An Engineering Analysis of Fire Development in the Hospice of Southern Michigan, December 15, 1985

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ABSTRACT

An analysis of the development of fire and flow of smoke in a multi-fatality fire is presented. The analysis methods used are the least sophisticated available consistent with reasonable accuracy. Fire growth, flashover, pre- and post-flashover spread of products, and impact on victims are addressed. Issues relative to post-flashover combustion chemistry and post-flashover corridor flow are raised.

SCOPE

This paper relates to the fire that occurred on December 15, 1985, in the west wing of the Hospice of Southeastern Michigan. Eight patients died in the fire. The flashed-over room of fire origin vented through a window to the exterior. Pyrolysis products that flowed through that window generated a flame on the building exterior. The door from the corridor to the fire room and those to some of the other occupied rooms were open at the time of the fire. It is believed that following flashover, the fire in the room of origin extracted oxygen from the corridor, resulting in incomplete combustion of those pyrolysis products flowing into the corridor. The gases flowing from the fire room were probably extremely high in carbon monoxide and possibly other products of incomplete combustion. The resulting environment was lethal to all but one of the occupants in rooms open to the corridor.

This analysis uses quantitative engineering tools to reconstruct the description of the conditions that occurred in the fire and to assess their usefulness in fire safety engineering efforts. An effort was made to use the least sophisticated approach that would give answers reasonably consistent with the evidence from the fire. In general, values used for both the thermophysical and combustion properties of materials are generic values or from tests of similar materials or items.

All pertinent data and information available were used in the analysis. Even so, significant assumptions were involved in the calculation. These are discussed in this paper or the referenced reports.

ANALYSIS

Brief overview. In December 1985, a fire that resulted in eight fatalities occurred in a patient room of this Hospice facility. The fire was investigated by local and state fire authorities and by the National Fire Protection Association (NFPA). Isner [1] has prepared a detailed investigation report. That report and private conversations with

Mr. Isner and several of the local investigators provided information for this study.

Briefly, the fire occurred in a bedroom wing of a Hospice. The fire initiated in a patient bedroom. It quickly developed to flashover at which time a window in that room failed. The door to the room of origin was left open. The doors to most of the other rooms were also at least partially open. Even though the total duration was brief, almost every patient in rooms with open doors in the wing died.

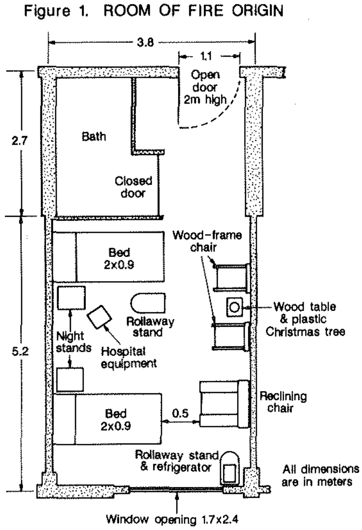
In June 1986, the author conducted a large-scale test with conditions similar to aspects of the Hospice arrangement. This test produced information on conditions developed in an unvented corridor and connecting rooms exposed to a flashed over space which is vented to the outside. It appears that this condition produces especially hazardous conditions on the unvented side.

Additional input from the study has been derived from a series of tests by Heskestad and Hill [2]. Data from these tests provide information about the probable manner in which post-flashover smoke flows from the room of origin into other spaces.

<u>Ignition cycle.</u> The fire started in room 207. A floor plan of room 207 is shown in Figure 1. While the exact time of ignition is not known, it has been established that various staff members had been in the immediate vicinity of the fire area within less than five minutes of its initial discovery without noting any abnormal conditions.

Figure 1 shows the approximate position of furnishings. This room opened onto the 2.8m by 18m corridor of the west wing of the Hospice. A total of seven such rooms were in the west wing. The fire was discovered spreading across a seat cushion and starting up the vertical surfaces of a reclining rocker chair. At this point, the staff member reported first signs of ignition of the socks on the feet of the patient in the nearest bed.

Figure 1. ROOM OF FIRE ORIGIN



Data source: National Fire Protection Association

First fuels. The data important in estimating fire growth in these items are:

A. Reclining chair. The reclining chair weighed approximately 33.6 kilograms. The chair was wood-frame, upholstered with foam polyurethane pads and covered with an olefin fabric. The chair stood 1.02 meters high. The projected floor area was approximately $0.75m^2$. The distance between the chair and the bed was estimated as between 0.3 and 0.5 meters.

B. The bed was a standard metal, hospital-type bed. The innerspring mattress had metal springs, cotton and sisal padding and vinyl hospital-type ticking. The mattress was covered with a urethane egg crate form of bed sore prevention pad. The pad was reported as being composed of ignition resisting urethane. Bed linens and covers were not fire retardant treated. The bed was occupied by a patient at the time of fire. The total area of the mattress was approximately $1.8m^2$.

C. Wood-framed chair. The wood-framed chair close to the recliner was believed to be made of similar materials to the upholstered chair but thinner and lighter construction with a total weight estimated at about 14 kilograms. The projected floor area is estimated at $0.5m^2$. The distance between this chair and the recliner is actually unknown but for the purposes of this analysis is estimated as 0.3 meters.

Estimating free burning rate. The individual burning rates of each of the three items listed above was based on the estimation table proposed by Nelson [3]. In accordance with that approach, the recliner is appraised as a moderate weight upholstered furniture item that produces a fast fire growth rate peaking at approximately 3000 kW. The wood-frame chair is appraised as light weight upholstered furniture developing a fast growth curve peaking at approximately 1250 kW. In view of the polyurethane pad, the estimate of burning rate on the bed is based on a fast developing fire until the total surface area of the bed is involved at which time the bed would continue to burn at approximately 500 kW/m^2 of floor area. For the purpose of this analysis, the bed is appraised as having a fast developing fire to a peak of 1000 kW at which time it is expected to have continued to burn at that rate.

Predicting the combined burning rate of the early ignited items. It is assumed that prior to flashover, the impact of one burning item on another sufficient to cause ignition does not significantly impact the burning rate of the ignited item. Each item ignited is considered to burn in the same manner as if it were the only item burning in a unconfined space. This assumption permitted the development of a single initial burning rate curve by estimating the time of ignition of each item and adding its individual burning rate to the fire, starting at that moment.

The method of estimating the moment of ignition of the second and third ignited item was the program for estimating radiant ignition of a near fuel in FIREFORM [4]. The technical basis is that developed by Babrauskas [5] and is limited to ignition of one furniture item from another near-by furniture item. This approximation, however, appears to fit the circumstances of the Hospice fire.

The ignition estimation procedure divides target fuels into the three classes of easily ignitable, within the normal range of ignitability, and hard (difficult) to ignite. Target items of these categories are assumed to ignite when the radiation on them reaches 10, 20, or 40 kW/m^2

respectively. For this analysis, the bed was considered as an easily ignited item based on the loose bed clothing. The wood framed chair was considered as an item within the normal range of ignitability.

If the bed was located 0.5 meters from the burning reclining chair, ignition should be expected when the level of energy is approximately 140 kW. This level of energy was attained by the burning chair approximately 50 seconds after the initiation of the expected fire curve. If conversely the separation from the chair were only 0.3 meters, the ignition level decreased to approximately 85 kW and the time of ignition would be approximately ten seconds sooner.

The wood frame chair is estimated to have joined the fire when the exposing fire reached approximately 600 kW.

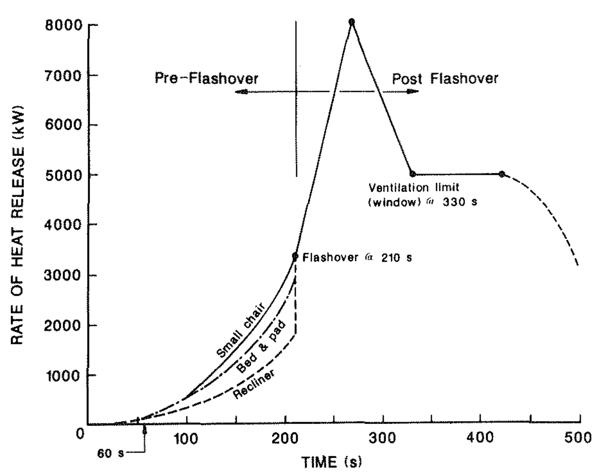
The summation of the individual burn rate curves into a single predicted fire curve is shown in the pre-flashover portion of Figure 2. This summation involves the inherent assumption that the burning rate of the ignited item is not significantly influenced by the initiating fire. This assumption is felt quite reasonable in the case of the ignition of the bed from the reclining chair. The ignition of the bedding occurred quickly without preheating of the principal fuel mass of the bed and spread away from the initiating fuel source. A similar but less positive analysis is appropriate for the burning of the chair. The free burning rate of that chair was however quite rapid and this analysis assumes no significant impact on the outcome from any under estimation of the actual burning rate in the incident.

<u>Pre-flashover fire development.</u> Two different procedures were used to estimate the development of ceiling temperatures and the descent of the smoke layer.

The Available Safe Egress Time (ASET) model [6], was used when the development could be modeled as a fire in an unvented space.

The estimation of temperature in the room of fire origin is based on the correlation of predicting temperature in a fire room [7].

Figure 2. IDEALIZED FIRE GROWTH
(Room of Fire Origin)



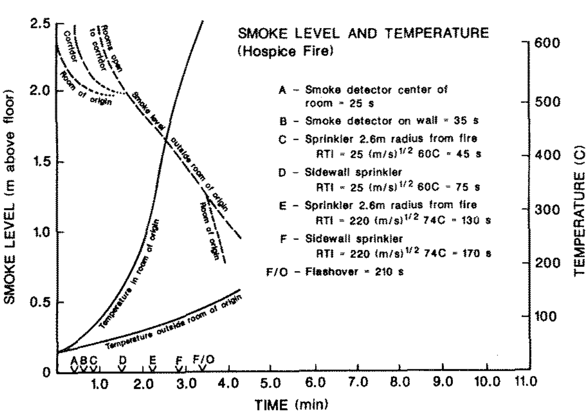
While no sprinklers were present, appraisals were made to determine the probable time of operation of both fast response and standard sprinkler heads. Simulated pendent sprinkler heads were located at the ceiling approximately 2.6 meters radially from the axis of the fire. Simulated sidewall sprinkler heads were located near the corridor end of the room 5.2m from the axis of the fire. The method used was based on the ceiling temperature and heat actuated device response correlations developed by Alpert [8] as assembled in the quasi-steady state computer program DETACT-QS [9]. The adjustments for including the impact of the hot gas layer on response [10] were included in the computational procedure used. ASET was used to input the smoke temperatures required by the Evans approach. The results indicated sprinkler response times from 90 seconds to 170 seconds depending on location, temperature rating, and thermal response of the sprinkler heads simulated. The specific results are listed in Figure 3.

Also, to facilitate this calculation, an adaptation of ASET was made to imitate venting of hot gases after the smoke layer in the room of origin descended below the soffit level. The approach used estimated the flow of gas through the doorway as a fluid passing through a weir and at each time increment, deduct from the accumulated gas in the room, the gas discharged. This approach is felt to be reasonable in the early stages of fire development but starts to break down when the fire draws air from the corridor. Since the item of interest is the time for early stage response devices to react, this approach is felt reasonable in this case.

There were no smoke detectors in the area, however, an analysis similar to that for sprinklers was made to determine the likelihood of the response of a smoke detector located in the same positions previously evaluated for sprinklers. DETACT-QS was used as though the ceiling were unconfined. This because smoke detectors respond to the products of particulate matter and not to the temperature of the hot gas layer. The results indicated that a smoke detector located in the center of the room would have responded in about 25 seconds while one located on the wall near the room entrance would have responded about 10 seconds later. See Figure 3.

Figure 3 shows the results of these calculations. Quintiere's correlation estimates the rise in temperature of the upper level gas in the room of origin and is used to predict the time of flashover. This program predicted an upper level temperature increase of about 550 K above ambient in 210 seconds. This was used as the criteria for flashover.

Figure 3. COMPUTED PRE-FLASHOVER CONDITIONS



ASET was then used to estimate the descent of the smoke layer in the various spaces in the West Wing up to the time of flashover. First ASET was run using a room area of $26m^2$. This simulation was stopped when the computations indicated that the smoke level had descended to the level of the soffit in that room (i.e., 2 meters above floor level). ASET was then restarted tracking the same fire but increasing the indicated floor area to a value equal to the floor area of the room of origin and the adjacent corridor ($72m^2$.)

To operate ASET, it is necessary to specify a heat loss factor. The value of this factor was estimated by operating the version of ASET that includes an open door at varying heat transfer coefficients. It was found that an effective heat factor of 0.9 produced temperature results almost identical to those produced by Quintiere's correlation.

When the computations indicated that the smoke level had again descended to 2 meters above the floor height, it was assumed that the smoke spilled under the soffits of the door entries to other patient rooms. ASET was then restarted in a final run with a total floor area of the fire room, the corridor, and all other rooms in the west wing open to the corridor. This run of the model was continued for 210 seconds of model simulation, the previously estimated time of flashover.

<u>Post-flashover--fire development.</u> Once flashover occurred, it is assumed that all the top surfaces of the room furnishings and at least one side of the backs of the chairs were subject to an energy flux estimated at approximately $80kW/m^2$. The total surface area exposed is estimated at approximately $7m^2$. The rate of pyrolysis of the furnishings was then estimated using the method adapted from Chapter 5 of Drysdale [11]. The basic equation is:

$$m'' = q''/L_v \quad (1)$$

Where: m'' = Mass Pyrolysis rate per unit area; q'' = Total Heat Flux on Material per unit area; and L_v = Heat of Gasification.

Since the prime interest is in the first minutes after flashover, the effect of charring on pyrolysis rate was not considered in applying this equation. If charring had been considered, it is likely that a reduction in the rate of burning would occur with time. This analysis assumed a heat of gasification of 2kJ/g. This is a typical value, representative of the values given for materials similar to those in the bedroom in Table 5.6 of Drysdale. The pyrolysis rate immediately after flashover was approximately 280g/s, decreasing as each item burned out.

Because the majority of the surface areas involved are composed of synthetic materials mixed with a lesser portion of cellulosic materials an estimated average heat of combustion of 30,000kJ/kg was used. Multiplying the heat of combustion times the mass rate gives the potential rate of heat release of approximately 8.4MW. This rate of heat release can only occur if sufficient air is present to complete the combustion.

With flashover, a section of the bedroom window approximately 1.2m wide by 2.4m high failed, opening a vent of that size to the outside.

Since the rate of burning in the room depends on the rate at which air can be drawn into the room, the ventilation factors for both the room door and the broken out window were calculated. Ventilation factor is defined as the area of the opening times the square root of the opening height.

The ventilation factor used for the room door was $3.1m^{5/2}$, while that for the open window was $4.5m^{5/2}$.

The rate of mass flow that can be drawn in by a flashed-over fire is a function of the ventilation factor of the opening to that space. Where more than one opening is involved, the usual procedure is to calculate each opening independently and add the results. An approximate relationship has been proposed by Thomas [12]. That relationship can be expressed as:

$$m_i \approx 0.5Ah^{1/2} \quad (2)$$

Where: m_i = rate of mass drawn into the space by the fire (normally considered to be air containing a mass oxygen fraction of 0.23); A = area of the opening (m^2); and h = height of opening (m).

Using the oxygen consumption concepts described by Huggett [13] it can be assumed the maximum amount of burning that can take place will be not more than 13.1 kJ/g of oxygen in the air drawn into the fire. For these calculations, an efficiency factor of approximately 0.75 was used. This is to account for both that portion of the oxygen in the entrained air that does not react in the fire room and that portion of the combustion that is incomplete. Incomplete combustion tends toward increased production of carbon monoxide (CO). The production of CO is a less efficient user of oxygen in terms of energy released than the total combustion process. The maximum rate of heat release in the space in a ventilation limited (post-flashover fire) is termed ventilation limit. Considering the efficiency factor 0.75 the working equation used was:

$$V_L = 1.1Ah^{1/2} \quad (3)$$

Where: V_L = ventilation limit (MW).

At flashover when there was still sufficient oxygen in the corridor, the mass flow through that opening contained close to the normal portion of oxygen and air. The maximum burning rate in the room is estimated to be approximately 8.3MW or almost exactly equal to the estimated rate of pyrolysis. The ventilation factor for the door was $3.1m^{5/2}$. By equation (3) the portion of the maximum burning rate obtained by flow through this door was 1.1 x 3.1 = 3.4 MW. The volume of oxygen from the corridor could sustain this combustion for only approximately 60 seconds before oxygen was depleted to a mass fraction of about 0.1. Additional oxygen from the rooms adjacent to the corridor extended this time. The exact amount could not be estimated. For purposes of this analysis, it is assumed that 60 seconds after flashover, the rate of heat release reached its maximum.

On the same basis, within another 60 seconds, the fire was unable to draw oxygen from the corridor and burning was sustained entirely from the oxygen drawn through the broken window. The result is a rate of heat release curve for the room of fire that follows the plot shown in Figure 2.

After about 330 seconds, it is felt that the combustion process in the fire room was sustained in the flashed-over regime by oxygen obtained from the window. At the same time, the fire continued to deplete any oxygen remaining in the products drawn from the corridor. The products discharged back into the corridor replacing the oxygen with CO and other products of incomplete combustion.

It is believed that the fire continued this way until enough of the fuel was consumed so that the potential rate of heat release from the pyrolyzed material dropped below the approximate 5MW. At that time, flame retreated into the room. Shortly thereafter, the fire dropped out of ventilation controlled burning and the final phase of the fire consisted of individual items burning. This is considered to be the termination of flashed-over conditions in the room. On this basis, approximately 40% of the surface area would have been consumed to the point of burnout before the room dropped out of flashover. While an exact measurement was not made of the remaining fuel, photographs indicate that this estimate is in the right order of magnitude.

It is also assumed that the items closest to the open window (the prime source of post-flashover oxygen) consumed most of the oxygen from the inflowing air as long as they continued to release large quantities of fuel. It is expected that their rates of combustion were more efficient than the other furniture in the room and they burned out first. The damage in the room tends to reinforce this.

The exposed surface area of the bed nearest the window, the recliner, and the chair is approximately 3.7m^2. When these three items completed burning, the exposed combustible surface area in the fire room was reduced below that necessary to sustain ventilation controlled burning.

Assuming that these three items burned at approximately 40$g/s/m^2$ and that these materials had a total weight of about 60,000g, the burnout time of these items was about seven minutes after flashover. This reasonably conforms with the description of the fire from witness accounts.

Impact of post-flashover environment on patients. Early in the fire event, the nursing staff was able to rescue the patient closest to the fire. He was not a fire victim. The staff, however, was not able to rescue the second patient in that room. That individual was subjected to lethal conditions at the time of flashover.

The major concern, however, is the conditions that prove to be lethal to persons in rooms with fully or partially open doors. It is understood that post-mortem examinations of the majority of the victims showed carboxyhemoglobin concentrations expected to be lethal to healthy persons.

In order to examine these conditions more closely, the previously mentioned experiments conducted at the National Bureau of Standards and at Factory Mutual Research Corporation, applicable to this incident, were examined.

The experiment at NBS was conducted as a direct result of this fire to better understand the actual post-flashover conditions. The experiment was conducted in a corridor arrangement shown in Figure 4. The fire was a gas burner in the room adjacent to the hood. This simulates a fire next to an opening to the exterior as occurred once the window broke in the Hospice. The rest of the test arrangement simulates internal, unvented spaces.

The fire was of sufficient size to sustain flashover in the room of fire origin, in this case approximately 5MW. Readings were taken in each of the rooms and in the vent stack. Figure 5 plots the development of the fire in the room next to the vent and conditions involved in the most remote room off the far end of the corridor. The data for the plots of

Figure 4. TEST LAYOUT

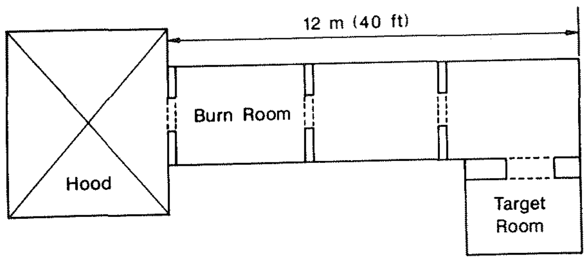
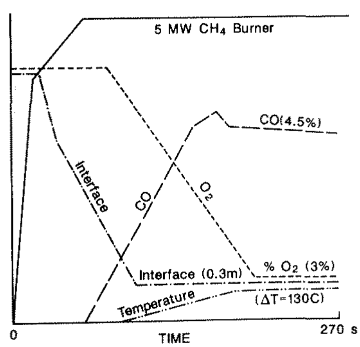


Figure 5. TEST DATA



the interface level and the temperature were derived from readings made by vertical stacks of smoke meters and thermocouples respectively. The CO and O_2 values were from probes located about 0.5m above the floor.

Conditions in the remote room depreciated rapidly in terms of increased carbon monoxide and descent of the smoke interface. This was followed closely by the reduction in oxygen. Despite the 5MW exposure, air temperatures in the remote room rose only slightly.

While one test is not sufficient to draw firm conclusions and further research in this area is needed, a preliminary inference to help explain the occurrence in the Hospice fire can be drawn.

This inference applies to conditions of internal venting from a fully involved fire where the rate of burning is sustained in a post-flashover level by a vent to the exterior. It is inferred that the conditions occurring on the interior are a function of the oxygen available from the building interior. To the degree that this inference is true, it applies during those periods of full involvement where the room of fire origin is sufficiently involved to establish a flow pattern and pressure that obstructs the passage of air from one side of the burning room to the other. Under these conditions, the gases discharged from the burning room to the building can be of a chemical composition closer to that inside the flame than those normally related to free burning combustion.

It also appears from these experiments that the extent of flame into the interior can be throttled by the lack of oxygen and that conditions in the exposed internal space quickly cool to a temperature below that necessary to complete the combustion process.

It would then be expected that under situations typified by the Hospice fire, the gases discharged from the burning room into the building interior can have a carbon monoxide concentration thirty to fifty times the magnitude of that being produced in the externally vented flame from the same fire.

In addition to the concentration of gases, Heskestad and Hill point out another phenomena increasing the post-flashover danger in a corridor. Heskestad and Hill conducted their experiments in a corridor. The experiments of interest are those where the room of fire origin was vented to both the exterior and to a unvented interior corridor, producing similar effects to those observed at NBS. In their experiments, however, the duration of the experiments were not sufficient to reach steady-state species production. Heskestad and Hill were more interested in the fluid dynamics involved. Their experiments produced a post-flashover wave front in a 2.44m wide by 18m long corridor somewhat in excess of 1m in depth. This front traversed the corridor striking the far end and returning as a layer of equal thickness under the initial layer to the point of origin. Propagation speeds of this smoke front up to about 1 m per second were observed. In their experiments, four tests involving fires of 522 kW produced flow rates ranging from 1.2 to 1.6 m/sec.

From the above, it is believed that the corridor in the Hospice remained tolerable up to the point of flashover but after flashover quickly (in less than 60 sec.) filled to a level close to the floor with a toxic gas containing high concentrations of carbon monoxide. Exact concentrations are impossible to predict without large scale experiments that would faithfully reconstruct all of the conditions in the hospice fire. For purposes of analysis, it is assumed that CO concentrations similar to those detected in the NBS experiments, in excess of 3%, possibly as high as 5%, were reached in the corridor soon after flashover in the fire room.

<u>Estimating post flashover smoke flow into remote patient rooms.</u> While some initial flow of smoke must have previously entered rooms open to the corridor, it is assumed that the principal flow occurred after a wave front of the type observed by Heskestad and Hill filled the corridor. An analytical estimate of the temperatures in the smoke was not made. However, the damage in the corridor demonstrated that the smoke cooled rapidly as distance increased from the fire source.

A principal interest was the flow of the post-flashover toxic gases into individual rooms and the subsequent filling of those rooms with toxic gases. The critical level was set at 0.6m (i.e. bed height, where the victims were found).

The estimate of smoke flow was made by treating the individual rooms as closed rooms with a fire having a virtual source located near the floor. The fire was assumed to have a rate of energy release equivalent to the enthalpy of the gases flowing into the room from the corridor. Since the smoke in the corridors had to be at a higher temperature than the atmosphere in the exposed rooms, smoke flow was from the corridor to the rooms. The flow of energy contained in the smoke flowing into a room was treated as a fire in that room. This allowed the closed room approximation (with some vent near the floor) required by the ASET model.

The enthalpy was derived using the formula:

$$Q = mc_p\Delta t \qquad (4)$$

Where: Q = enthalpy or rate of energy flow; m = mass flow of hot gases; c_p = specific heat (of air); and Δt = temperature of hot gases above ambient.

The value for m was derived by using the equations for smoke flow programmed in FIREFORM. By combination, the following working equation for initial energy flow from the corridor into a room is derived.

$$Q = 14.5WD^{3/2}\ (1/T_0\ -\ 1/T_f)^{1/2}\ (T_0/T_f)^{1/2}\ (T_f - T_0) \qquad (5)$$

Where: T_f = the average temperature of the hot gas layer (K); T_0 = temperature in the downstream of the opening (K); W = the width of the opening (m); and D = the depth of the smoke in the opening (m)

The rate of energy flow is a function of both opening size and fire temperature. Both the exact temperatures (T_f) and the width of the opening (W) are not fully known. To obtain a range, the initial flow was calculated at a condition where the door was wide open and the corridor smoke temperature 500C. The size of the opening was set at 1.1m wide by 2.0m high. At the other extreme, flow was calculated for a smoke temperature of 100C and width of the opening of 0.2m. In the former case, the initial energy flow is estimated at 1700kW; in the latter case 50kW. In each instance, the flow decreases as the exposed room fills with hot gases. In sample calculations, considering no decrease in energy flow, the temperature rise within the room prior to filling the room to the 0.6m level was modest. Other calculations showed that reductions in energy flow up to 50% made little difference in the estimated time to fill the rooms to 0.6m above the floor.

Several test runs of ASET were made to determine the heat loss fraction that would produce the assumed exposure temperature in the corridor. A heat loss fraction of 0.95 appeared to be reasonable. On this basis, the filling of a patient room to the point where the smoke layer was approximately 0.6m above the floor would occur in about 40 seconds for a room exposed to 500C smoke through a wide open door. The same conditions would occur in about 160 seconds in the case of the room exposed to 100C smoke through a door open 20%. The assumptions in this analysis are broad and these figures should be taken as general indicators. They do demonstrate, however, that the flow of gases from the corridor into the individual rooms occurred in a short time in the most distant rooms as well as in those proximate to the fire and that a relatively small opening was sufficient for this to take place.

Summary: The estimates developed by the preceding procedures appear to track closely the reported conditions and produce a feasible explanation of the development of the fire and the resulting toxic conditions. The methodologies used are felt to be sufficiently developed and credible to be used in fire incident reconstruction and fire safety design decisions.

Issues of post flashover combustion chemistry and flow in corridors are raised. More research and the development of engineering analysis capabilities are critically needed in these areas.

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