NISTIR 89-4061

AN ENGINEERING VIEW OF THE FIRE OF MAY 4, 1988 IN THE FIRST INTERSTATE BANK BUILDING LOS ANGELES, CALIFORNIA

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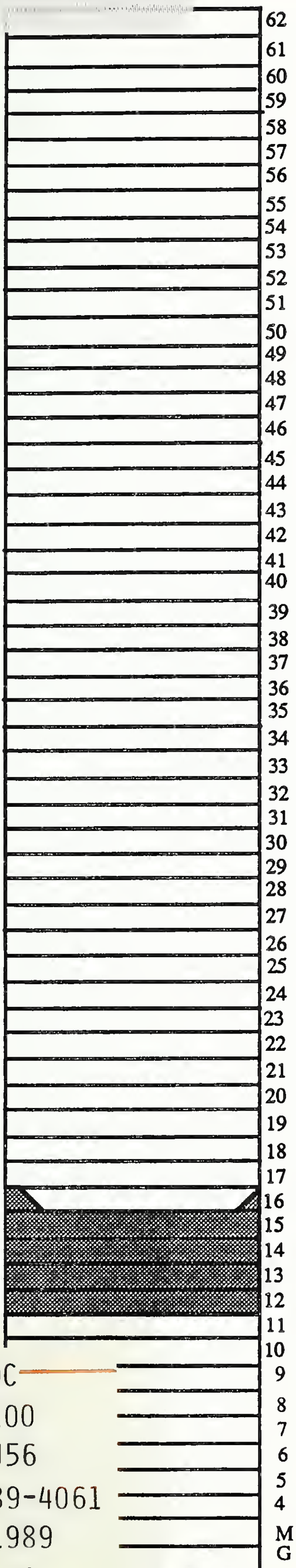
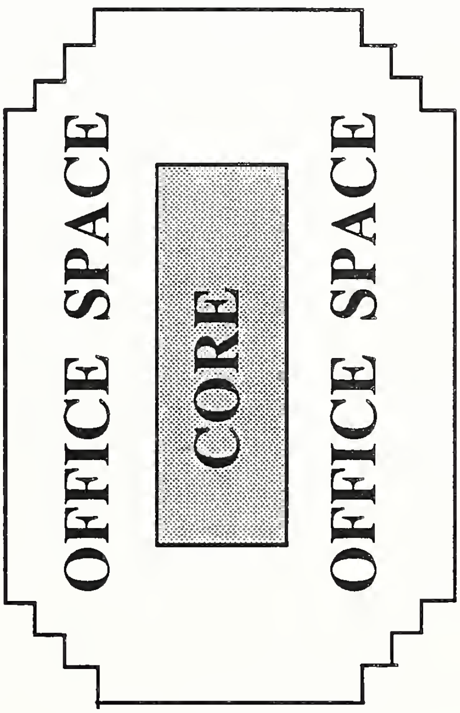
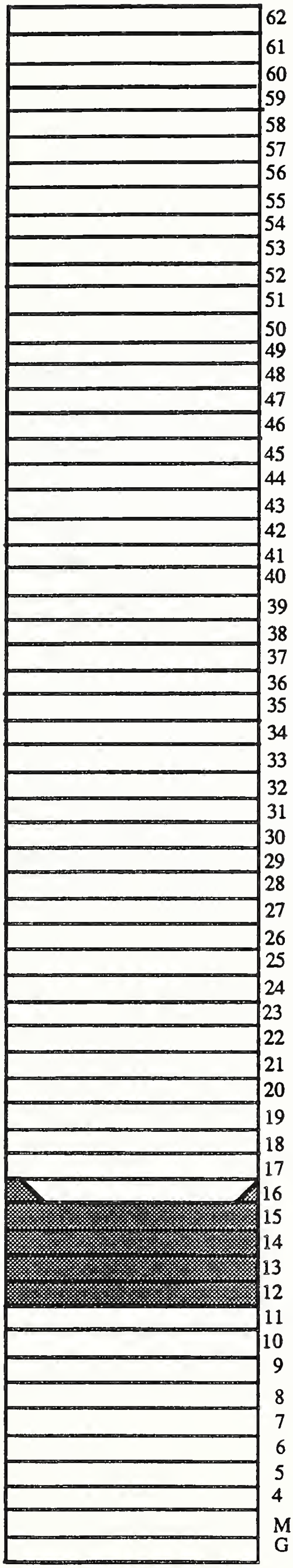
March 1989







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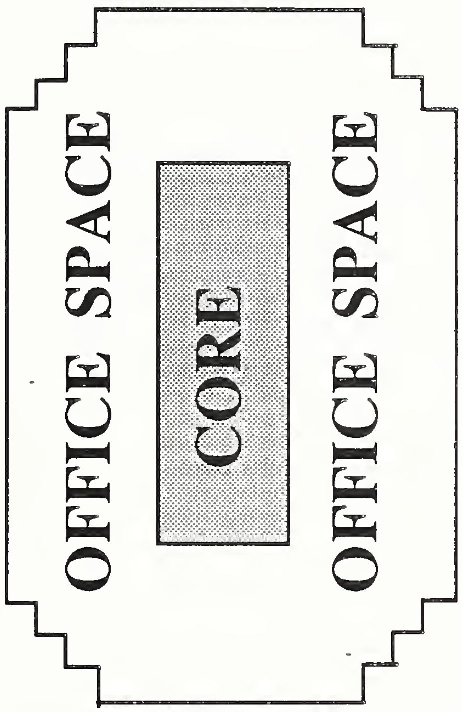

March 1989

U. S. DEPARTMENT OF COMMERCE
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Ernest Ambler, Acting Under Secretary for Technology
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Raymond G. Kammer, Acting Director

An Engineering View of the Fire of May 4, 1988 in the First Interstate Bank Building Los Angeles, California

Harold E. Nelson
Center for Fire Research
National Institute of Standards and Technology

This presentation views the fire in the First Interstate Bank Building in terms of the phenomena of fire, its impact, the response of building elements, and some of the fire safety implications involved. Concepts expressed in this presentation were developed through on-site inspection and subsequent technical analysis. The details of this analysis and the computations involved are in a separate report now in review. This discussion traces the development of the fire, with digressions at points where a discussion of the pertinent fire phenomena is appropriate.

BRIEF STORY OF THE FIRE

An after hours fire initiated on the 12th floor. Once established, it spread through this floor and propagated to the 13th, 14th, 15th, and part of the 16th floor over a period of about two hours. Furnishings, finishes, utilities, and ceiling systems on floors twelve through fifteen were destroyed. The windows on these floors broke out. One building employee perished when he responded by elevator to the fire floor. A few late workers and maintenance personnel were trapped above the fire. Some experienced emotional trauma, however, there were no additional fatalities. Smoke damage permeated through the building with heavy damage from the 12th floor to the top of the building.

PERTINENT DETAILS

Building Structure.

The building is a 62-story steel-frame tower. Figure 1 shows a number of the details in schematic elevation section. Structural members and floor decks are protected by direct-applied fire proofing.

Exterior Perimeter.

The perimeter of the building is entirely glass. The glass is supported by vertical, aluminum mullions on five-foot spacing. From window sill to ceiling height, transparent glass window fills each space. At the ceiling level, there is an aluminum lintel with a glass spandrel panel from there to the sill above. There is glass fiber material between the end of the floor slab and the glass panel.

Ceiling.

Each floor has a suspended ceiling hung approximately four feet below the floor slab. The ceiling system is a concealed spline system with non-fire rated mineral tiles. Light fixtures (see figure 2) are interspersed at about five foot intervals in both directions in the ceiling.

HVAC Arrangement.

The heating ventilating and air conditioning (HVAC) system supplies air at the perimeter and through every fifth light fixture. The other light fixtures are return air fixtures with two approximately 6-inch square return air grills in each fixture. The ceiling void is a return air plenum with air drawn to four return air shafts. There is one return air shaft in each corner of the central core. As shown in figure 3, the HVAC system is divided into four vertical zones. The floors involved (12-16) are in a zone that covers the 12th through 32nd floors. The plenums on all of these floors are common to the same return air shafts. Each opening from a plenum to a return air shaft is protected by a fusible link operated fire damper. The shafts are enclosed with fire rated gypsum board on both sides of steel studs.

Elevators.

There are multiple rises of elevator shafts (see figure 3.) The fire floors are served by the low rise elevators. The entrances to all of these elevators are located in an elevator lobby. On floors (including the 12th, but not the 13th, 14th, 15th or 16th floors) this lobby is separated from the office area by smoke detector operated fire doors. The mid- and high rise elevator shafts have no openings to the fire floors. In addition there are two elevator in a full building height portion of the high rise shaft that open on all floors. One (elevator 33 where the victim perished) opens to a separate freight elevator lobby.

Office Floor Arrangement.

Each floor is approximately 22,000 sq. ft. Of this, about 7,000 sq. ft. is the core area. The remaining 15,000 sq. ft. is in office use. The subdivision of offices varies from floor to floor.

Figure 4 shows the layout of the 12th floor at the time of the fire. Most of the 12th floor was an open office landscaped "trading floor." The individual workstations were equipped with personal computers, monitors, and other electronic equipment. Extensive power and signalling wiring systems were involved. There was a small series of perimeter offices along the north end of the building and the north half of the east side of the 12th floor.

The population density on the trading floor was in the range of 70-80 sq. ft. per person. This density is quite high in terms of office usage but within the distribution ranges observed in fire load studies.

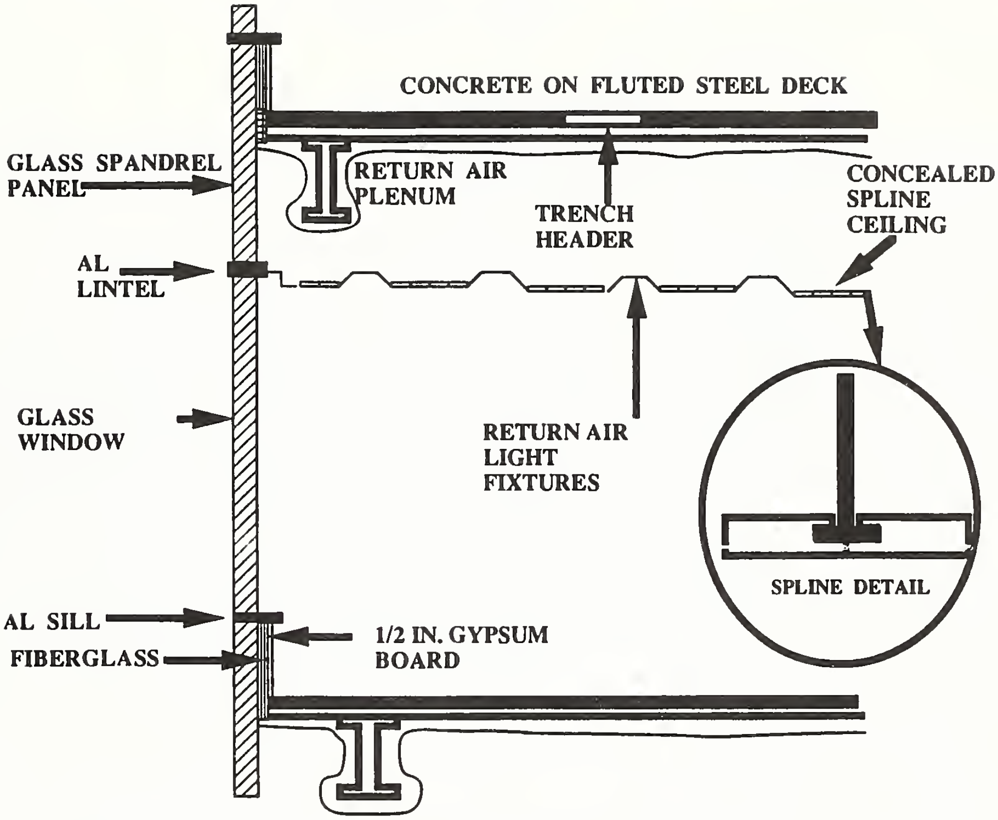


FIGURE 1. SELECTED BUILDING ELEMENTS

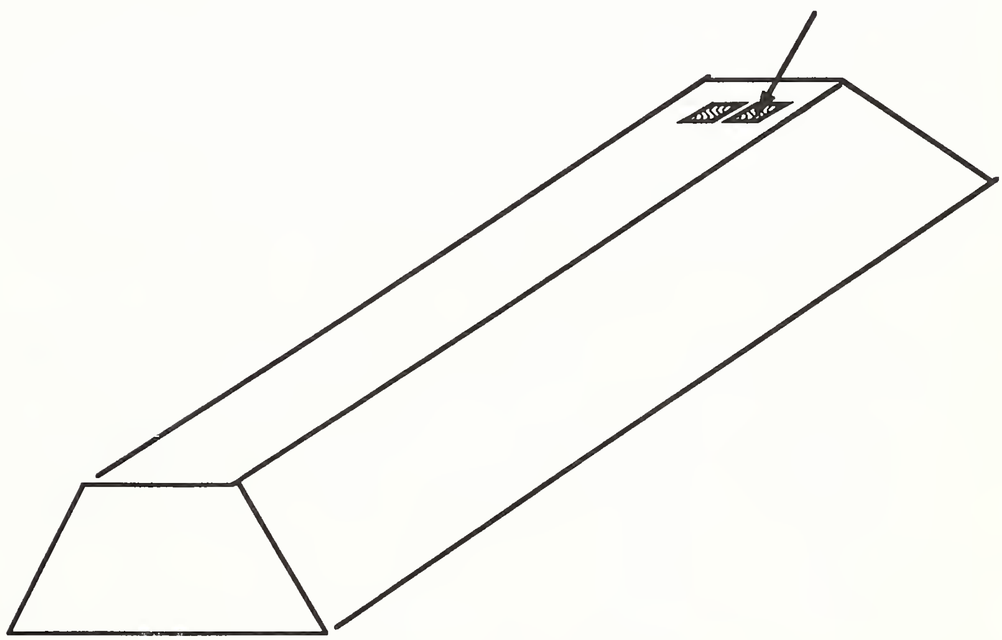


FIGURE 2. RETURN AIR LIGHT FIXTURE

The 12th floor was the only trading floor in the building. The other floors involved in the fire were mostly separate offices with smaller open groups of support activities.

Smoke Detector Arrangement.

The response of the smoke detectors was a principal source of data in recreating the fire. Each office floor has five smoke detector zones numbered zones 2 through 6. The layout is shown in figure 5. Zone 3 covers the area where the fire originated. Zone 6 is a special zone covering both the main elevator lobby and the small lobby in front of the freight elevator. There are smoke detectors located in the plenum space above the ceiling in zones 2-5. The smoke detectors in zone 6 are under the ceiling in the elevator lobbies and the freight elevator vestibule. In zone 3, there is one additional smoke detector located beneath the ceiling at the entrance door to the exit stair. That exit stair has a pressurized vestibule. In addition to the detectors described above, there were detectors connected to magnetic-hold opens for doors at each end of the 12th floor elevator lobby. These detectors, however, were reported as not connected to the fire alarm system.

Automatic Sprinklers.

The piping and sprinkler heads for an automatic sprinkler system had been recently installed on the 12th floor. The sprinkler system, however, was not yet in service. The system had quick response sprinkler heads. The type of head involved has a response time index of about 50 (sec-feet)$^{1/2}$. While these heads had no effect on the fire, the time and size of fire when the heads fused was appraised.

FIRE DEVELOPMENT

Engineering Approach

The engineering approach was based on established techniques that are generally available in engineering literature. Important aspects of this analysis of this fire are discussed below.

The Available Safe Egress Time model (ASET) as presented in FIREFORM [1], modified to account for the consumption of oxygen, was used to predict the temperatures, level, and oxygen content of the smoke layer. This method was used until the calculations indicated a smoke level temperature of 1112 degrees F (600 degrees C.) After this it was assumed that flashover[1] conditions had occurred and the ASET model no longer applied.

[1] Flashover as used in this presentation is a condition where the smoke level reaches a temperature that radiates sufficient energy to raise exposed unignited surfaces to their ignition temperature. The result is rapid ignition of the previously unignited surfaces. Where there is a significant quantity of such surfaces, as in this case, there is a very rapid increase in burning rate. This is often occurs at about the same time as a burnout of unignited fuel in the smoke layer also often called flashover.

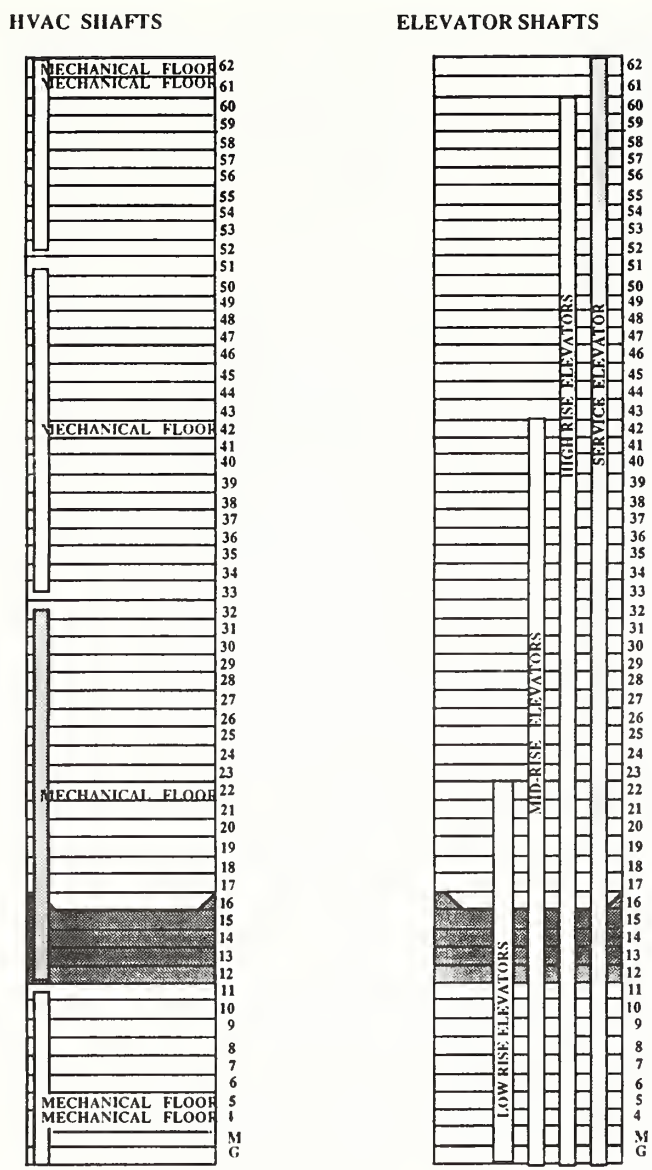


FIGURE 3. SHAFTS

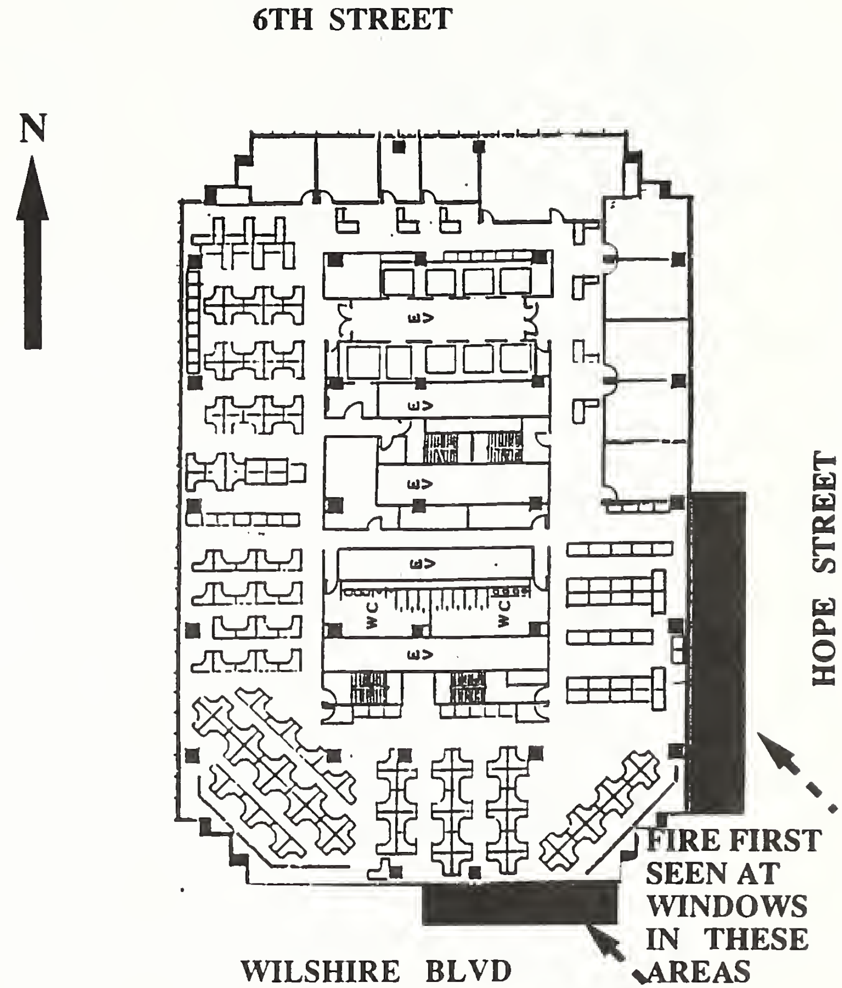


FIGURE 4. LAYOUT OF 12TH FLOOR

Following the widespread ignition associated with flashover level smoke layer temperatures, the entire 12th floor (and subsequently 13th through 15th floors) became involved in flame. Temperatures in the involved spaces were assumed to have risen substantially, but no attempt was made to calculate them. Rather attention was given to estimating the length of flame extension and the availability of combustion air as such related to the type of combustion that took place. This was felt important to understanding the mechanisms of fire propagation between floors. The approach used to estimate flame extension for conditions where there was adequate combustion air supply within the building was based on the flame length equations for flame height presented in Drysdales' text [2.] The extension of flames impinging on ceilings was estimated based on the recent work of Gross [3]. For those conditions where there was not sufficient combustion air within the building, the estimated flame extension out of the window was based on the equations initially formulated by Yokoi [4]. The estimated availability of combustion air was based on equations presented by Walton and Thomas in the SFPE Handbook of Fire Protection Engineering [5].

In another aspect of the analysis the calculated relationship of the response of smoke detectors to the growth of fire was made. This was done to assist in determining if and when certain smoke detectors detected smoke development and initiated alarm signals. The analysis was then used as an additional factor in attempting to identify the likely point of fire initiation. The FIREFORM [1] version of the computational model, DETACT-QS, was used to estimate the response of detectors.

Origin.

The exact point and time of fire origin has not been firmly established. Both the field examination and subsequent analysis place highest credibility on a fire that started in one of the rows of computerized workstations used in the trading floor. The timing and positioning of fire, as traced in this presentation, have been derived by relating the response of the smoke detectors to the potential range of speeds of fire growth considering the types of workstations present. This assumes that all of the smoke detectors that were connected to the fire alarm system responded as designed.

APPROXIMATELY 10:25-10:27 P.M.

Start of Analysis.

The fire trace discussed above indicates an open flaming fire of 10-20 kW approximately 3 minutes prior the 10:30 pm operation of the first smoke detector. The flame probably had a base about 6 inches in diameter and a height of about 18 inches. This is the start of analysis in this presentation. While figure 6 depicts the flame on top of the workstation it might actually have been on top of the workstation, under it, or between workstations.

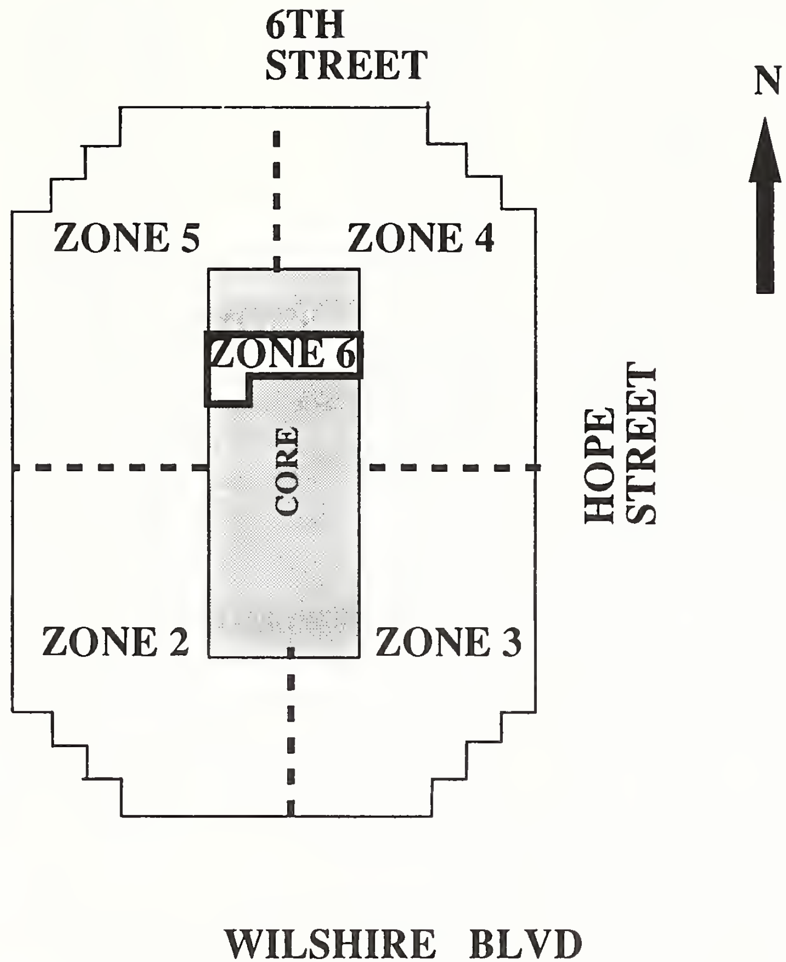
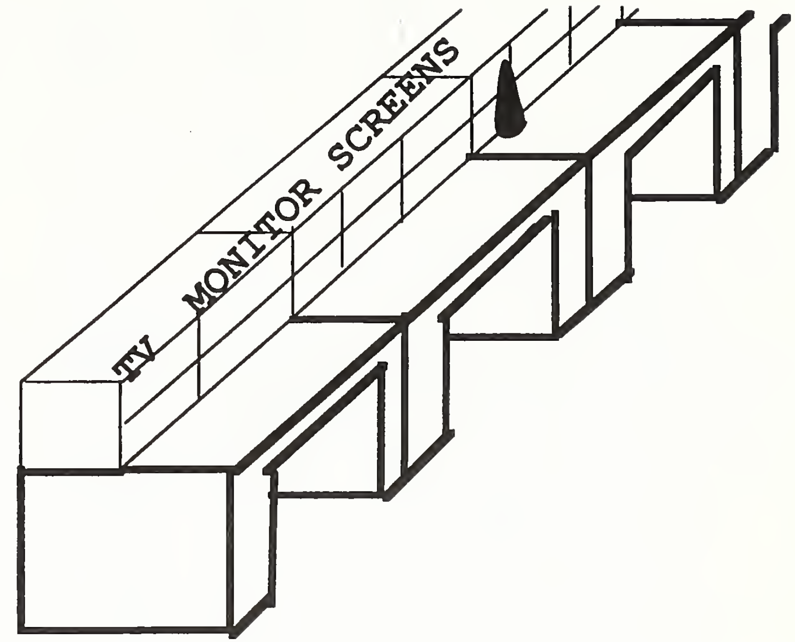


FIGURE 5. FIRE ALARM SYSTEM ZONES



12TH FLOOR ABOUT 10:25 - 10:27 A SMALL FLAME (<20KW) EXISTS INVOLVING SOME PART OF A WORKSTATION

FIGURE 6. INITIAL FIRE ON A WORKSTATION

Initial Workstation.

A combination of best available test data and principles of radiant energy transfer and ignition susceptibility were used to predict the initial (pre-flashover) fire growth and item to item spread in the early stages of fire development on the 12th floor. The limited availability of good test data on burning rate development of real world furniture and equipment limits the reliability of this approach to the reasonableness of the test data used. In this instance existing full scale test data for involving a single workstation similar to those on the 12th floor was used to predict the burning rate of the first ignited workstation. The ignition of exposed workstations and their subsequent rates of burning was derived on the basis of radiant energy transfer from the flame produced by the burning workstation, the response of exposed workstations to that radiation, and the temperature response of these workstations to such radiation. The subsequent burning rate was, however, a judgement prediction. The logic in this judgement is discussed in the following section entitled, Fire Spread and Involvement of Additional Workstations.

The burning of the initial workstation is believed to have approximated that produced in a test of a computer workstation complex previously tested in the furniture calorimeter at the Center for Fire Research [6]. The rate of heat release curve used is shown in figure 7.

Fire Spread and Involvement of Additional Workstations.

In the First Interstate Bank Building, workstations were in rows. The development of the fire along and between rows was driven by radiation from the growing flame. The preheating of exposed workstations caused their fire growth rates to be faster than that of the initial workstation.

Consequently, the growth rate assigned in analyzing subsequently ignited workstations was that used for a "fast fire" as described in NFPA 72E. The resultant free-burn fire growth curve, derived from calculating this spread as a series of individual radiant ignitions of workstations, is shown in figure 8. This curve is compared to both the fast and moderate fire growth curves of NFPA 72E.

The calculated burning rate starts out at a growth rate somewhat slower than that for the moderate curve but increases after several workstations are involved to a rate greater than the fast curve. Only the first 11 minutes of fire development is shown. As the fire approached that time the onset of flashover conditions and resulting fire environment rather than free-burn characteristics controlled the burning rate.

Flame Height (Extension) from the Developing Fire.

As the fire grew, the fire base increased and the rate of heat release from the fire increased. Flame height is a function of rate of heat release and area of fire base. The theoretical free burn flame height from the fuel array presented by the rows of workstations peaked at about 18-20 ft. See figure 9. Since the ceiling was only 6-9 ft. above the fire (depending on whether the

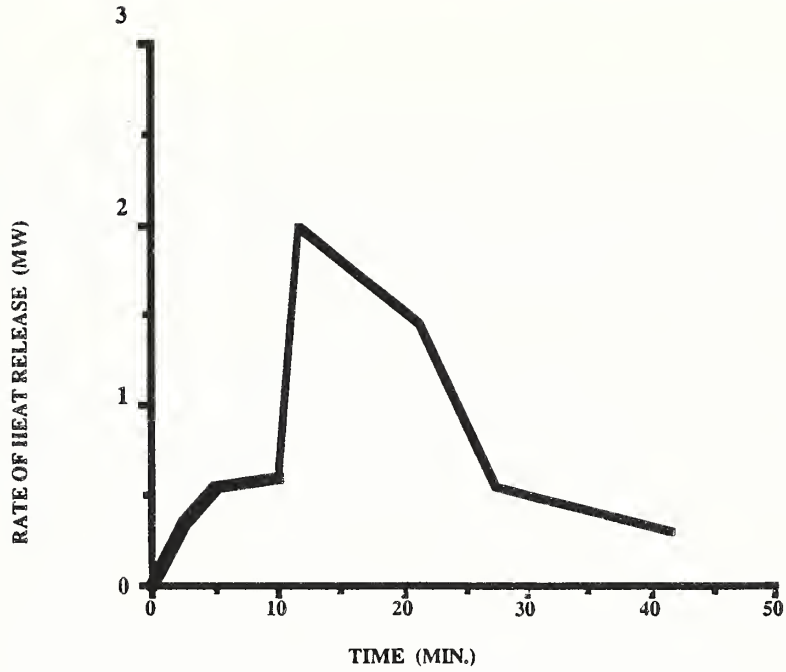


FIGURE 7. RATE OF HEAT RELEASE, TYPICAL COMPUTER WORKSTATION

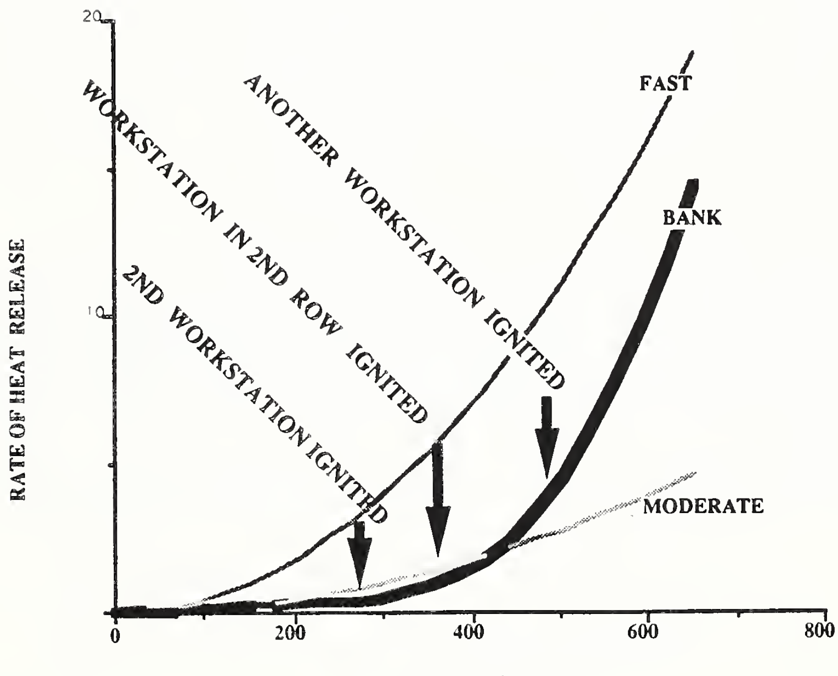


FIGURE 8. ESTIMATED FREE-BURN RATE OF HEAT RELEASE OF GROUPS OF WORKSTATIONS AS FOUND ON TRAIDING (12TH) FLOOR

fire was on the floor or the top of the workstation), the flame touched the ceiling when the rate of heat release was between 1/2 and 1 MW, (i.e. 5 1/2 to 6 1/2 minutes into the fire.) After the flame reached the ceiling, it extended along the ceiling spreading radially a distance about equivalent to that portion of the theoretical flame height cut off by the ceiling.

10:30 P.M. (FIGURE 10)

NOTE: The fire spread depicted in the figures in this presentation place the fire in the position indicated by the author's calculations to be one, but not the only, possible area of origin. If the fire started near the southeast corner, as theorized by other investigators a similar propagation starting from a different point of origin took place.

Fire and Smoke Conditions.

The analysis of smoke conditions includes the temperature, thickness of the upper layer, and the oxygen content in that layer. Until flashover (10:37 p.m.) these values were calculated using the ASET model [1]. By 10:30 p.m., the fire has grown to 250 kW. There is a ceiling jet starting to fill the ceiling area. The depth of this ceiling jet is less than 1 ft. The smoke temperature is estimated at 150°F.

Detector Response.

The time of response of each smoke detector zone is recorded by the fire alarm system. The times used are from the building fire alarm system records. At 10:30 p.m., the first detector response occurs in zone 3. The location of smoke detectors in zone 3 is indicated by the black dots over the exit door and in the ceiling space in figure 10. It is believed that this response is from the detector located in front of the exit stairway. Calculations using DETACT-QS [1] indicate that this response is appropriate for a detector located about 40 ft. (plus or minus 10 ft.) away and 6 ft. over the fire source. Once this detector operated, there is no more additional discernable data from zone 3. It is therefore impossible to determine when the detector in the plenum in zone 3 responds.

Sprinkler Heads.

By 10:30 p.m. (depending on the relationship of the sprinkler head location relative to the point of fire origin) one or more sprinkler heads have fused. Sprinkler head response calculations (again using DETACT-QS) place the size of fire at time of fusing of the first head at 40 to 250 kW. In tests at CFR, fire control of test cribs allowed to burn until a burning rate of 250 kW was achieved were controlled by application rates as low as 0.1 gpm/ft.^{2}.

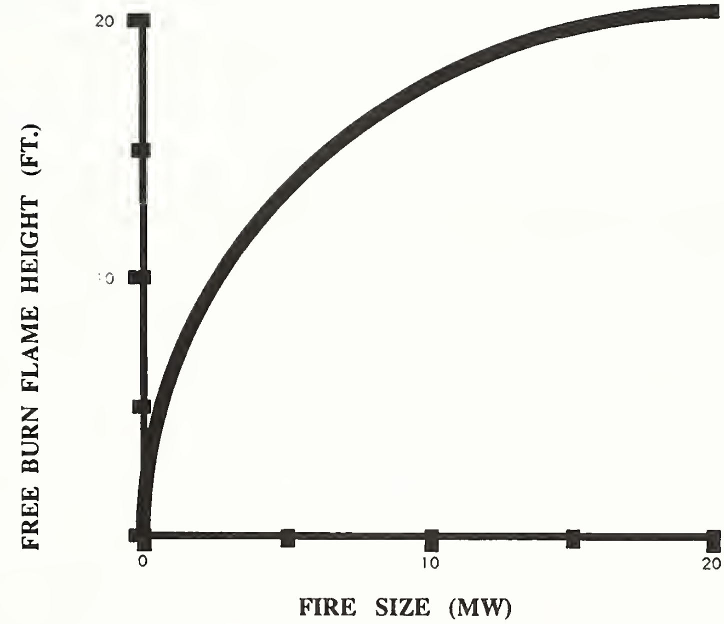
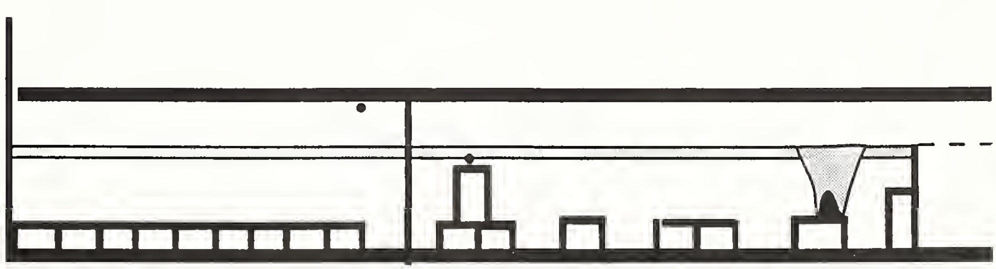


FIGURE 9. APPROXIMATE FREE BURN FLAME HEIGHT



12 TH FLOOR - 10:30 PM - 250 KW FIRE - CEILING JET <1FT. DEEP
SMOKE TEMPERATURE 150 F - DETECTOR RESPONDS IN ZONE 3 - ONE OR MORE SPRINKLER HEADS FUSED

FIGURE 10. CONDITIONS AT 10:30 P.M.

10:32 P.M.(FIGURE 11)

Fire and Smoke Conditions.

The fire has grown to 500 kW. The fire has spread to at least one additional workstation in the row where the fire started. The smoke layer under the ceiling is about 18 inches thick and 160 F.

Detector Response.

At 10:32 detector response occurs in zone 4 closely followed by response from zone 6.

Smoke and heat flow through the light fixtures was calculated. In view of the wide dispersion of these fixtures, the farthest a detector in the plenum could be from the plume rising out of a vent is approximately 3 ft. The calculations indicate a detectable smoke stream at about 10:32 p.m. from the fire hypothesized. This matches the recorded response time. Since the ASET [1] calculations used are a zone model that assumes that the smoke layer under the ceiling throughout the entire floor is the same depth and temperature, the calculations do not in themselves identify which light fixture and which detector respond.

The assumption of equal smoke conditions throughout the floor is, of course, incorrect. Temperature, if not depth of smoke is less at positions more distant from the fire source. Lower temperatures at locations more remote from the fire source reduce the rate of flow into the ceiling in those areas. As a first order assumption, it can be concluded that the zone that came in second (zone 4) was closer to the fire. Lacking any other information, this is a reasonable speculation. However, since zone 2 responds during the following minute, this speculation must be treated with caution.

Estimating Probable Areas of Ignition Source.

Figure 12 shows an arc about 40 feet away from the smoke detector over the entrance to the stairwell with the smoke vestibule. It is felt likely that the location of the source of ignition is within about 10 feet of this arc.

Figure 13 depicts the post fire remains of wooden workstations on the Hope Street side of the 12th floor. The portion depicted extends from the partition separating the private offices from the open trading floor space to the south end of the central core. A sloping pattern of destruction descends from the top of the workstations at the north end of the space shown to the floor at the south end of this area. Destruction extends to floor level from this point across most of the south end of the floor. In many fires the lowest point of burning is taken as indicative of the point of fire origin.

If both the burn pattern evidence and the calculations related to detector response could be considered fully reliable the point of origin would be close to the arc shown in figure 12 at a point south of the end of the central core in a position closer to zone 4 than to zone 2. However, in view of the size and rate of development of this fire both the burn pattern evidence and the

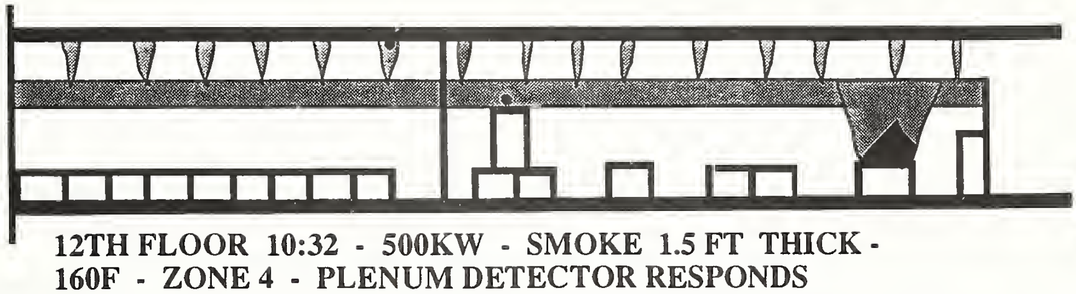
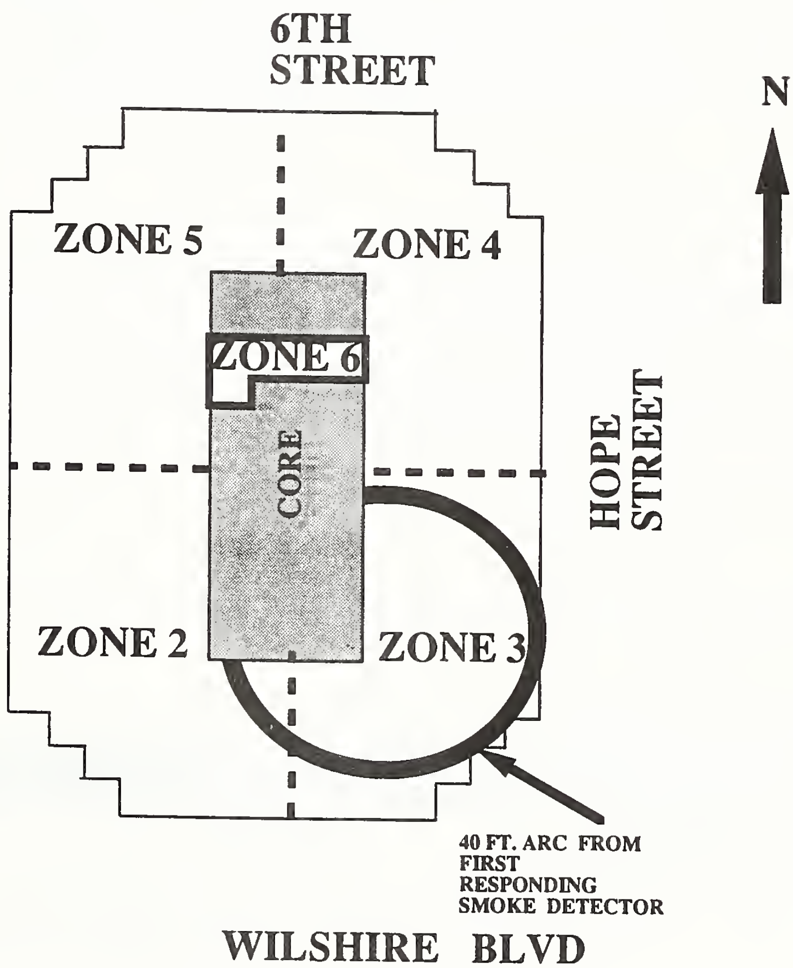


FIGURE 11. CONDITIONS AT 10:32 P.M.



FIRE ALARM SYSTEM ZONES

FIGURE 12 LIKELY POINTS OF FIRE INITIATION detector response calculations must be treated with caution. More conclusive evidence would be needed to reach an irrefutable conclusion.

10:33 P.M. (FIGURE 14)

Fire and Smoke Conditions.

At 10:33 p.m., smoke has filled the 12th floor to a depth of about 4 ft. The fire is approximately 1 MW. Smoke temperature is in the range of 200°F and the plenum is beginning to fill with smoke well beyond a haze.

Smoke Detector Response.

At 10:33 p.m. the smoke detector in zone 2 of the 12th floor responds.

10:35 p.m. (FIGURE 15)

Fire and Smoke Conditions.

By 10:35 p.m., the fire size has increased to about 4 MW. A second row of workstations has been ignited. The smoke layer is about 4 ft. thick (a little below head height). The smoke temperature is 325°F (well beyond human tolerance).

Smoke Detector Response.

By 10:35 p.m. all of the detection zones on the 12th floor have sounded.

Activities of Fire Victim.

At this time or soon thereafter, the victim leaves the sub-basement and takes the freight elevator to the 12th floor.

10:36 P.M. (FIGURE 16)

Fire and Smoke Conditions.

By 10:36 p.m., the fire has grown to the range of 7 MW. Smoke is about 5 feet thick (about 4 ft. above the floor) and in the range of 500°F.

Smoke Detector Response.

Smoke from the plenum sweeps up through the return air shafts. During the next 2 minutes, smoke detectors respond for multiple zones on almost all of the floors between 12 and 32. These are the floors served by common return air shafts. (See figure 3.)

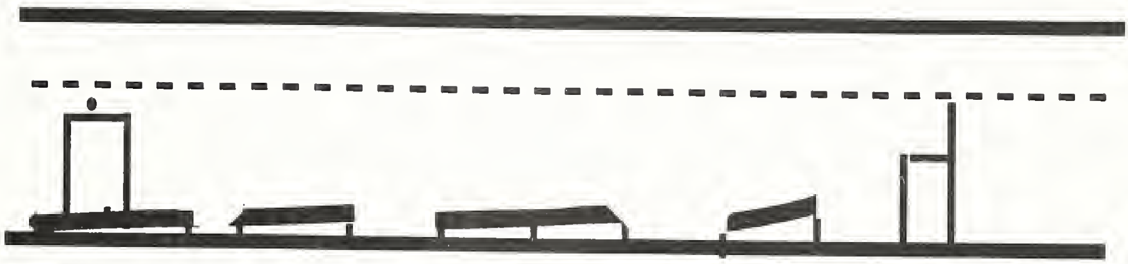
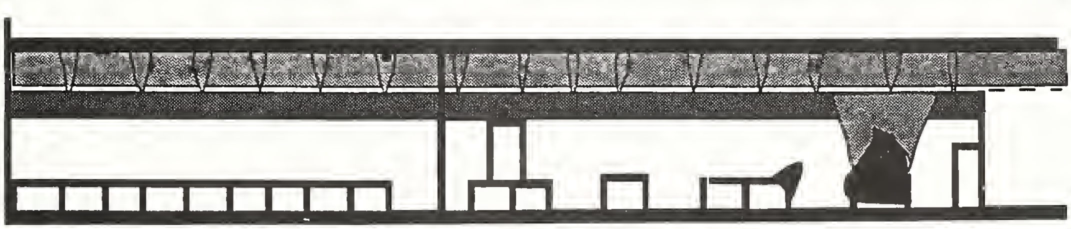


FIGURE 13. BURN PATTERN IN WOODEN FURNITURE ON HOPE ST. SIDE



12TH FLOOR 10:33 - 1000KW - SMOKE <2 FT THICK - 200F - ZONE 2 - PLENUM DETECTOR RESPONDS

FIGURE 14. CONDITIONS AT 10:33 P.M.

10:37 P.M. (FIGURE 17)

Fire and Smoke Conditions.

The fire is estimated at 10 MW. The smoke is about 7 foot thick (down to about 2 ft. above the floor) and has a temperature around 1100°F. The oxygen content in the smoke is 14% with normal air still available near the floor. This provides enough oxygen to allow continued combustion. The smoke temperatures reaches the flashover level.

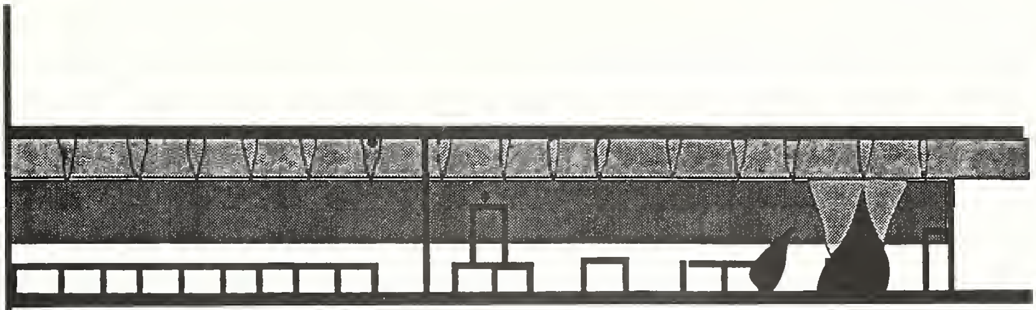
Smoke of this temperature (1100 F) emits heat radiation capable of igniting most common combustible materials. Such a sudden ignition results in the phenomenon often called flashover. If sufficient air for combustion of all of the newly release fuel vapors is unavailable, all or a portion of the fuel vapors produced from the radiant heating may not all burn. Hence, whether of not the full involvement of a large space in flame usually associated with flashover is actually achieved depends on whether the windows break prior to os subsequent to the development of flashover triggering conditions (i.e. smoke temperature of 1100 F.) In this fire, neither the evidence nor physics provides a basis for an assumption on whether window breakage or flashover conditions occurred first. (See the later discussion of glass breakage.)

Likelihood of Flashover in a Closed Space.

In many fires in a closed space the fire smothers itself (the fire starves for lack of oxygen) without reaching flashover conditions. A study was made of factors important in determining whether or not a fire will lead to flashover (rather than smother itself) in a closed space. The ASET [1] model was used to make this study.

In a fast developing fire, key parameters include the area of the floor and the height between the base of the fire and the ceiling. The closer the base of the fire to the ceiling, the more likely that the fire will develop ceiling temperatures capable of causing flashover (thereby causing window breakage, resulting in a continuous air supply) before the smoke layer both reduces its oxygen level below that capable of supporting combustion and descends low enough to starve the fire. Where the base of the fire is further from the ceiling, the cooling effect of the entrained air slows down the development of ceiling temperatures. In such case a much larger floor area is necessary to provide a sufficient air reservoir to produce flashover temperatures in a closed space. The differences are shown in figure 18.

Further study to better relate these factors as well as fire growth rates and maximum fire size to flashover in closed space would be valuable. However, these calculations demonstrate a potential associated with open office arrangements with concentrated grouping of combustible work areas. Where such concentrations occur in spaces involving large floor areas and relatively low ceilings, there can be sufficient combustion air within the space to allow a developing fire to reach flashover conditions. This even if no additional air is introduced into the space.

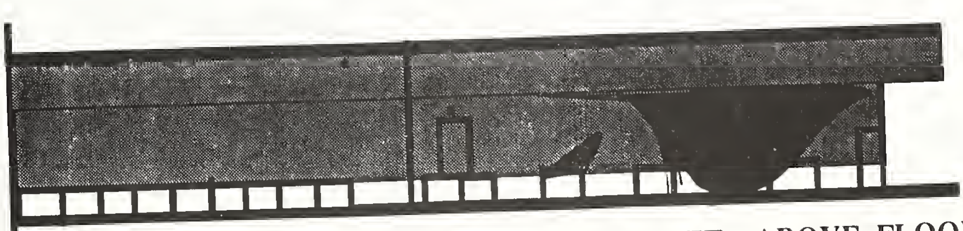


12TH FLOOR 10:35 - 4MW - SMOKE 4 FT THICK - 325F -
ZONE 2 - ALL 12TH FLOOR DETECTORS RESPOND

FIGURE 15. CONDITIONS AT 10:35 P.M.

12TH FLOOR 10:36 - 7MW - SMOKE 5 FT THICK - 500F -
ZONE 2 - DETECTORS RESPOND ON FLOORS ABOVE

FIGURE 16. CONDITIONS AT 10:36 P.M.



12TH FLOOR 10:37 10MW SMOKE NOW 2 FT. ABOVE FLOOR
1100 F OXYGEN 14%

FIGURE 17. CONDITIONS AT 10:37 P.M.

Glass Breakage. (FIGURE 19)

One reason that it is not possible to determine whether the windows broke before or after flashover is that glass characteristically breaks in two manners.

a. <u>Radiant heating without flame contact.</u> If flame does not contact the glass surface, heating of the glass is by radiant energy. In that case, the portions of the glass shielded from direct radiation do not heat-up as quickly as that portion exposed to direct radiation. As this occurs, internal stresses build up in the glass due to the greater thermal expansion of the more heated surface over the shielded surface. Theoretical calculations have indicated that when the temperature difference between the shielded and unshielded portions of the glass reaches about 100 F, radial cracks will travel from the boundaries quickly reaching a point of failure of the glass.

b. <u>Flame in contact with glass.</u> Where direct contact is made between flame and glass, a thermal shock causing massive stresses between the hot side and the cool side of the plate occurs. This causes rapid cracking through the glass and failure of the glass whether or not general heating of the glass has taken place. The thicker the glass, the more likely this type of failure.

On this basis, if the fire source location is near the core, flames probably did not reach the glass prior to the development of flashover temperatures. Flashover conditions then produced radiation that heated the glass to its point of failure. Conversely, if the point of initiation was close to the windows, flame contacted the glass and the windows broke prior to flashover. In this latter case the early venting of the fire may have prevented the development of true flashover conditions.

For purposes of this analysis flashover was considered to have occurred if the calculations indicated a smoke level temperature of 1112 F (600 C.) or more. Even if such temperatures were not actually achieved, the spread of fire by item to item radiation resulted in progressive spread across the furnishings and filling of the space with flame. The importance of flashover is the near simultaneous ignition of blocks of items caused by radiation from the hot smoke.

The limited information on the time sequence of spread of fire around the 12th floor indicates that the fire spread faster in the portion of the space nearest the area of ignition and the spacial progression slowed down as the fire extended to the opposite side of the building. The damage on the 12th floor also was greatest near the side and end of early development. This may be indicative of higher (flashover range) smoke temperatures during the initial development in this area. This followed by cooler smoke temperatures due to the cooling effect of the excess air entering the building as a result of the massive opening area that develops as more and more windows break.

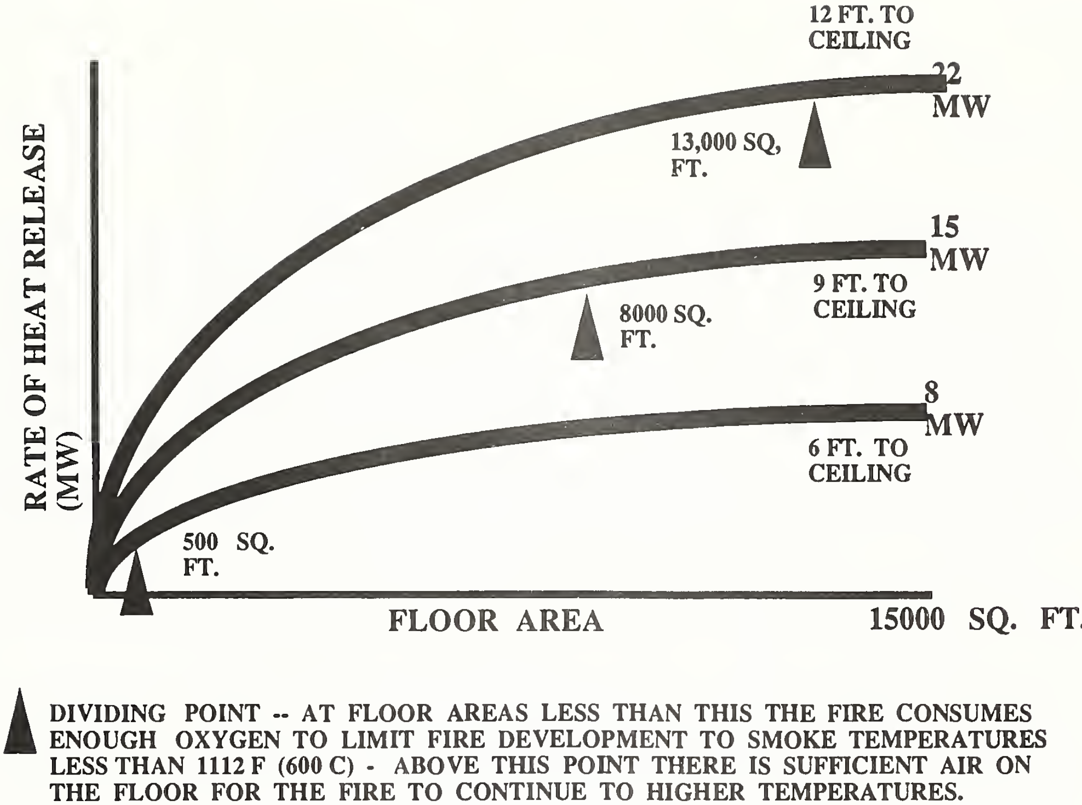


FIGURE 18. MAXIMUM FIRE SIZE IN A CLOSED SPACE AS A FUNCTION OF FLOOR AREA AND DISTANCE FROM FIRE TO CEILING

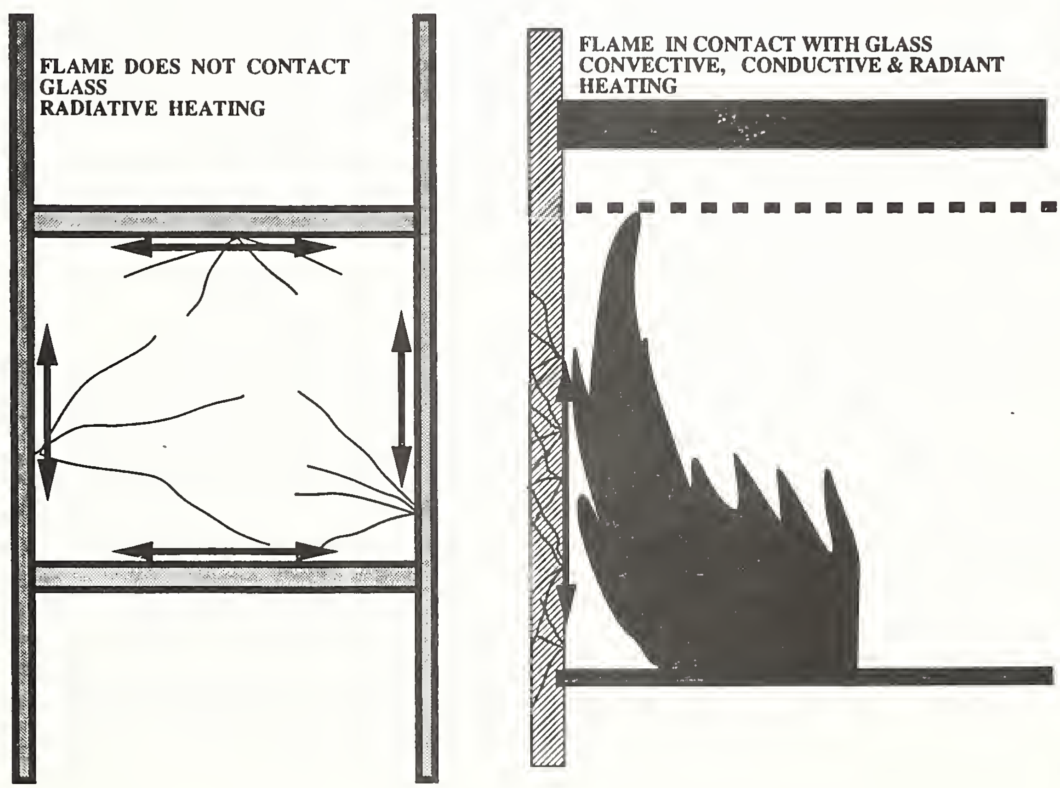


FIGURE 19. FIRE CAUSES OF GLASS BREAKAGE

Activities of Fire Victim.

At approximately 10:37 p.m., the bank employee who has responded in the elevator is heard on his walkie-talkie radio calling for help. His message was cut short. While actual flame had not yet reached the freight elevator lobby, it is likely that he is inundated with smoke heated to over 500 F. This estimate of lower than calculated temperature is an arbitrary judgement of the author. Even a temperature as high as 500 F implies a condition hundreds of degrees less than that calculated for the general work area. The estimated temperature drop is believed to result from the cooling effect of energy losses to the ceiling and walls encountered by the smoke as it moves from the area of actual fire involvement to the freight elevator. This is felt to be consistent with our analysis.

10:37 P.M. - 10:40 P.M. CONTINUED PROPAGATION

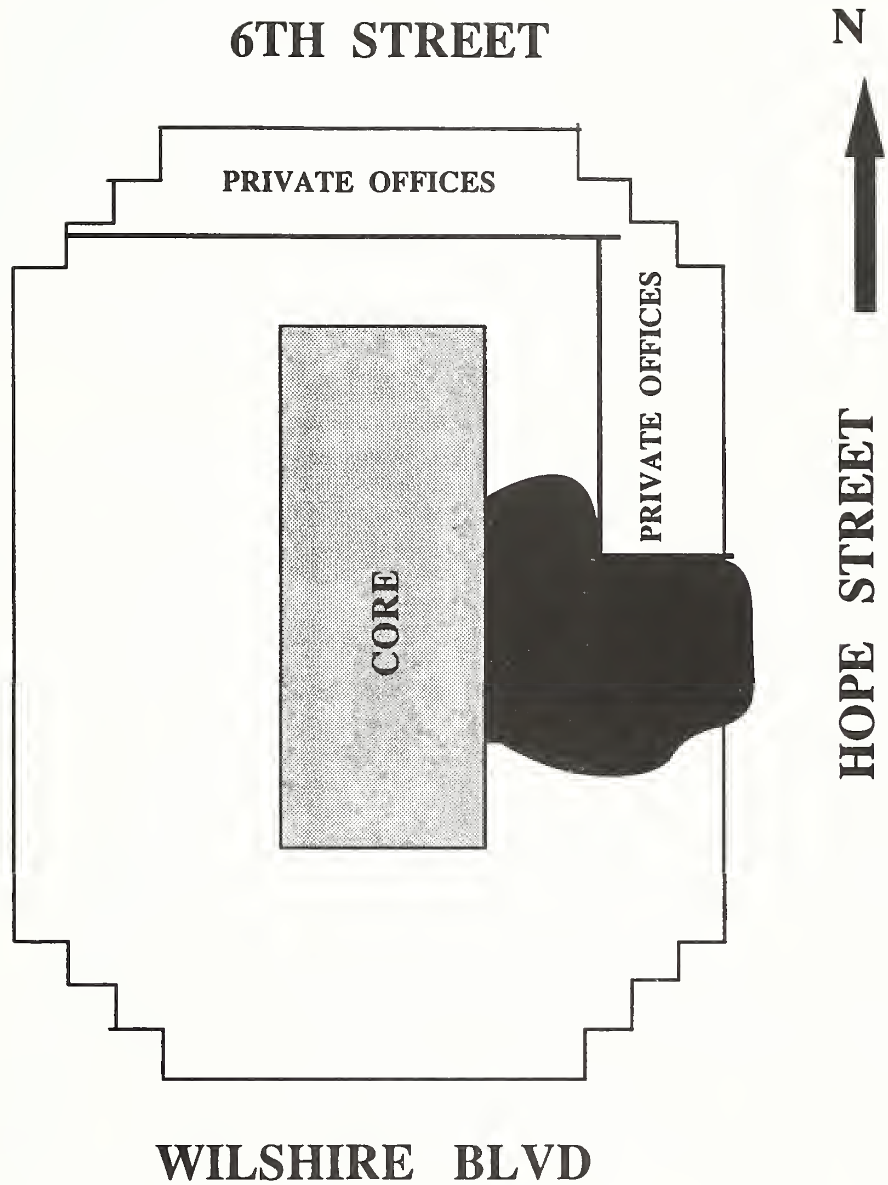
Fire Conditions.

The most likely occurrence is localized high (flashover range) temperatures produced by the flame and high temperature gases nearest the fire source. This caused window breakage in the immediate area. It is likely that the initial venting of the fire, depicted in figure 20, occurs before involvement of other portions of the floor. At the moment of breakage it is possible that the resulting opening is large enough to allow the fire to draw into the floor all of the air needed for the complete combustion of the material burning at that time.

The fire, however, continues to grow and propagate by radiating from the flame and hot gases from the fire source to unignited rows of workstations. This results in progressive enlargement of the very high temperature zone which fractures more windows, producing a larger opening for drawing air into the fire. This allows the fire to spread, the flame to increase and the production of hot gases to continue. As a result more windows break. This again vents the fire and the cycle repeats. With each cycle the ratio of the air on the 12th floor available for combustion to the air needed to complete the combustion of all the fuel released by the burning material decreases as the fire grew, and increases as windows break.

Compartment Burning Rate, Theory.

In fire the available air supply within a compartment has important impacts on both the degree that fuel is converted to energy within the compartment and the rate that ignited combustibles supply fuel to the fire. When the amount of air is exactly in balance with the amount of fuel (i.e. after combustion, there is neither unburned fuel or unused air left) burning is referred to as stoichiometric. This ratio of fuel to air is referred to as the stoichiometric (fuel to air) ratio. The ratio of fuel supplied to air supplied divided by the stoichiometric ratio is called the equivalence ratio. In an automotive engine, the carburetor performs this function. The ratio of the air available to the air required for stoichiometric combustion is called the excess air ratio. When there is an excess of air the equivalence ratio is less than 1.0. When there is not enough air the condition is refereed to as fuel rich and the equivalence ratio is greater than 1.0. Most accidental



ABOUT 10:37 FIRST WINDOWS BREAK

FIGURE 20. AREA OF FIRE INVOLVEMENT AT 10:37

fires do not burn at the stoichiometric ratio, especially when they burn within a compartment.

a. <u>Rate of Heat Energy Released Within a Compartment from the Fuel Supplied.</u> When there is an excess of air (equivalence ratio is less than 1.0) all or nearly all of the burning will take place within the compartment and the products will be much the same as those that would be produced by burning of the same material in the open. If conversely the air in the compartment is insufficient (equivalence ratio is greater than 1.0) the combustion within the compartment will be incomplete. Any products leaving the compartment will contain unburned fuel and other products of incomplete combustion. Typically, there is an increased concentration of carbon monoxide (CO) in these products. If these gases are contained in a flame vented from a window or other opening where additional air is available, the unburned fuel gases are likely to complete the combustion process adding to the extension of the flame. If not, it is possible that no more combustion will take place. In either case the amount of energy release within the compartment for any given rate of fuel gas generation is as much controlled by the air available within the compartment as by the rate of fuel gas generation. In sum, only that portion of the fuel gases that finds air and actually combusts within the compartment adds energy (heat) to that compartment.

b. <u>Rate of Fuel Release Within a Compartment.</u> The rate of fuel release is an interdependent function of the properties of the exposed fuel, its arrangement, and the incident energy impinging on it. The incident energy comes from the flames produced by burning materials and from the hot smoke and surfaces in the compartment. The rate of heat release within the compartment is a dominant factor in the temperature conditions in the smoke layer and resulting heating of surfaces. When the equivalence ratio is less than 1.0, there is excess air and the energy release within the compartment is due to the rate of fuel gas generation. This is usually called a "fuel-controlled fire." After flashover conditions develop, given the availability of combustible surfaces, the equivalence ration is usually greater than 1.0. This is called a "ventilation-controlled fire." In a ventilation controlled fire the supply available air controls the rate of energy release within the compartment. In such case the smoke contains excess fuel which can burn outside the window or at another point where the smoke vents.

Figure 21 depicts the possible burning states of a fire in a compartment for a fixed amount of involved combustibles (i.e. fuel load.) The ventilation air supply represents the possible variation in window or door vents (or other features) that can be the source of air supply for the fire. For low ventilation the fuel produced can exceed the stoichiometric value. This depends on the degree of heat transfer from the fire and the compartment environment and the nature of the combustibles. As ventilation increases (e.g. windows break,) the same combustible fuel load can achieve different rate of fuel gas generation. Ultimately, in every vented compartment fire, this reaches a state in which excess air prevails. This fire undoubtedly experienced all aspects of this fire behavior. Before the windows broke and the initial oxygen was consumed, the fire on the 12th floor was to the left of the stoichiometric line as shown on figure 21. As the windows broke the fire state moved to the right of that line.

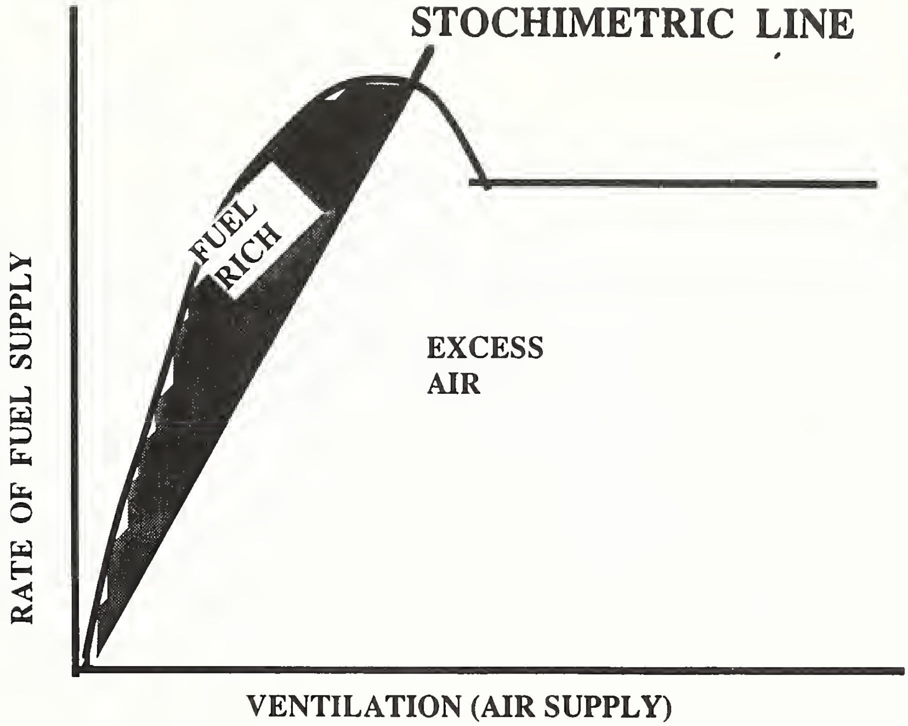


FIGURE 21. COMPARTMENT BURNING RATE THEORY

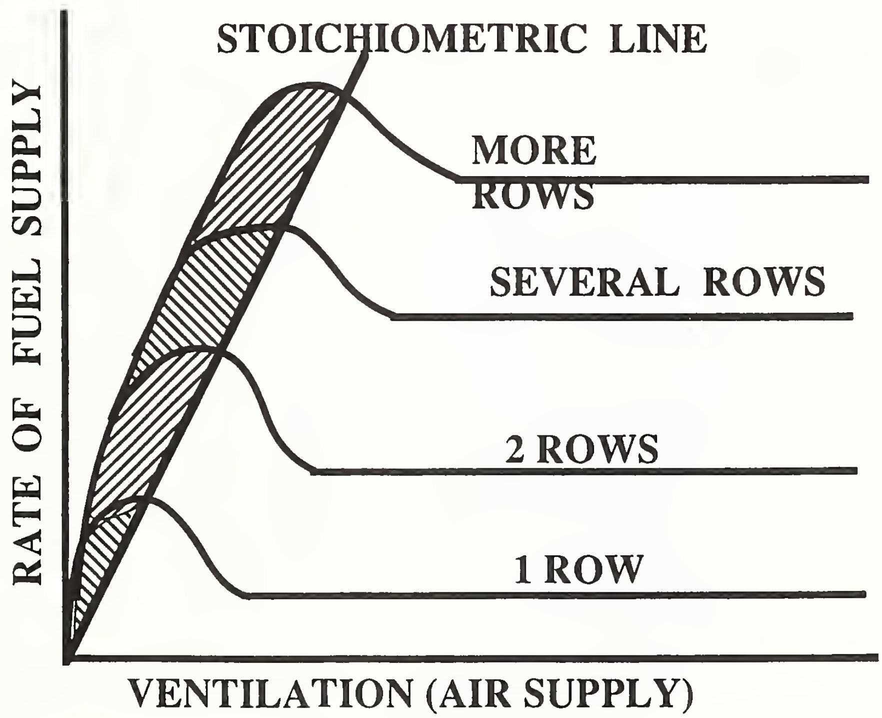


FIGURE 22. COMPARTMENT BURNING RATE THEORY APPIED TO EARY STAGES OF THIS FIRE

Compartment Burning Rate Theory Applied to This Fire.

Figure 22 depicts a growing condition such as occurred in the bank building. As more and more fuel enters the picture, the required ventilation to move from fuel rich to air rich increases. It is believed that a condition stepping through these ranges probably occurred as the fire propagated around the 12th floor. Unfortunately, the lack of photographs or eye witness descriptions during the that period prevents confirmation.

Flame Extension from Broken Windows.

At the time of first breakage, it was likely that the fire is on the fuel rich side and expelled significant quantities of unburned gases forming a large flame, such as shown in figure 23. Such a flame could have broken glass and started some ignitions on the floor above or, failing to break the glass, radiated the material on the 13th floor preheating it. Since no ignitions are reported on the 13th floor at this time, the latter condition is more likely.

10:40 P.M.

Fire Spread.

Figure 24 estimates the extent of spread through the 12th floor at 10:40 p.m. As time progresses, the fire spreads across more surface area and windows are broken out over Wilshire Boulevard. By about 10:40 p.m., there are reports of extensive fire on both the Wilshire Boulevard and the Hope Street sides of the building. The prime means of fire spread continues to be radiant ignition of groups of workstations by the flame extension from the burning fuel. Shortly after 10:40 p.m., fire starts to progress along the west side of the building.

Retreat of Flame Extension.

As more windows broke, the amount of ventilation increases. An estimate of the fuel available versus the oxygen available through broken windows indicates that when all of the surface area is involved and all of the windows are broken there is at least twice as much air available as needed to burn the fuel. By the time about half the window glass failed the fire retreats into the building. After that point, there is an excess of air supply causing the flame height to stabilize in the 15-20 foot high range plotted in figure 9. Such a flame can, however, attack the glass spandrel panel. Photographs taken during the fire, but not part of this report, show this. Some of the photographs also show localized long flames extending from individual office compartments as they became ignited and flashed over. This exception fits the previously described compartment burning rate theory.

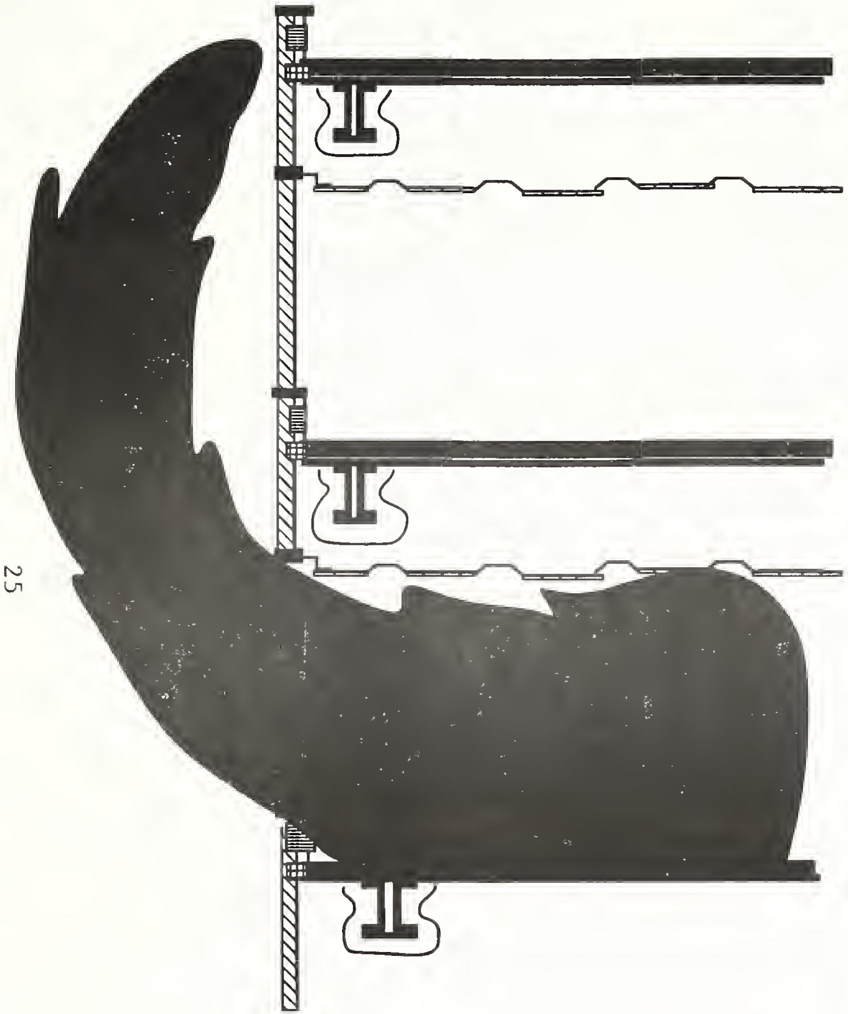
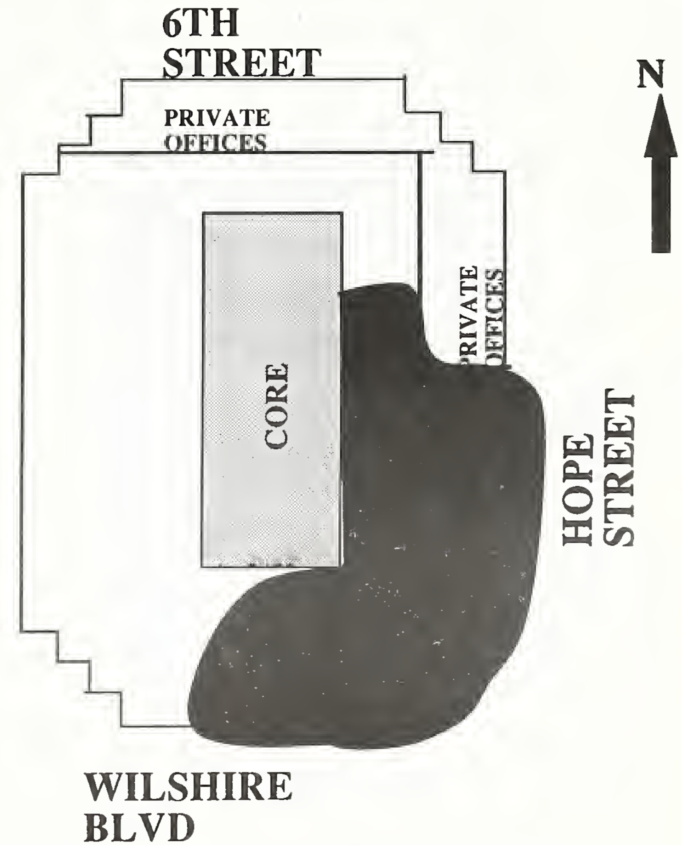


FIGURE 23. EXTENTION OF FUEL RICH FLAME



ABOUT 10:40 SPREAD COVERS
MORE THAN 1/4 OF PERIMETER

FIGURE 24. AREA OF INVOLVEMENT
AT 10:40 P.M.

11:00 P.M.

Spread to Thirteenth Floor.

Fire spreads to the 13th floor at about 11:00 p.m. Flame emitting from most of the 12th floor windows. In view of the ventilation provided by the broken windows the length of flame extension is a function of air-rich burning. The extension is in the range shown in figure 25. Exceptions appear on video tapes where extensive flame emission come form windows of individual offices (presumably as the individual rooms flashover.) It is likely that at least portions of the suspended ceiling have failed by this time (11:00 p.m.) thereby exposing the spandrel panel and end of the floor slab to direct flame impingement.

Four different potential means of fire transmission between floors were noted from photographs, video tapes, fire department observations, and post fire evidence. It is impossible to determine which caused the first ignition or which was most prevalent. These four identified fire transmissions means are:

a. Massive extension of flame covering the window area on the floor above.

b. Failure of the suspended ceiling and glass spandrel panel, followed by lapping of the flame around the end of the floor slab.

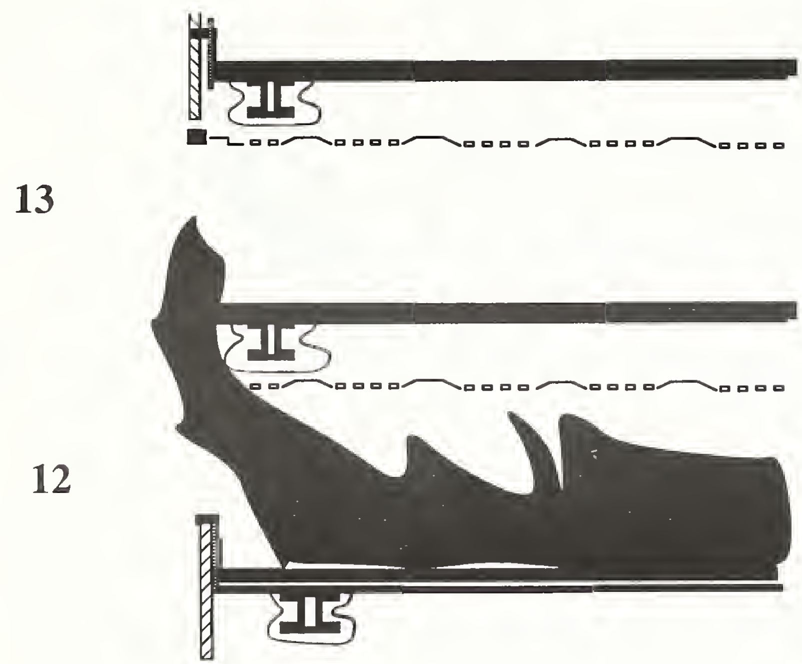
c. Flame transmission between the glass spandrel panel and the end of the floor slab. In this instance the actual transmission of fire may have resulted from failure of the gypsum board panel extending from the window sill on the floor above the fire to floor level, failure of the aluminum window sill or mullions, or failure of the glass spandrel panel.

d. Passage of flame through spaces around pipes and other penetrations of the floor slab. This route was evidenced by burn traces in the core area.

11:30 P.M.

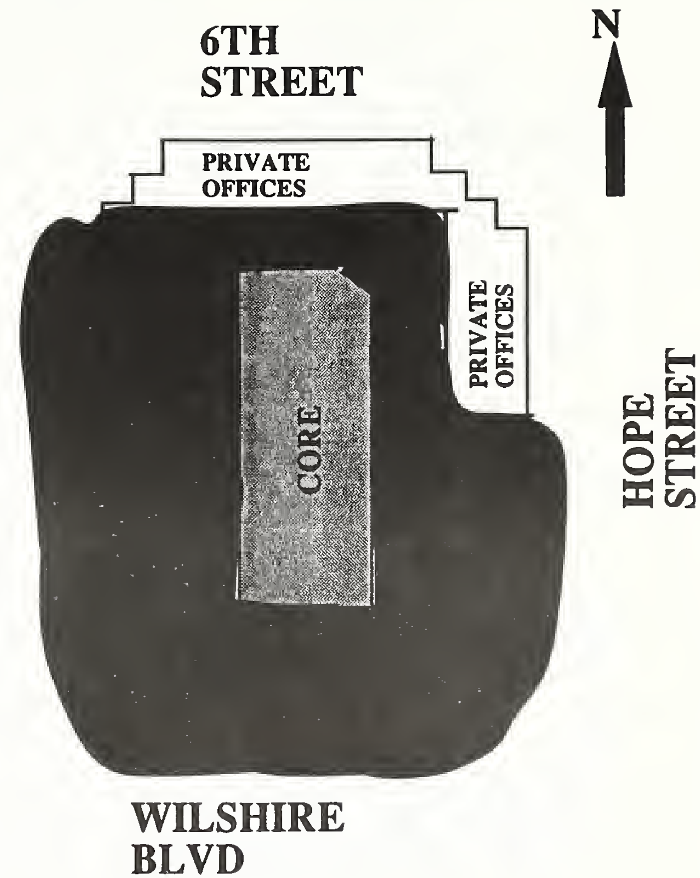
Spread to Northwest Corner of 12th Floor.

Photographs indicate that the fire reaches the northwest corner of the 12th floor at about 11:30 p.m. Fire involvement is estimated as shown in figure 26. Propagation around the floor slows as more of the floor becomes involved. It is possible that a portion of the flame is pulled towards the center of the building once the 13th floor is involved. This can reduce the flame extension along the ceiling, slowing down the rate of radiant ignition of new workstations and other fuel. Photographs indicate that during the next 30 minutes the fire progressively penetrates the offices along the north wall from west to east, reaching the northeast corner about midnight. It appears that the ceiling-high gypsum board partitions enclosing these offices retard their involvement.



ABOUT 11 PM IGNITION ESTABLISHED ON 13TH FLOOR

FIGURE 25. FIRE EXTENTION TO 13TH FLOOR



ABOUT 11:30 PM FIRE WRAPS FLOOR EXCEPT OFFICES -
FIRE EXTENDS TO OFFICES DURING NEXT HALF HOUR

FIGURE 26. AREA OF INVOLVEMENT AT 11:30 P.M.

11:40 P.M.

Spread to 14th Floor.

It is reported that the fire spreads to the 14th floor at about 11:40 p.m. As shown in figure 27, the means of extension is similar to the spread to the 13th floor. It is believed that by this time the involved floors may be reacting to each other resulting in raising the neutral plane on the 12th floor and lowering it on the 13th. If so there was a modest enhancement of the flame extension on the 13th floor. This is depicted by the difference in the shape of the flames shown in figure 27.

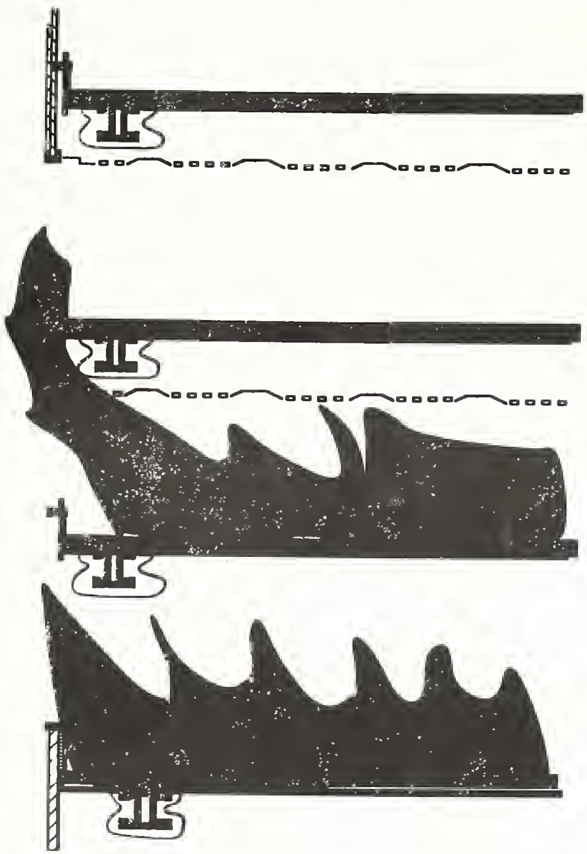
Inter Floor Fire Dynamics.

As each floor becomes involved, and the windows break, the dynamic relationship between the floors changes. Late in the fire, photographs show the flame inside the floor area away from the windows on the lower floors and emitting from the windows on the upper floors. It may be that all four floors operated as a single fire zone and with a neutral plane near the center of the 14th floor. At the same time, however, fuel is beginning to burn out on the first ignited floors reducing their impact. A delicate balance exists between the rate of burnout of the lower floors and the speed of advance to the next uninvolved floor. It is not possible to determine if by midnight the fire was on the verge of establishing a steady state of advance up the building or was slowing down as it moved away from the heavy fuel concentrations on the 12th floor. It may well be fortunate that the fire department was able to make a stand when they did. The relationship between the time of spread to the next floor and the duration of burning for a floor is critical in determining the continued propagation up the building. The duration of burning depends on the mass of fuel available, its rate of involvement over the floor, and its rate of consumption. We estimate this time as between 40 and 60 minutes on each floor during this fire. The lesser the fuel load on a floor the shorter the burn time. If any significant increase had occurred in the ratio of burn time to spread time the end result could have been an unstoppable fire.

12:20 A.M.

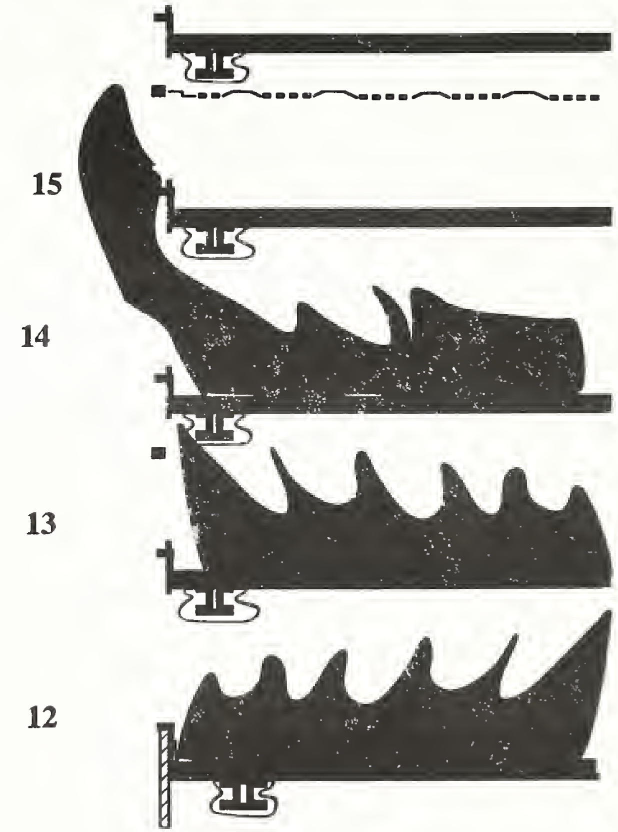
Spread to the 15th Floor.

The reported time of extension to the 15th floor is about 12:20 a.m. Figure 28 depicts the envisioned relationship of flame orientations. This emphasizes the concept that flame being drawn in on the lowest floor and pushed out on the highest floor with the upward movement of the neutral plane.



ABOUT 11 :40 PM IGNITION ESTABLISHED ON 14TH FLOOR

FIGU RE 27. SPREAD TO 14TH FLOOR



ABOUT 12:20 AM IGNITION ESTABLISHED ON 15TH FLOOR

FIGURE 28. FIRE EXTENTION TO THE 15TH FLOOR

12:50 A.M.

Spread to the 16th Floor.

Figure 29 shows a very tall flame extension from the 15th to 16th floor. The fire department now stops the fire on the 16th floor. Direct fire damage is limited to the north end and the south west corner of the floor. The 16th floor is the only floor where a fire stop is made soon enough to preserve evidence of the means of fire propagation. The burned ceiling portion over unburned furniture in the south west section of this floor is evidence of exterior flame penetration lapping from the 15th floor onto the 16th floor ceiling. An extensive flame is necessary to produce this result.

AFTER 1:00 A.M.

Smoke Conditions in Upper Floors of Building.

Conditions on Floors 17 through 32.

The smoke conditions up to the thirty-first floor are dominated by the system of shafts and floor openings through this region; the 12th through the thirty-first floors being a common air handling system.

Conditions Above the 32nd Floor.

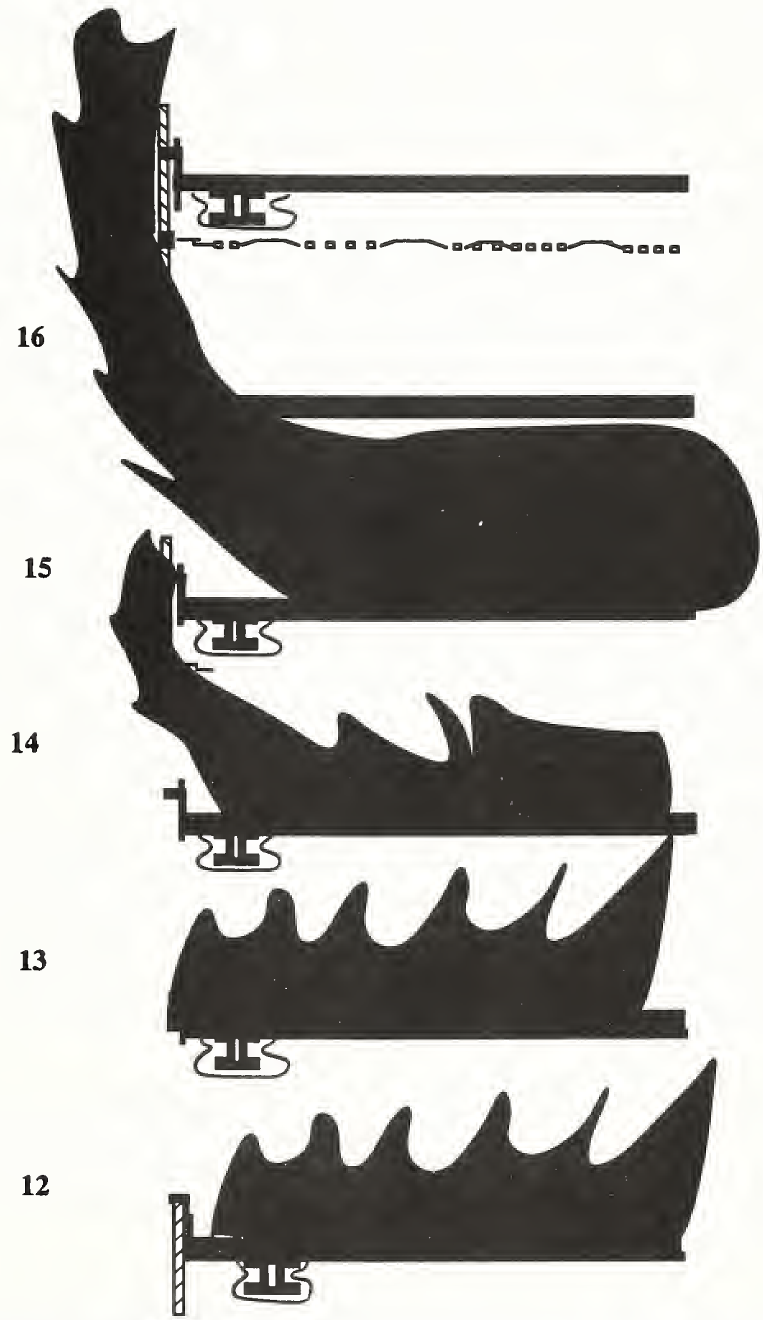
Smoke is transported to the upper section of the building (above the 32nd floor) by those shafts that extend full height. By far the most important smoke path is the freight elevator shaft. This, because of its height and because the door to this shaft stands open on the 12th floor through the course of the fire. The leakage between the open door and the elevator car being about 5 to 10 times that of a closed elevator door.

Stack Effect.

Figure 30 depicts the pressure relationships involved. The off-set in the pressure diagram reflects the broken windows and fire pressure on the fire floors. Therefore, it is likely that up to 1/3 of the products entering this shaft comes from one of the fire floors. (The other 2/3 or so being drawn in through the elevator doors on floors not involved in the fire.) Estimates were made of the rate of flow from the shaft to the various floors in the upper portion of the building, the leakage from these floors to the outside, and the resulting level of contamination concentration on each of the floors. Given enough time, equilibrium eventually occurs and the atmosphere on the floor becomes the same as that in the shaft.

Contamination Concentration.

Appraisal was made of the increase of smoke concentration in the upper floors of the building during a two-hour period. The results are approximately that shown in figure 31. After two hours, the atmosphere on the top floors approaches that in the shaft. At that time the atmosphere in the top floors is around 1/3 as toxic as that on the fire floor. It is probably fortunate for those trapped in the upper portion of the building that most of the



ABOUT 12:50 AM IGNITION ESTABLISHED ON 16TH FLOOR

FIGURE 29. FIRE EXTENTION TO THE 16TH FLOOR

burning occurs in a highly air rich situation. The production of carbon monoxide can be as much as thirty fold higher in fuel rich conditions than in the excess air state. This could have been the nature of burning if less windows had broken of the building had been designed with less windows.

SUMMARY.

Everyone involved in the investigation or analysis of this fire has recognized both the potential value of sprinkler protection and the vulnerability of continuous glass wall construction with out supplemental protection.

It is felt that additional important implications include:

1. The recognition that open arrangements in office settings can develop to flashover. There is a demonstratable fire potential associated with open office arrangements that contain concentrated grouping of combustible work areas. Where such concentrations occur in spaces involving large floor areas and relatively low ceilings, there is usually sufficient combustion air within the space to allow a developing fire to reach flashover conditions. This even if no additional air is introduced into the space. The traditional light hazard expectations often associated with offices do not apply in these cases.

2. High space utilization office landscape have the potential, even without the assistance of flashover, of spreading fire over large areas producing fires of major portions.

3. There is an important relationship between the release of fuel from a burning array as the result of the heat impinging on it and the availability of oxygen (air.) These relate to efficiency of combustion. Efficiency of combustion is in turn a major determinant of the ability to burn, room layer temperature, carbon monoxide production, oxygen content, fuel transport, and flame length.

4. Given enough time, it must be expected that fire products will be spread by natural forces to remote portions of a building. The degree of problem ensuing will be a function of the efficiency of combustion of the fire, the tightness of the shafts and other communicating passages, the presence or absence of smoke control systems, the height of the building, and the weather conditions at the time. Analysis of the potential involved is important if persons may have to take refuge in the building during the fire.

5. Floor to floor propagation is a potentially serious problem in window wall buildings. The knowledge of flame extension from windows, particularly where petroleum base polymers are involved is insufficient. A better understanding of the relationships between burning rates and flame lengths is needed.

6. In this fire the duration of burning on a floor and the rate of fire propagation from floor to floor were close to each other. A longer duration fire or a faster floor to floor spread could result in an unstoppable fire. Longer duration condition would be expected where a

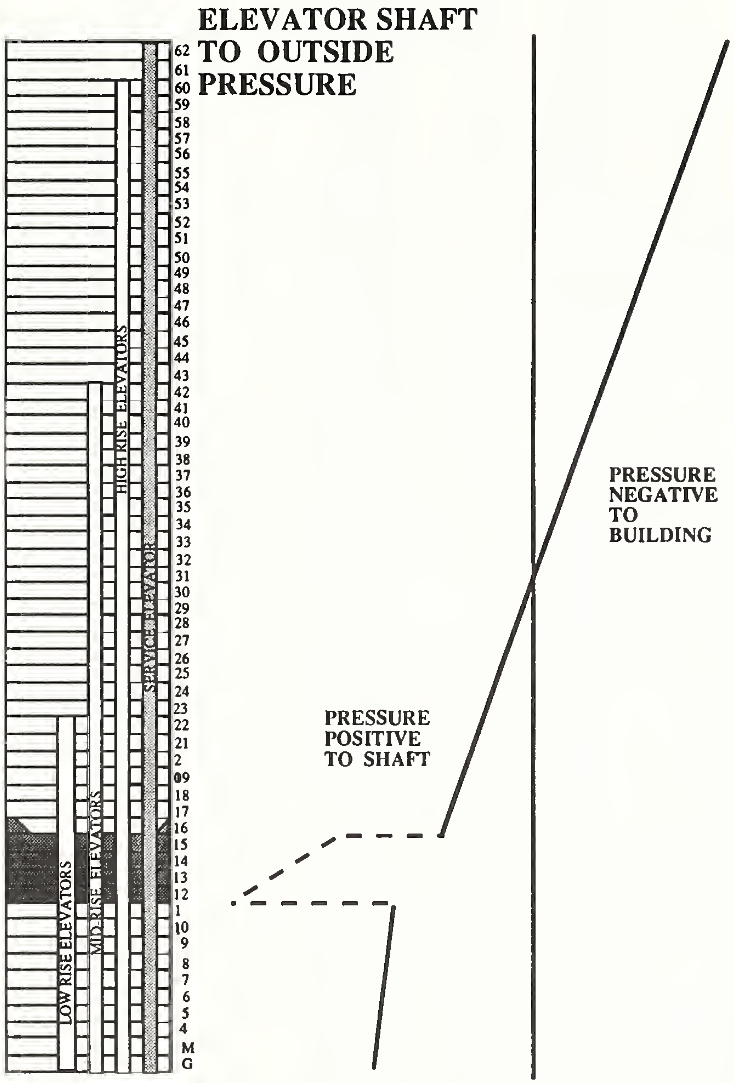


FIGURE 30. POSSIBLE PRESSURE PROFILE BETWEEN ELEVATOR SHAFT AND OUTSIDE

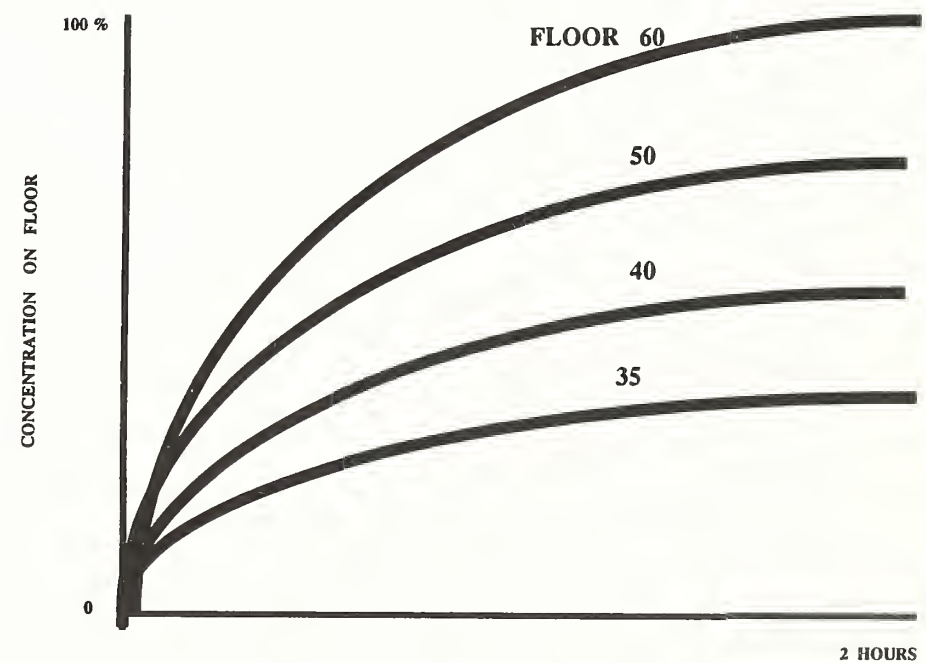


FIGURE 31. CONCENTRATION OF SMOKE ON FLOOR AS COMPARED TO SMOKE IN ELEVATOR SHAFT

higher total fuel load existed, such as commonly occur with merchandising displays or extensive use of combustible interior finishes.

7. This analysis demonstrates some of the values of analytical calculations in reconstructing the events involved in a fire. The use of these tools, particularly on scene, can be of great assistance to both fire investigation and guidance on prevention of reoccurrence of similar fire incidents.

Trans-Fire Triangle.

The analysis of this fire demonstrates important inter-dependent relationships between the mass burning (pyrolysis) rate, the rate of heat release, and the available air (oxygen) on the course of a fire. The following is an attempt to depict this important concept in the familiar fire triangle format.

The fire triangle has been in use for years to depict both the phenomena of ignition and the phenomena of extinguishment. Figure 32 is an expansion of that triangle that attempts to depict the inter-relationships of heat, oxygen, and fuel during the course of a fire. In this triangle depiction, the heat from the flame or other source causes the fuel to pyrolyize (give off combustible material.) The combustible pyrolysis products burn to the extent that oxygen is available. The amount of heat energy produced and the type of combustion products (particularly the production of CO and CO_2 as well as the consumption of oxygen) are governed by the oxygen available to those products. The amount of energy released is then a major determinant of the increase or decrease of the temperature of both the flame and the surrounding space. Understanding of these relationships can help in important fire safety, architectural, and building use decisions.

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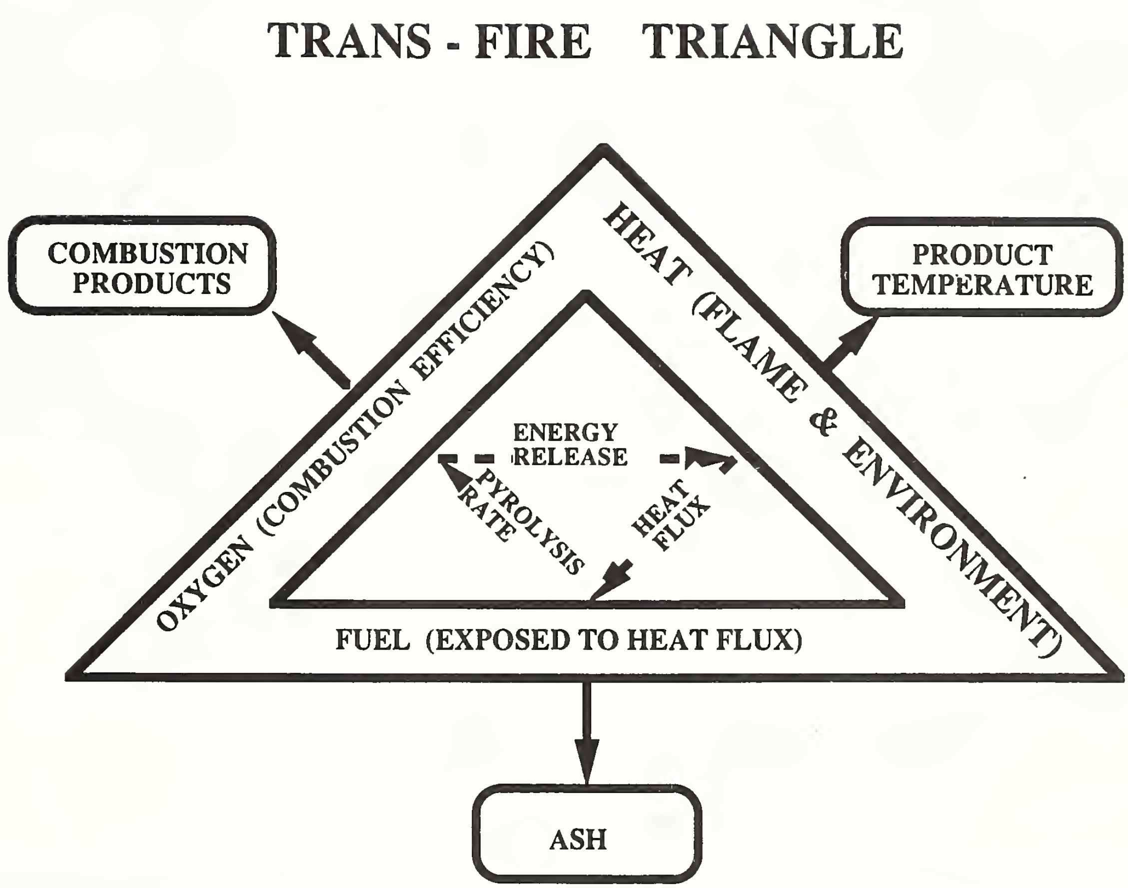

FIGURE 32. TRANS-FIRE TRIANGLE

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Harold E. Nelson

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

The course of the fire is traced in terms of developing fire phenomena. Special emphasis is given to burning rate of building furnishings, smoke layer temperature, layer level, oxygen consumption, combustion efficiency, flashover, exterior fire propagation, detector response, sprinkler operation, smoke movement and some contamination.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

Burning rate; detector response; fire incidence; fire investigations; fire models; flashover

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