effects governed by the buoyancy flux of the heat source. They also showed that Froude number scaling, as discussed by De Ris[6], would in the circumstances, provide representative modelling of the parameters governing the fire growth, and that modelling at one-third scale would provide results of value in indicating conditions at full scale.

Thus a series of scaled open channel and model tests were undertaken in order to further our understanding of the fire dynamics. The tests involved mainly 100 mm^2 section open channels, 1/3rd scale sections of open channel escalator, and a fully roofed model of the upper (passenger) section of the Piccadilly shaft connected to the front section of the ticket hall complex. A full description of the tests themselves can be found in References 7-9.

Open Channel Tests

Fire development was assessed on 2 m long x 100 mm^2 cross-section open channels which were either of plywood construction lined with corrugated cardboard or of various types of plywood without any lining. The channels were inclined at 30 degrees and set alight at a point near their bases. The tests were all conducted in still air conditions. In some tests thermocouples were fixed at the top of the channel to record the gas temperatures as the fires progressed into the "ticket hall" area.

The progress of the fires was recorded using video and still cameras. These were then used to obtain the velocities of the flame fronts as they progressed up the open channels. The results indicated that the flame front from a fully developed fire across the escalator advanced up the escalator at an exponentially increasing rate.

In all of the tests, the advancing flame fronts were observed to remain virtually within the channel and to extend ahead of the visible pyrolysis front, the extent to which seemed to vary with the length of the burning zone. This is illustrated in the sequence of three photos, shown in Figure 6, taken at 3 sec intervals. These also illustrate the inherent nature of the flame structure when it is lying in the channel, namely to curve inwards towards the centre of the channel off the two vertical sides.

When the flame fronts reached the end of the channels they emerged with sufficient momentum parallel to the channel to produce a sustained wall jet effect on any simulant horizontal ceiling in that region.

Some additional tests on a 0.4 m length of 100 mm^2 section channel, lined with corrugated cardboard, showed that the flames did not remain in the channel to the extent observed in longer channels, and as a consequence the rate of flame propagation was slower. A test on a 2 m long, one-third scale wood-lined channel gave a similar result. These results suggested that a down-

Figure 6a. Flame front advancing up an open channel ahead of the burning region.

stream channel length to channel width ratio of not less than 10:1 appeared to be necessary before the flame would remain in the channel.

THIRD SCALE MODEL TESTS OF THE SHAFT AND TICKET HALL COMPLEX

General Description

A series of four fire growth tests were carried out on a length of escalator which formed part of a one-third scale model of the passenger side of the Piccadilly shaft and the ticket hall complex extending back to the ticket office. A 10 m long section of escalator was modelled, which was placed at an angle of 30 degrees inside the scaled shaft. The escalator was placed on the left hand side of the shaft (when viewed from the bottom) in a position corresponding to that of the No. 4 escalator of the Piccadilly shaft.

The upper 7 m section of the escalator was independent of the lower 3 m section, so that it could be mounted on load cells and its weight

Figure 6b. Flame front position 3 seconds later.

Figure 6c. Flame front position 3 seconds later.

determined prior to, and during, a fire. The facia panels were attached to the tunnel side walls and not to the weighed escalator section.

The tunnel ceiling was not painted for the first test. For the second and third tests, the ceiling was painted with two coats of white emulsion, but these were not considered representative of the paint layers existing at King's Cross during the time of the incident. In the final test, the ceiling was painted to a London Underground specification intended to reproduce the surface spread of flame characteristics of the actual ceiling.

At the rear of the ticket hall model there was a plenum chamber, separated from the ticket hall by a partition which simulated the blockage effect of the ticket office. From the plenum chamber, combustion products were exhausted via a single vertical stack.

On the right hand side of the wooden escalator the area corresponding to escalator No. 5 was covered over at the deckboard level with steel sheeting. The area corresponding to escalator No. 6 was left free as a walkway. A rail for a moving camera position was positioned along the centre line of the tunnel (subsequently removed after the first two tests). The view looking up the escalator tunnel is shown in Figure 7a and of the ticket hall area in Figure 7b.

During the experiments detailed measurements were made of temperatures, weight loss, heat fluxes, and gas velocities at various locations. In addition, the concentrations of oxygen, carbon dioxide and carbon monoxide were recorded continuously in the exhaust stack. Comprehensive photographic records of the tests, involving up to five video and five "still" 35mm cameras, were also taken.

All of the instrumentation was connected to a data logging and processing system based on a minicomputer (approximately 100 channels), which sampled all of the data channels at a rate of once per second.

Results and Discussion of Results

Visual Observations

The visual records from the first three tests showed that following ignition (at about the first half metre marker), flame was soon established across the full width of the escalator channel, with the flame front tending to remain low in the channel as the fire began to develop. The fire then progressed up the channel at an exponentially increasing rate of growth. The fire, because it was ignited on the right hand side only in the fourth test, took longer to establish itself across the whole of the escalator section than in the previous three tests (some 9 min), but thereafter it behaved in a similar manner. This is shown, just after ignition of the left hand side, in Figure 8.

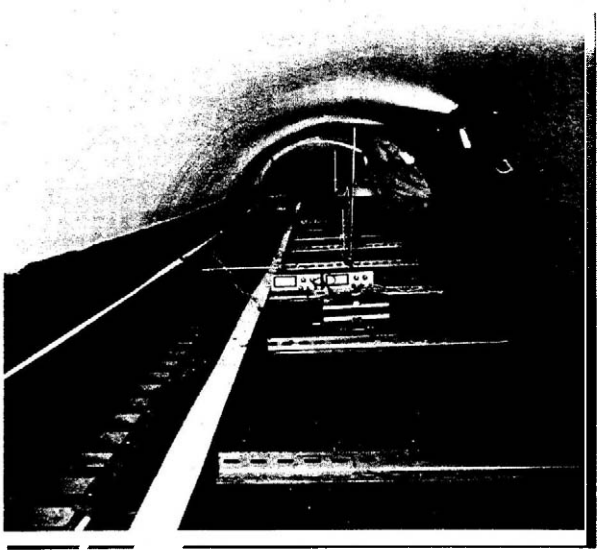

Figure 7a. A view of the escalator from the foot of the shaft.

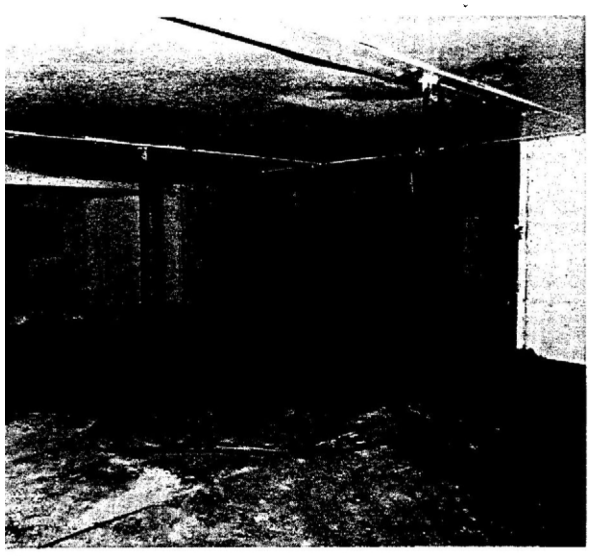

Figure 7b. A view of the booking hall looking towards the throat and shaft.

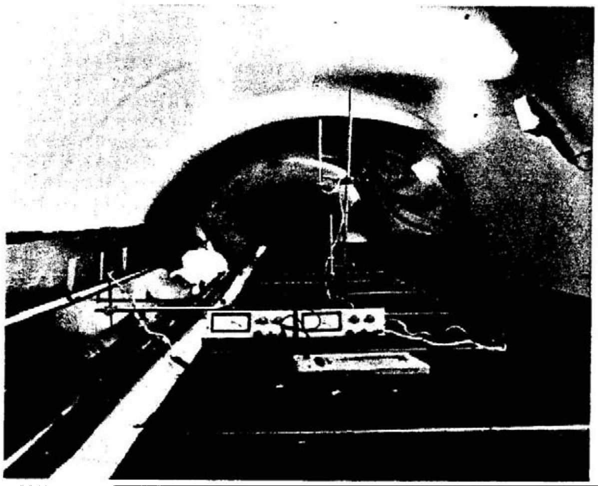

Figure 8a. The fire just after ignition of the left hand side (Test No. 4). View from foot of shaft.

During the first two tests, ignition of the left hand balustrade occurred within 2 min of the start of the fires. This was some 4 and 9 min respectively, in the third and fourth tests. In all tests, the left hand facia boards caught fire some 20-40 sec later, at around the 1-2 m markers. At this time the flame fronts in the channels were well ahead of this point, particularly so in the last test. In general, the flames on the burning facia remained nearly parallel to the escalator. However, flames from burning near the top of the escalator shaft appeared to corkscrew over the tunnel roof both before and after the flames emanating from the escalator channel had entered into the ticket hall. At all times and in all of the tests the flame fronts within the escalator channel remained ahead of the pyrolysis fronts on the balustrades which were themselves ahead of the pyrolysis fronts on the facia boards. The rates of advance of the flame fronts taken from the visual records of all four tests, are shown in Figure 9.

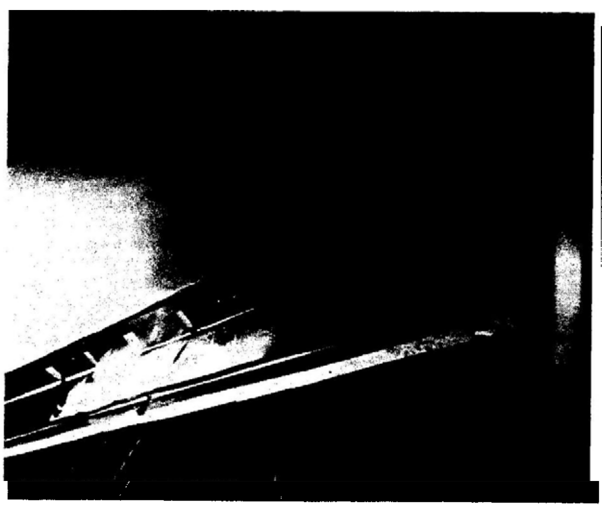

Figure 8b. The fire just after ignition of the left hand side (Test No. 4). View from right side shaft camera.

During each of the four tests it took about 80, 55, 65 and 45 sec, respectively, after ignition of the left hand balustrade, until a continuous ejection of flame into the ticket hall and across the ticket hall ceiling began. The emergence of the jet of flame (Test No. 4) as seen respectively from the right and left hand sides of the ticket office is shown in Figures 10a and 10b. This was preceded by a visible glow on the tunnel ceiling as the flame front progressed upwards, and the occasional flickering of flames out of the shaft.

Air Temperature Measurements

The vertical temperature profiles obtained on the centre lines at all three measuring stations showed that the peak temperatures were between 800-1000 °C within the escalator channel. The corresponding near-ceiling temperatures were lower in all cases but increased progressively in magnitude towards the top of the escalator shaft. The results indicated that sharp temperature fronts were observed at all three measuring stations, which coincided with the visible flame fronts advancing up the channels. Some of these features are illustrated in Figure 11 which shows, for all four tests and at the lowest measuring point, the maximum gas temperatures in the escalator channels and the gas temperatures 25 mm below the tunnel ceiling. Figure 11 also illustrates the degree of

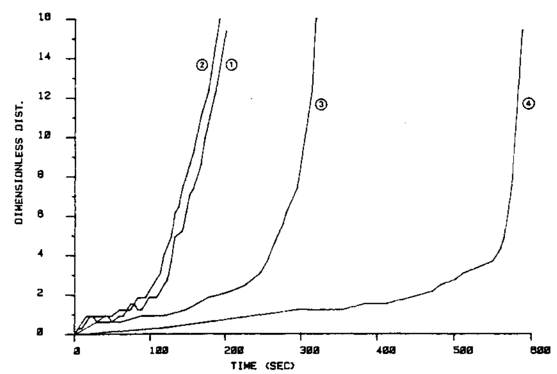

Figure 9. Rate of advance of flame up escalator trench (all four 1/3 scale tests).

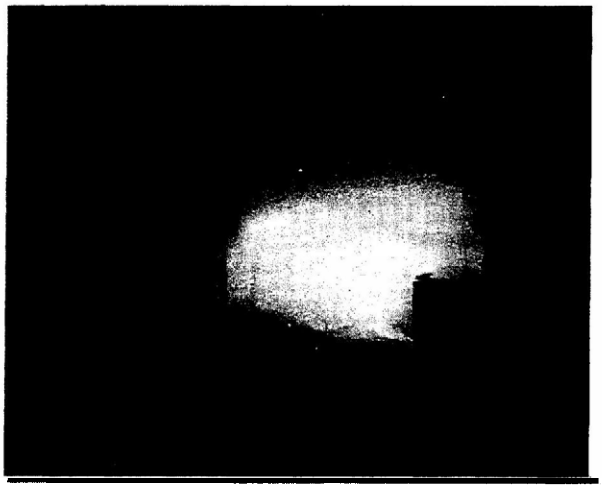

Figure 10a. Continuous ejection of flame into the booking hall. Scene from left hand side of hall.

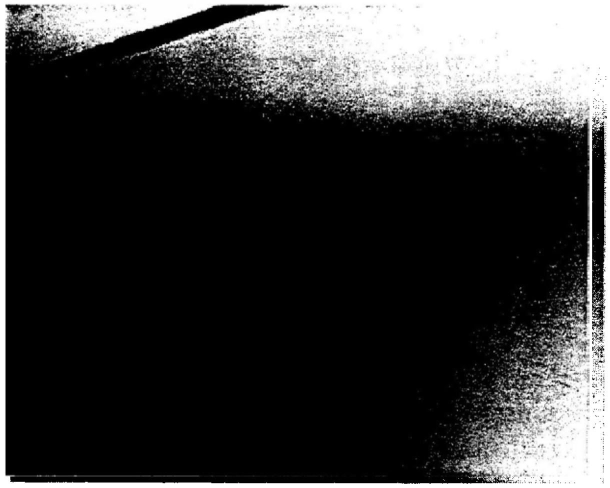

Figure 10b. Continuous ejection of flame into the booking hall, seen from angled window at right hand side.

potential preheating which could occur at the tunnel ceiling prior to the arrival of the flame front. The temperature profiles confirmed that as the flame fronts approached the ticket hall they were advancing in same cases at speeds in excess of 8 m/min, in agreement with the visual observations. The peak rates of temperature change at the top of the escalator were in the region of 40-60 °C/sec, and these occurred within a matter of seconds following the continuous eruption of flames into the ticket hall.

The temperature profiles taken near the exit of the horizontal section of the escalator channel showed similar peak temperatures to those observed within the sloping section. However, the positions of the peaks had moved to a region above the top of the channel. In general, these temperature fronts were more diffuse than at the measuring stations within the sloping sections of the tunnel and were also in accord with the counter-clockwise spread of the combustion products (looking down the shaft) observed from the visual records. The temperature profiles on either side of the ticket office suggested that continuous thermally stratified layers were created below the ceiling following the arrival of the flamefronts in the ticket hall. Prior to this, the temperatures on either side of the ticket office built up gradually. The temperature rises were lower on the left hand side of the ticket office than on the right hand side, and indicated that the majority of the gas flows in each test were to the right hand side of the ticket office. Qualitatively these were in agreement with the computer predictions. The rates of temperature rise on the left hand side of the ticket office, 0.2 m below the ceiling, were about 20 °C/sec

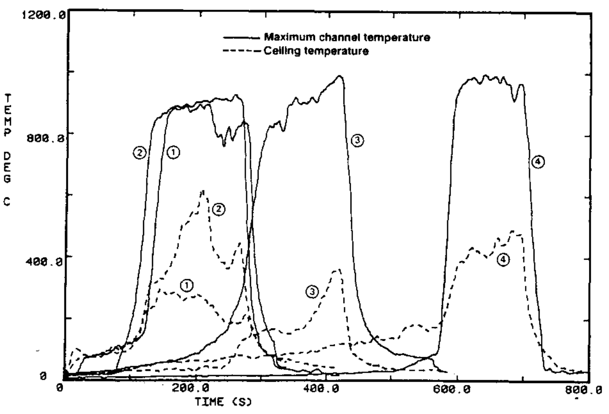

Figure 11. Maximum channel and near-ceiling temperatures from all four 1/3 scale model tests.

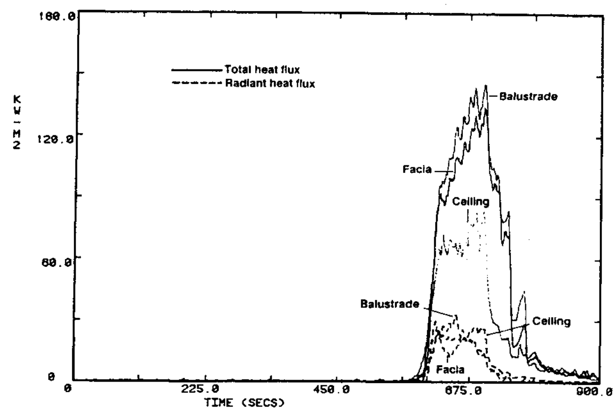

Figure 12. Total and radiant flux measurements in the balustrade, facia, and ceiling (from Test 4).

during the last two tests and were lower prior to and after the arrival of the flame fronts than at the top of the escalator.

Heat fluxes

The total heat fluxes received by the left hand balustrades, facia panels and the tunnel ceiling were measured at various positions during each test. Typical measurements (from Test 4) are shown in Figure 12 for a position near the top of the shaft. The total heat flux to the ceiling was always much less than that received by the balustrades or facia panels immediately below. The peak radiant heat fluxes to the ceiling and balustrades were roughly the same and were about 25 kW/m^2. Thus the substantial increase in total heat flux to the balustrade and facia was due to an increase in convective heat flux, probably as a result of increased turbulence in the burning region, together with an increase in gas velocities especially near the top of the escalator. The total heat flux on the facia panel was about 10 percent less than that received by the balustrade. Such heat fluxes imply very rapid onset of pyrolysis in the presence of a flame, with typical preheat times of 10-20 sec.

Parametric Analysis of Model Results

The data can be considered in the context of the Froude criteria for modelling fires[6] and a parametric flow analysis of the type described in Reference 4.

The flow upstream of the fire is largely determined by the buoyancy flux, this being directly related to the heat release rate. Thus measurements of this parameter, used in conjunction with simple plume models, can be used to ascertain expected levels of temperatures and velocities both across and along the duct. Such calculations largely confirm the measurements of temperatures and velocities observed during the tests.

The Froude modelling technique permits some predictions of conditions at other scales. It is based on maintaining geometric similarity, the flow Froude number, and the ratio of time averaged mass burning rate to convective mass flux per unit area. On this basis temperature will be independent of scale, velocity will scale as $L^{1/2}$ (L is some characteristic dimension) and heat release rate should scale as $L^{5/2}$. However, since transient phenomena involving solid state heat transfer do not obey the same scaling laws and Froude modelling violates proper scaling of radiation, convection, and fuel bed geometry, difficulties are encountered in specifying times for fire development, and the heat release rate is not easy to control. However, it is difficult to make progress unless the heat release rate is scaled as $L^{5/2}$. Consequently at emergence of flame into the booking hall the model heat release rates suggest a fire with a heat output of 15-25 MW. Similarly, gas velocities at the top of the escalator extrapolated from the one-third scale simulations are predicted to be in the range 8-12 m/sec. Measured temperatures and their rates of rise are directly comparable.

The progress of the fire on a larger scale is rather more difficult to predict, as this is dependent upon heat transfer from the preceding flames and hot gases which is not properly accounted for in the model. The data suggests that convection is the dominant mode of heat transfer at the scale of the experiments. However, an examination of measurements at both one-tenth and one-third scale imply a linear dependence of radiative transfer with scale. This would mean, that even if convection were to be independent of model scale, then it would still be the principal mode of heat transfer. There is some evidence to suggest that since velocities scale with $L^{1/2}$ then so does the convective heat transfer coefficient. Again the experiments suggest a near linear scale variation of convection. This is difficult to reconcile with other data determined on what are essentially smooth surfaces and it is more probable that the measurements on the smallest models are strongly influenced by Reynolds number effects and do not form sufficient basis for extrapolation.

Thus one possible way to make progress is to follow De Ris[6] and assume that the convective heat flux scales on $L^{1/2}$.

Considering the fuel as thermally-thick the heat up time, Δt to the firepoint temperatures follows the simple relation

$$\Delta t - \rho C_p k (T - T_a)^2/2q^2 \qquad (1)$$

where ρ = the material density,
C_p = material specific heat,
k = thermal conductivity,
T = the firepoint temperature,
T_a = the ambient temperature,
and q = the incident heat flux,

which for convection only scales as L^{-1} since $q \sim L^{1/2}$. This then implies that the rate of fire spread is inversely proportional to the scale. It, therefore, follows that the time for square of the model fire to spread between two equivalent points varies with the inverse model scale and times on the models can be directly related to the full scale event. However, if the radiative flux scales with L, as can be tentatively implied from model data, then the times for fire spread will be further reduced, by a factor of up to 50 percent. Additionally, the enhanced flame stretch up the channel due to the growing fire will tend to accelerate the flame spread and reduce fire spread times. An initial appraisal of the lengths of the pyrolysis zones and heat release rates indicate that the length of such flames follow a power law relation with fuel burning rate with an index which, as would be expected from the nature of the situation, falls between that currently observed for a turbulent wall flame and that for a free diffusion flame from a horizontal fuel bed.

The situation is somewhat analogous to the vertical spread of flame on a wall, a situation which, following the treatment of Delichatsios[10], seems amenable to a relatively simple analysis. A similar approach for the *trench effect* (the term now commonly used to describe the phenomena which results in the fire largely remaining in an inclined channel) incorporating experimentally derived relationships for flame length, extent of the pyrolysis zone, and heat transfer coefficients (for example with heat release rates), shows some promise as a predictive tool, and in addition gives the explicit dependence of the rate of fire spread on such parameters as material and channel geometry.

Thus the scaled model tests provide both a qualitative picture of the fire spread mechanism and quantitative data from which extrapolations of the likely rate of fire spread at full scale can be inferred taking into account the increasing rates of radiative and convective heat transfer to the combustible material observed in the tests. They also provide basic data for modelling the rate of advance of the flamefront based on flame spread up thermally-thick inclined surfaces. They were therefore presented to the Enquiry as the basis of a technical explanation for the incident, as described in Reference 11.

The fourth one-third scale model test, in which the fire was started on the right hand side, was in our opinion in good qualitative agreement with the events on the night of the fire, particularly with regard to the fire growth after the left hand side of the escalator was alight.

Conclusions - Lessons to be Learned

The "Trench Effect"

The aerodynamic effect that concentrated the fire products in the escalator trench and resulted in the rapid flame spread up the escalator has come to be known as the *trench effect*. It was an important outcome of the scientific investigation, as it demonstrated the possibility of greatly enhanced rates of flame spread in certain situations. Three factors combine to give this effect: the slope of the escalator; the trench profile which affected the lateral movement of air and hot combustion products; and the presence of flammable materials on the floor and sides of the trench.

As similar geometrical situations also containing flammable materials may exist in buildings and industrial environments, the relative contributions of these three factors is a matter for further scientific investigation. Such questions as the effect of angle of slope on fire growth rate, the behaviour of a fire in a trench with flammable materials on the floor (but not on the sides) and the behavior of materials other than wood all need to be addressed. The Health and Safety Executive has therefore started detailed investigations of some of these features.

The Production and Movement of Smoke in a Complex Building

The King's Cross fire illustrated the speed with which smoke can be circulated in complex buildings, including recirculation into areas not necessarily in the main direction of the ventilation flow.

Above all, the fire illustrated once more the importance of the provision of smoke free routes as most of the fatalities were caused by exposure to smoke, and many survivors had to escape through the hot dense smoke.

There are two complementary approaches to this problem — the reduction of smoke emission in the event of a fire and the isolation of escape routes from any smoke that is produced in a fire (and, of course, for life safety, that includes isolation from exposure to carbon monoxide and other toxic gases). Hence the assessment of materials should take account not only of flammability characteristics but also of smoke producing characteristics.

Perceptions of the Fire in Progress

In general people have certain perceptions of fire and the dangers associated with it, based on their observations of controlled fires (such as bonfires or stubble burning) and on observations of accidental fires. They develop an awareness of danger based on certain signs, such as large billowing flames or copious smoke emissions, and a tolerance of fire situations from which such signs are absent. Clearly, these perceptions of danger differ widely between individuals.

The King's Cross fire exemplifies this point. Some witnesses stopped and watched the fire shortly before flashover, two witnesses probably saw the initial entry of flame into the ticket hall, and some witnesses ran from the station at a much earlier stage because of the presence of relatively light smoke.

The King's Cross fire had been burning for more than 15 minutes and then, within a period of 30 seconds or so, conditions within the ticket hall went from being somewhat hot and smoky, but free of flame, to being engulfed in flames and thick black smoke. The smoke then swept through the passages to the street level access points, causing scores of people to flee for their lives.

Thus failure to perceive the fire as a genuine threat to life until it was too late, together with the absence of an escape route free from exposure to the smoke and fumes from the fire, created the conditions which lead to a major loss of life.

Safety Management

The management responsibilities for safety matters for the Underground system were found by the Public Enquiry[12] to be diffused through the personnel structure. This diffusion resulted in the identification of some risks and intentions to improve the risks. Although the Underground company had a legal responsibility to provide an economic and safe system of transportation, the Enquiry found that only the economic aspects were pursued effectively.

The Report[12] of the Enquiry contains 157 recommendations. Some of the major areas covered by the recommendations are listed below:

- All aspects of fire precautions should be improved, including means of escape; fire prevention and the means of achieving it; fire detection and extinguishment; and selection of materials to minimise the fire and smoke hazards.
- Personnel and technical aspects of communication should be improved.
- Special emergency training procedures should be developed.
- Improved liaison between the staff of the Underground and the emergency services should be achieved.
- The replacement programme for escalators should be speeded-up and the design of new escalators reviewed to remove the hazard potential as identified in the Investigation.
- All escalator installations should be improved quickly.
- Better signage systems should be designed and installed.
- The management of safety should be simpler and responsibility placed on a non-executive director of the Board of the London Underground.
- A system of safety auditing should be established.
- Change the present legislation so that the application of the fire safety law to the Underground is unambiguous.

It is to the credit of everyone concerned that, some three years after the incident, most of these recommendations are either in place or well in hand.

Acknowledgements

The authors wish to acknowledge the considerable amount of assistance given by other members of the Research & Laboratory Services Division of the HSE when undertaking the investigation, in particular members of the Fire and Process Hazards Section.

REFERENCES

1. Moodie, K., and Wharton, R.K., "Fire at King's Cross Underground Station, 18th November 1987, Part 1: "Damage Assessment," RLSD Incident Report No. IR/L/FR/87/54, 1987.
2. Wharton, R.K., "Fire at King's Cross Underground Station, 18th November 1987, Part 5: Ignition Tests and Characterization of Samples," RLSD Incident Report No. IR/L/FR/88/6, 1988.
3. Simcox, S., Wilkes, N.S., and Jones, I.P., "Fire at King's Cross Underground Station, 18th November 1987: Numerical Simulation of the Buoyant Flaw and Heat Transfer," AERE-G 4677 Harwell, May 1988.
4. Britter, R.E., and Linden, P.F., "Fluid Mechanics and Physical Modelling of King's Cross Fire," CERC Report No. FM 17/88, July 1988.
5. Britter, R.E., and Linden, P.F., "Fluid Mechanics and Physical Modelling of King's Cross Fire - Flaw in the Booking Hall," CERC Report No. FM 19/88, July 1988.
6. De Ris, J., "Modelling Techniques for Predictions of Fires," *Applied Polymer Symp. No. 22*, Wiley, 1973.
7. Moodie, K., Jagger, S.F., Bettis, R.J., and Beckett, H., "Fire at King's Cross Underground Station 18th November 1987, Part 11: Scale Model Fire Growth Tests," RLSD Incident Report No. IR/L/FR/88/22, 1988.
8. Jagger, S.F., Willoughby, D.B., Beckett, H., Bettis, R.J., and Moodie, K., "Fire at King's Cross Underground Station, 18th, November 1987, Part 17: Further One-third Scale Fire Growth Tests," RLSD Incident Report No. IR/L/FR/88/37, 1988.
9. Jagger, S.F., Beckett, H., Harper, P.J., Regan, N.J., and Willoughby, D.B., "Fire at King's Cross Underground Station, 18th November 1987, Part 16: The LUL One-third Scale Fire Growth Test," RLSD Repayment Contract No. IR/L/FR/88/38, 1988.
10. Delichatsios, M.A., "Turbulent Convective Flows and Burning on Vertical Walls," *19th Symp. Combustion*, pp. 855-868, 1982.
11. Moodie, K., "Fire at King's Cross Underground Station, 18th November 1987, Part 12: Assessment of Fire Dynamics (updated version)," RLSD Incident Report No. IR/L/FR/88/26, 1988.
12. Fennel, D., "Investigation into the King's Cross Fire," HMSO, 1988.