CHARACTERISTICS OF TRANSPORT AIRCRAFT FIRES MEASURED BY FULL-SCALE TESTS

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SUMMARY

This paper discusses full-scale transport aircraft cabin fire tests conducted in the United States under postcrash fire conditions. The logic behind the development of fire test scenarios is described, including a comparison of fire involvement by external fuel fire penetration through an opening or by fuselage burnthrough. Early full-scale tests in the 1960's and 1970's that furnished data on the characteristics of cabin fires are briefly described. Past test activities addressing facets of the fuselage burnthrough problem are also discussed. The impact of environmental factors (such as wind, door opening configuration, and fuselage orientation) on fire penetration through openings and the resulting cabin hazards is discussed on the basis of past test activities. The majority of the data presented in the paper are from a recent full-scale test to determine fire/hazard progression in a postcrash cabin fire environment with emphasis on post-flashover conditions, to examine factors affecting occupant survivability, and to evaluate the performance of a protective breathing equipment filter. The paper often discusses and cites past studies addressing important cabin fire characteristics and concepts, such as flashover, stratification, and survivability.

INTRODUCTION

Full-scale fire tests are required in any credible activity to improve fire safety in a man-made enclosure, whether that enclosure be a transportation vehicle, building or house. A full-scale fire test may be defined as a realistic experiment, conducted at a 1:1 scale ratio between enclosure and test article, to simulate a fire scenario that has occurred in the past or is likely to occur. The essential elements of a full-scale fire test are a test article, an ignition source, instrumentation, and a means of simulating and/or controlling ambient conditions or adjacent structures affecting the test results (e.g., ventilation, wind, etc.). Although the test article, ignition source, and ambient controls vary considerably depending on the specific type of enclosure being tested, the instrumentation employed is fairly common for all applications. The purpose of the bulk of the instrumentation is to record the life-threatening conditions created by the fire inside the enclosure as a function of time in order to describe and understand the results of the experiment and allow for the development of meaningful conclusions and recommendations. The environmental conditions often monitored include temperature, heat flux, smoke density, and various gas concentrations, including asphyxiants, irritants, carbon dioxide, and oxygen.

Why are full-scale fire tests important? Basically because full-scale fire tests furnish extensive data that usually cannot be obtained in a reduced scale setting or by theoretical calculations with the same degree of confidence with respect to the validity of the results. The objective of a full-scale fire test is usually for one or more of the following reasons:

1. To characterize the fire environment in order to better define or understand the problem;
2. To evaluate or demonstrate the performance of a fire safety improvement (also may require a baseline test to determine the degree of improvement or benefit);
3. To furnish data in support of studies to derive fire safety design requirements or to determine the degree of correlation with small-scale test results or physical/theoretical modeling predictions.

Perhaps the most difficult and expensive type of full-scale fire testing of a man-made enclosure is the aircraft passenger cabin subjected to a postcrash fuel fire. Briefly consider the size of an aircraft cabin, the cost of interior furnishing materials, and the problems associated with employing a large fuel fire as an ignition source. To properly simulate the geometry of a wide-body cabin for fire testing, as representative of the larger commercial transports, requires a test article of 15-20 feet in diameter and a minimal length of approximately 100 feet. The cost of furnishing a representative cabin section is enormous due to the quality and complexity of aircraft interior materials; e.g., the cost of a "typical" sidewall composite panel is on the order of several thousand dollars. Employing a fuel fire as an ignition source creates problems associated with flame control if conducted outdoors and safety and pollution if done inside a building. Until the establishment of a dedicated full-scale fire test facility at the Federal Aviation Administration (FAA) Technical Center in 1980, the number of full-scale aircraft fire tests and the application of the results as a basis for design improvements was rather limited.

AIRCRAFT FIRE SCENARIOS

Fire fatalities in transport aircraft accidents occur either as the result of fire developing in-flight or as a consequence of crash fire. Until recent years, the FAA research, engineering and development (R, E & D) program to improve cabin fire safety has mainly focused on the postcrash fire problem, simply because all fire fatalities involving United States carriers over the past 15 years have resulted from postcrash fire. This paper will concentrate on full-scale fire tests under postcrash fire conditions.

Fatal in-flight fires occur far less frequently than postcrash fires. However, a number of catastrophic in-flight fires have occurred in United States built aircraft operated by foreign carriers; e.g., Varig (1973), Saudia (1980), and Air Canada (1983). A common characteristic of these accidents and fatal in-flight fires, in general, is that the origin of the fire was in a hidden or inaccessible area. In recent years, FAA has placed greater stress on in-flight fire safety as evidenced by current R, E & D activities dealing with hidden fire protection, enhanced emergency smoke venting, a computerized fire detection/advisory system, and electrical wiring arc tracking characteristics (1).

Postcrash fires are usually initiated by the ignition of jet fuel released by parts of the fuel system damaged by the crash. One may expect that the intensity of the fuel fire and potential fuel fire hazards to aircraft occupants will increase as the severity of the crash increases. In this regard, Horeff has ranked six classes of postcrash fire for hazard severity, based on assessment of the likelihood of impact survivability (ability to survive crash trauma) and the number of occurrences in actual aircraft accident experience (2). For example, the most severe case was major fuel spill fires due to wing/partial wing separation and the least severe case was non-fuel spill fires due to ignition by friction. Because of the potential severe fuel fire hazards in accidents with major fuel spillage, FAA has supported R, E & D programs for anti-misting kerosene and fuel system crashworthiness that aim at minimizing or eliminating the fuel fire hazard. However, irrespective of the likelihood of success of these inherently complex concepts, other factors in the postcrash fire scenario may be of greater importance than the intensity of the fuel fire is to occupant survival. One such important factor is the integrity of the fuselage in that area which is adjacent to the fuel fire. Two conditions are possible: (1) a crash rupture or emergency exit opening, or (2) an intact fuselage. Based on a consideration of past accidents, experimental studies, and fuselage design, it is apparent that a fuselage rupture or opening represents the worst case condition and provides the most significant opportunity for fire to enter the cabin. By contrast, ignition and significant involvement of the cabin interior materials by the burnthrough mode is expected much later in time than when direct fire penetration through an opening occurs.

Because fatal aircraft accidents involving fire are fairly infrequent and dissimilar to one another, it becomes difficult to describe a "typical" accident. However, one can hypothesize a realistic accident scenario where burning interior materials control the probability of escape. In order to be representative of past accidents, the fire originates as a pool of burning fuel, adjacent and external to the fuselage. The fuel fire must be relatively large, perhaps on the order of 50-100 square feet, in order to be realistic. If the primary concern is with the dangers of burning interior materials, the fuel fire by itself must not preclude escape. Therefore, the fuselage must be relatively intact along the length adjacent to the fuel fire to prevent direct exposure of escaping occupants. An opening in the fuselage the size of an emergency exit door allows for the ignition of cabin interior materials by the adjacent fuel fire. In order to evaluate the role and performance of interior materials, ambient conditions surrounding the fuselage are selected to prevent or minimize combustion products generated by the fuel fire from entering the cabin. The fire scenario described above was developed by FAA for utilization with a C-133 wide-body test article to evaluate cabin interior materials (3). Full-scale fire test series were conducted to evaluate the effectiveness of seat cushion fire blocking layers (4) and fireworthy interior composite panels (5), and to develop low heat release test requirements for interior panels (6). The test results were invaluable in the development of improved laboratory fire test standards issued in recent years by FAA for seat cushions (7) and interior panels (8,9).

As briefly discussed earlier, ignition of interior materials by an external fuel fire by the mode of fuselage burnthrough is expected to occur much later in time than when fuel fire penetration occurs directly through a fuselage opening. This clearly appears to be the case for wide-body transports; e.g., B-747, DC-10, and L-1011. The fuselage walls of these aircraft (comprised of aluminum skin and heavy structural elements, a thick blanket of thermal-acoustical insulation, and a honeycomb composite interior panel) are an effective fire barrier and will resist burnthrough for several minutes. The burnthrough resistance of a wide-body fuselage was evidenced during the Continental DC-10 accident at Los Angeles in 1978 (10). In this accident a large fuel fire burned for 2 to 3 minutes before extinguishment by the crash fire rescue service. Over this interval the cabin furnishings were spared of fire although windows showed evidence of melting and interior panel seams were slightly heat/flame damaged. It is likely that had the fire burned longer the initial sustained flame penetration would have been through the windows. For standard body aircraft (e.g., B-727, B-737, DC-9, etc.) it is expected that fuselage burnthrough may occur earlier because of the presence of aluminum sidewall panels in many of these airplanes. Aluminum sheet is far less burnthrough resistant than honeycomb composite panels. However, reported accident findings do not present a consistent behavior. In the B-737 accident at Calgary in 1984, fire erupted due to failure of the left engine and ignition of fuel released from the damaged nearby fuel tank (10). Fire was observed immediately when the engine failed and intensified as the airplane was gradually brought to a halt almost 2 minutes later. Yet, the 119 passengers and crewmembers were able to evacuate in an estimated 2-3 minutes, although portions of the cabin filled quickly with smoke when exits were opened and windows melted through somewhat shortly after evacuation commenced. Fire penetration, initially through melted windows and later through the separated aft section, the latter which reportedly occurred after completion of evacuation caused the interior to be eventually gutted. By contrast, in the B-737 accident at Manchester in 1985, which had a similar fire scenario as the Calgary accident, 55 occupants perished primarily from inhalation of toxic gases from the cabin fire. At Manchester it is believed that fire penetrated into the cabin very quickly by melting through the lower fuselage skin and entering by way of the baseboard air return grills. Wind conditions reportedly caused the flames to be drawn into the cabin. Also of relevance to fuselage burnthrough resistance is a 727 ramp fire at Anchorage in 1987. A large fuel fire erupted on the ground adjacent to this airplane when it was inadvertently towed into a loading walkway, causing a fuel tank to be punctured and fuel spillage. Although a large portion of the fuselage skin was melted away, fire did not spread into the cabin. In this incident, the 727 fuselage acted as an effective fire barrier and prevented fire penetration into the cabin.

EARLY FULL-SCALE FIRE TESTS

The earliest full-scale aircraft fire tests provided a foundation for the development of a permanent full-scale test capability at the FAA Technical Center. The following is a brief description of these early tests and some significant results.

The first FAA aircraft fire tests were performed in the early 1960's in five C-97 aircraft under similar postcrash fire conditions (11). The tests were unique to this day in that jet fuel was continuously poured fore and aft of the wing on each side of the C-97, resulting in a fire which grew in size. Since the main objectives were to examine the capabilities of helicopter downwash and ground fire-fighting equipment in postcrash fire rescue operations, the aircraft was void of interior materials. A major conclusion of relevance to this paper was that "the fuselage broken open from impact or with openings next to fire areas offers a much more hazardous condition than the relatively closed fuselage."

FAA's first airplane fire tests to examine the combustion characteristics of cabin materials were conducted in the mid-1960's in a DC-7 fuselage (12). In situ fire tests at different cabin locations determined the relative ease with which the various materials would ignite and burn. In the last two tests the fire was allowed to burn out of control. Both tests culminated in a flash fire which grew from a relatively small fire that appeared harmless. The flash fire propagated at a calculated rate of 68 feet per minute. Up to the time of the sudden occurrence of the flash fire, ambient temperature and carbon monoxide concentration inside the cabin continued to remain low compared to human survival limits.

The Air Line Pilots Association (ALPA) conducted two tests in 1966 to determine if survival time could be extended during a cabin fire by using high expansion foam to completely fill the occupied portions of the cabin interior (13). The test articles were AJ-2P patrol bombers, fitted with a cabin mockup section almost 15 feet long. The fire source was 20 gallons of jet fuel placed in a 3-foot by 5-foot pan adjacent to the fuselage on the upwind side. Although the second test revealed serious drawbacks with the high expansion foam system, the first test provided useful baseline data. It was determined that the initial burnthrough of the 0.035-inch skin occurred at 1:03, which is somewhat longer but consistent with aluminum skin melting times measured in full-scale tests by Geyer using much larger fuel fires (14). Cabin light transmission measurements indicated "extreme stratification of smoke density" throughout the test and sudden cabin flashover at 7:40; both phenomena have been consistently observed in FAA full-scale fire tests in the C-133 wide-body test article.

In 1967-68, the Aerospace Industries Association (AIA) conducted an extensive Crashworthiness Development Program to find ways to increase passenger survivability following an aircraft accident (15). One aspect of the program was to examine the increase in postcrash fire survivability provided by improved cabin materials. The aft 24 feet of a 727 fuselage was subjected to a 30- by 30-inch fuel fire inserted halfway into a 3-square-foot opening in the fuselage, simulating a crash rupture. The AIA tests were conducted outdoors, as were the earlier full-scale tests described previously, which caused changes in the fuel fire behavior between tests due to differences in ambient wind conditions. A wind barrier surrounding the fuel pan was ineffective in providing a repeatable fire condition. The main concern was whether the ambient winds would force fuel flames to penetrate into the fuselage opening, and whether the degree of flame penetration would be reasonably invariant over the test duration and consistent between tests. The degree of flame penetration into the cabin and the resulting level of heat/flame exposure of interior materials has a significant effect on the rate of fire spread in the cabin. Isolation from fluctuating ambient wind conditions was a prime consideration in the decision by FAA to establish a permanent full-scale fire test facility.

Notwithstanding the problems associated with fluctuating winds, the AIA tests produced a number of important findings. Again, as observed in tests by other organizations, flashover and stratification were dominant characteristics. Also, when the fuselage was furnished with present in-service materials, flashover occurred earlier and when ceiling temperatures were lower as compared to the tests with improved materials.

In the early 1970's the National Aeronautics and Space Administration (NASA) ran tests in a 15-foot 737 fuselage section to examine the benefits of advanced fire resistant materials developed by the space program (16,17). To circumvent the outdoor problems associated with variable winds, the 737 test article was closed and a fan was employed to provide a longitudinal air flow. The ignition source was a 1- by 1-foot pan containing one quart of jet fuel placed beneath an outboard seat. The reduction in cabin visibility caused by the smoke produced by the burning fuel was significant and surprising, considering the relatively small quantity used. The results indicated that the advanced materials decomposed rather than ignited when subjected to the small ignition source, they did not support fire propagation, and they did not produce a flash fire (17).

FUSELAGE BURNTHROUGH TESTS

Over the past 20 years, a number of test activities have addressed facets of the fuselage burnthrough problem. However, because none of these activities dealt with the problem in a comprehensive manner, the FAA recently initiated a test program, as outlined later, to attempt to determine the mechanism and time framework for fire penetration into a cabin and ignition of interior materials. The following is a brief description of past studies related to fuselage burnthrough.

Geyer subjected aluminum sheets, mounted to a stainless-steel-covered 707 fuselage, to an adjacent 2500-square-foot fuel fire and recorded the increase in skin temperature as a function of time (14). Two types of alloys and four skin thicknesses (0.016, 0.020, 0.040, and 0.090 inch) were tested. The large fire pit provided relatively complete fire envelopment of the fuselage and maximum fire exposure. In conjunction with the experimental effort, a mathematical model was formulated which permits calculation of the temperature increase with time of the aluminum skin of an aircraft fuselage when exposed to fire (18). The model considers the aircraft skin backed by a layer of thermal-acoustical insulation and takes into account heat gain by radiation and convection and heat loss by radiation and conduction. Reasonably good agreement was obtained between the experimental and theoretical temperature-time profiles (14), illustrating that the mathematical model may be used as a predictive tool. As an example, the model predicted that a 0.040-inch aluminum alloy sheet under maximum fuel fire exposure would melt in 30 seconds, assuming the melting temperature of aluminum alloy at 1200 °F. Another test series employing 300-square-foot fire pits at three different distances from the test article exhibited slower temperature rises of the aircraft skin, which resulted from the different fire pit locations and the poor fire coverage caused by variable wind conditions on the relatively narrow fires (30 feet long by 10 feet deep). Thus, careful consideration must be given to fuel fire size, distance of fuel fire from fuselage, ambient wind conditions, and possibly other factors when attempting to apply the mathematical model to analyze the outcome of an actual aircraft accident.

Sarkos exposed a 28-foot titanium fuselage to a 400-square-foot fuel fire to determine the improvement in cabin conditions resulting from a burnthrough-proof fuselage (19). Not surprisingly, a flash fire occurred at 1:55, attributed to the ignition of combustible pyrolysis gases from room temperature vulcanizing (RTV) silicone pressure sealant, used extensively on the titanium skin, and from the silicone binder employed in the thermal-acoustical insulation. Small-scale fire tests with 2-foot-square panels, matching the cross-section of the titanium fuselage, corroborated the role of the silicone sealant and binder in creating a flaming ignition source and combustible gases that could yield a flash fire (20). The titanium fuselage test results illustrated the potential pyrolysis and ignition of materials adjacent to fire barriers at elevated temperature.

NASA demonstrated the ability of a passenger cabin surrounded by a burnthrough-resistant shell to protect passengers over a prolonged period from a severe external fuel fire (21). Basically, the protective shell consisted of a 2 1/2-inch layer of isocyanurate foam, an ablative foam that converts to a stable char when subjected to heat. To prove the concept, a C-47 fuselage section was divided into two compartments, with one compartment essentially protected with the isocyanurate foam attached to the inner fuselage skin and the other compartment fitted with typical aircraft insulation, and surrounded by a massive fuel fire (5000 gallons). The results indicated that the unprotected compartment was destroyed in about 2 minutes, while the protected section remained largely intact and provided a survivable environment for about 12 minutes. The test was regarded as a first step, recognizing that many problems, such as window protection, weight penalty, and various installation and service considerations, would have to be solved before such a system could be considered.

As discussed earlier, the best information available indicates that in at least two aircraft postcrash fire accidents (DC-10, Los Angeles, 1978 and B-737, Calgary, 1984) the initial or incipient burnthrough of the fuselage was through the windows. A contemporary window system consists of an outer pressure-holding pane and an inner fail-safe pane, both constructed of stretched acrylic, and a thin anacoustic pane attached to the interior panel, constructed of polycarbonate or cast acrylic. It has been observed during experiments that window failure occurs when the stretched acrylic panels shrink and fall out, allowing the fuel fire flames to penetrate into the cabin through the window opening.

NASA has developed a high-char-yield epoxy trimethoxyboroxine transparency that resists burnthrough (22). After an analysis of various options, it was decided that the most practical way to use the epoxy window as a fire barrier in a contemporary window system was as the inner fail-safe pane. To determine the improvement in burnthrough resistance provided by a window system containing an epoxy inner pane, a series of four tests were conducted by FAA in the C-133 wide-body test article (23). In each test the behavior of the acrylic and epoxy window systems were evaluated side by side, mounted on a DC-10 fuselage skin section, when subjected to an 8- by 10-foot fuel fire. The main difference between each test was in the type of insulation and sidewall materials mounted on the cabin side of the test section. It was determined that, on the average, the contemporary acrylic window system failed in about 3 minutes, whereas the improved epoxy window system provided about 1 minute of additional protection. This approach was not pursued further when it was established that the epoxy pane did not exhibit adequate impact resistance to suggest its used as a replacement for stretched acrylic.

The conventional fiberglass insulation and honeycomb composite sidewall panels in contemporary commercial airplanes provide some degree of resistance against burnthrough and ignition of interior materials by a fuel fire. This was clearly evidenced in the DC-10 accident (Los Angeles, 1978) and the 727 incident (Anchorage, 1987) where major portions of the aluminum skin were melted away but the cabin interior was not set afire before extinguishment of the external fuel fire. To better understand and quantitate the fuselage burnthrough problem, FAA is conducting a full-scale test program using surplus aircraft fuselages subjected to a 400-square-foot fuel fire. Basically, the fuel fire is set adjacent to an intact fuselage section instrumented with thermocouples, heat flux transducers, and cameras to attempt to determine penetration locations, firepaths, and important event times. The last of three tests was completed in a compartmentalized test article in a wheels-up configuration; i.e., test article resting on ground. The preliminary findings are as follows:

1. The aluminum fuselage skin melted in about 1 minute.
2. The fiberglass insulation acted as a fire barrier in areas where the fuselage skin melted away and prevented any heat damage to the sidewall panels.
3. Earliest penetration of small flame into the fuselage was at door edge areas (however, no sustained burning was observed).
4. Smoke obscuration inside the cabin, apparently due to pyrolysis of materials adjacent to the heated fuselage, occurs much earlier than significant flame penetration.

Currently, preparation for an additional series of tests with the landing gear deployed is under way with completion planned by spring 1989.

POOL FIRE IMPACT ON AIRCRAFT FUSELAGE

Consider the condition of a large external fuel fire adjacent to a fuselage opening. For the case of minimal flame entry into the opening, the primary impact of the fuel fire on the fuselage interior is high levels of radiant heating confined to the immediate vicinity of the fuselage opening. Experimental and theoretical studies have analyzed this case for a Type A door opening in the fuselage. Using various diameter fuselage models and pool fire sizes, the maximum thermal radiation through the opening was established (24). A maximum value of 1.8 Btu/ft^2-sec was measured at the fuselage symmetry plane at an elevation of one-half the door height. By treating the fuel fire as a radiating body at 1874 $^{\circ}$F, the theoretical thermal radiation profiles inside the fuselage were computed (24) and are shown in figure 1. For example, thermal radiation to the floor varies from 14 Btu/ft^2-sec at the door to near zero at the symmetry plane, indicating the magnitude of the extreme gradients in radiant heating. Therefore, because of the fire resistance of aircraft interior materials, under the conditions of minimal flame entry into the fuselage opening, the fire will be confined for a period of time predominantly to those materials immediately adjacent to the fuselage opening. Also, very little of the thermal radiation from the fuel fire is directly absorbed by the cabin air.

The factors that greatly affect the case of flame entry into the fuselage opening are wind conditions, door opening configuration, and fuselage orientation. The worst case is when the fuel fire is upwind of the fuselage and there are openings on the downwind side of the fuselage. In this case, full-scale tests in a DC-7 fuselage (25) and 1/4-scale model tests (26) have shown a rapid development of nonsurvivable thermal conditions within the fuselage. The results were due entirely to the fuel fire effects since both test articles were devoid of interior materials. On the other hand, if no downwind doors are open, but instead there are additional doors open on the upwind side but not exposed to the fire, the hazard development in the cabin will be greatly retarded. The results of full-scale tests (25) for these two cases are shown in figure 2. Also shown is the case with all doors closed, which matches the upwind-door-only-open case until the absence of ventilation through a door opening causes the temperature to increase at a faster rate. Another case is when the pool fire is downwind of the fuselage. For this scenario the hazard development within the cabin will be primarily from radiation in a manner similar to the pattern described in figure 1.

In order to examine survivability when wind conditions cause significant flame penetration into the fuselage, a number of tests were conducted in the C-133 test article without interior materials (27). The tests were conducted outdoors and under wind conditions that forced the fuel fire flame into the test article. Two doors were employed, one adjacent to the fuel fire and the other 60 feet away on the same side of the fuselage. Generally, the fuel fire hazards inside the fuselage accumulated more rapidly as the wind speed increased. On the basis of measurements taken at a height of 5 feet 6 inches, and at a location 30 feet away from the fire, it was concluded that both elevated temperature and smoke obscuration were greater deterrents to survivability than was carbon monoxide. At this measurement location, the concentration of carbon monoxide never reached 100 ppm under severe wind conditions that caused temperatures to exceed human survival limits and smoke to totally obscure visibility. Thus, it appears that for those accident scenarios in which fuel fire hazards are injected into the cabin, the main early threat to occupants, before burning interior materials become a factor, will be elevated temperatures and reduced visibility from smoke.

POSTCRASH CABIN FIRE CHARACTERISTICS

The cabin hazard characteristics of a postcrash fire dominated by burning interior materials in a wide-body aircraft have been reported previously using a C-133 test article (3,4,5,6). A realistic scenario was conceived and developed, consisting of an intact fuselage with an opening adjacent to an external fuel fire under quiescent wind conditions, that creates cabin conditions in which survivability is controlled by burning materials and not by burning jet fuel (3). The remainder of this paper describes a recent and final C-133 test, employing more extensive cabin furnishings and interior panels, to examine several aspects of postcrash fire survivability not heretofore studied.

Objectives: The objectives of the test were as follows:

1. Determine fire/hazard progression in postcrash fire environment with emphasis on post-flashover conditions.

2. Examine factors affecting survivability.

3. Evaluate performance of "generic" protective breathing equipment (PBE) filter.

Experimental Approach: The overall experimental arrangement is shown in figure 3. The forward cabin was completely furnished over a length of 45 feet, in contrast to previous tests where only a small section surrounding the fire door was furnished with up to three rows of seats. In this test there were 14 rows of seats, in a double-triple-double seating configuration, and a single triple seat in front of the galley, for a total of 101 seats. Surplus aircraft seats protected with fire blocking layers were used. The carpet was 90/10 wool/nylon. The sidewalls and stowage bins were surplus assemblies constructed of epoxy-fiberglass honeycomb panels. The ceiling was composed of flat sheets of epoxy-fiberglass and epoxy-Kevlar™ honeycomb panels.

There were a number of other features that differed from past tests. The test was conducted for 12 minutes, as compared to 1-5 minutes in previous tests that were terminated shortly after flashover, in order to examine post-flashover survivability. The ceramic insulation that protected the fuselage roof in the vicinity of the fire door was removed to allow for possible fire burnout in this area with potential venting consequences on the cabin environment. Finally, to enhance realism a small number of carry-ons were placed in stowage bins and beneath seats.

Instrumentation generally consisted of temperature and heat flux sensors in the forward, furnished cabin and gas, smoke, and temperature collection/measuring devices in the rear, unfurnished cabin. The instrumentation has been described previously (3,4). An interesting refinement for this test was a gas sampling line switching arrangement for the continuous analyzers (CO, CO_2 and O_2) at stations 650 and 880 that allowed for changing to a lower sampling location when the analyzer became saturated. PBE filter performance in terms of possible clogging and gas removal (primarily CO) was also measured in the rear cabin. Filter clogging was determined by measuring the pressure drop across six filters at low, medium and high air flow rates at two elevations located slightly aft of the galley (28). Gas removal effectiveness was determined by mounting a filter on a box connected to a breathing machine and continuously measuring the concentrations of CO, CO_2 and O_2 inside the box (29). The box represented the air space inside a smoke hood when donned by an individual.

Test Results: To summarize, survivability was dominated by cabin flashover and extreme fire hazard gradients such that the fire hazards decreased fore to aft and from ceiling to floor. Furnishing the test section more extensively with interior materials had no observable effect on the outcome; i.e., the fire characteristics were similar to previous tests. Over the 12-minute test duration the cabin fire did not burn through the fuselage roof area where the ceramic insulation had been removed. Intense cabin flaming, triggered by the flashover, persisted for about 1 minute and appeared to self-extinguish when oxygen levels diminished substantially. The most notable observations after the test were that the entire ceiling was consumed by fire, as were the outboard seats in the immediate vicinity of the fire door. For the remaining seats the most striking observation was that the dress cover of the seat back cushion was largely burned away but that the fire-blocked foam was still present.

The thermal characteristics of the flashover were measured by thermocouples placed slightly above the center seat top at rows 5, 7, 9 and 15 (row 4 was at the fire door). As shown in figure 4, it appears as if the onset of flashover occurred at 210 seconds and, based on the separation between the rising portion of the profiles, propagated at about 60 feet per minute, or at a rate of one seat row about every 3 seconds. Before flashover, the seat top temperature was near ambient value. The flashover caused peak temperatures of 1600 °F to 1900 °F. The trailing edge of the profile indicates self-extinguishment of the cabin fire and gradual cooling of the interior.

The intensity and duration of flaming combustion in the upper cabin caused by flashover was measured by total heat flux transducers, located at the center seat top of rows 1, 4 and 13, pointing toward the ceiling (figure 5). The data indicate that total cabin fire involvement continued for approximately 1 minute and that the intensity was considerably greater near the fire door but tapered off toward the front and rear of the furnished cabin.

Pronounced stratification of cabin fire hazards was evidenced by measurements and visual observation. Even on the symmetry plane at station 880, in the aft cabin across from the exit door opening, the temperature varied considerably from floor to ceiling (figure 6). For example, the peak temperature at the ceiling exceeded 900 °F, while at one foot above the floor the temperature was about 125 °F. Heat stratification occurred before and after flashover.

Based on light transmissometer measurements on the symmetry plane at station 880, at elevations of 5 feet 6 inches, 3 feet 6 inches, and 1 foot 6 inches, the sudden reduction in visibility caused by smoke created by the flashover was evidenced (figure 7). The data indicate that the smoke descended downward at a rate of 8 feet per minute and, at a given elevation, the percentage light transmission from smoke accumulation changed from 100 to zero in 15 seconds. Visibility reduction due to smoke preceded in time any apparent impairment to occupants from elevated temperature or toxic gases.

Gas concentration profiles on the symmetry plane at station 880, at elevations of 5 feet 6 inches, 3 feet 6 inches, and 1 foot 6 inches, are plotted for CO_2, O_2 and CO in figures 8, 9 and 10, respectively. As discussed earlier, the data are in segments because the gas analyzers were switched to sampling lines located lower in the cabin when the readings saturated. Analysis and comparison of the graphs indicate a rapid increase in CO_2 and CO concentrations and a corresponding reduction in O_2 concentration because of flashover in the forward cabin. Significant stratification of all three gases was evident throughout the test. Gas concentrations and O_2 depletion were extremely high in more than half of the upper cabin. Only in the lower several feet of the cabin were the concentrations low enough to perhaps allow for escape over a short period of time. In the lower cabin the primary threat to survival appears to be CO, due to the relatively high O_2 concentrations and moderate temperature rise.

Hydrogen fluoride (HF) and hydrogen chloride (HCl) profiles at station 880, at 5 feet 6 inches and 1 foot 6 inches, are shown in figure 11. The trends are very similar for these water-soluble acid gases as exhibited by the dry gases CO and CO_2; i.e., the acid gases were generated as a result of flashover and the acid gases are also significantly stratified.

At station 880 the temperature profiles shown in figure 6 were analyzed to determine the thermal threat to survivability. The fractional effective dose (FED) concept introduced previously (3) was employed to compute whether incapacitation would occur as a result of elevated temperatures. The thermal FED profiles shown in figure 12 indicate that at 4 feet and below, survival may be possible from the thermal threat alone. To generalize, the temperature measurements taken throughout the cabin indicate that the thermal threat decreases the farther away you are from the fire and the closer you are to the floor.

The cabin hazards data suggest that survival may be possible in a post-flashover environment near the floor in a crawling position and close to an exit door opening where fresh outside air is entering the cabin. To examine this hypothesis, CO and O_2 concentration measurements were taken just inboard of the aft exit door opening at an elevation of 1 foot 6 inches (figure 13). The fluctuating nature of the curves suggests a delicate exchange at this location between combustion gas exhaust and fresh air intake. An FED analysis of the CO profile indicates that incapacitation would occur at about 560 seconds, assuming a negligible effect from the lowered oxygen concentration (approximately 18 percent), any other toxic gases, and any elevated temperatures. This time of incapacitation is about 6 minutes after the onset of flashover. One may conclude that there is a survival zone surrounding an exit door opening wherein survival is possible in a crawling position for several minutes in a post-flashover cabin environment.

The function of a PBE filter is to remove toxic gases and smoke particulates from a combustion environment in order to furnish breathable air to the wearer. One potential problem is clogging from massive deposition of smoke particulates. To examine this effect the pressure drop was measured across filters drawing air at three different flow rates, representative of a range of inhalation rates, placed at 5 feet 6 inches and 3 feet 6 inches, at station 880. As shown in figure 14, a rapid increase in pressure drop occurred immediately following flashover because of the high loading of smoke particulates. However, the results are inconclusive since the pressure gauges could not be read after the initial increase because of smoke obscuration. Nevertheless, the data indicate a potential problem that requires further study.

The other aspect of PBE filter performance examined was effectiveness in removal of CO, which is generally considered the most hazardous toxic gas produced by a fire. Figure 15 presents the results with the breathing machine/box arrangement briefly discussed earlier (28). The high concentrations of CO measured downstream of the filter indicate that the filter was apparently saturated by the extremely high concentrations of CO produced by cabin flashover, allowing large quantities of CO to pass through. Thus, the particular filter evaluated appears unable to cope with the high levels of CO produced by flashover. Whether PBE, in general, can and should be effective in a post-flashover cabin environment is a broader issue that needs to be addressed.

Another recognized problem with filter-type PBE is that this type of equipment was not designed for use in a fire environment with oxygen depletion. Measurements of O_2 downstream of the filter with the breathing machine/box arrangement illustrate the obvious; i.e., oxygen depletion in the cabin environment will be experienced downstream of the filter, but only after a lag time of 30-60 seconds, caused apparently by the effects of the initial volume of fresh air beneath the PBE hood and the O_2 concentration in exhaled air.

ADDITIONAL WORK

Full-scale tests provide the essential data needed to understand the characteristics of postcrash cabin fires. Current FAA test activities will broaden this data base and, hopefully, improve our understanding of the postcrash fire environment. As summarized in the paper, full-scale tests are being conducted to determine the mechanisms and time framework for fuselage burnthrough by an external fuel fire. A new, comprehensive full-scale test activity is also underway to evaluate the effectiveness of an onboard cabin water mist fire suppression system. Tests are planned in both standard-body and wide-body test articles. Fire scenarios will include an external fire adjacent to a fuselage opening, as studied previously by FAA, and a new scenario consisting of cabin fire penetration by floor burnthrough. Wind will be simulated and varied for each scenarios. Thus, the water mist test program will provide data comparisons that have received little attention in the past; i.e., the effects of fuselage volume (standard- versus wide-body cabin) and fire scenario (immediate versus delayed flame penetration, quiescent versus finite wind).

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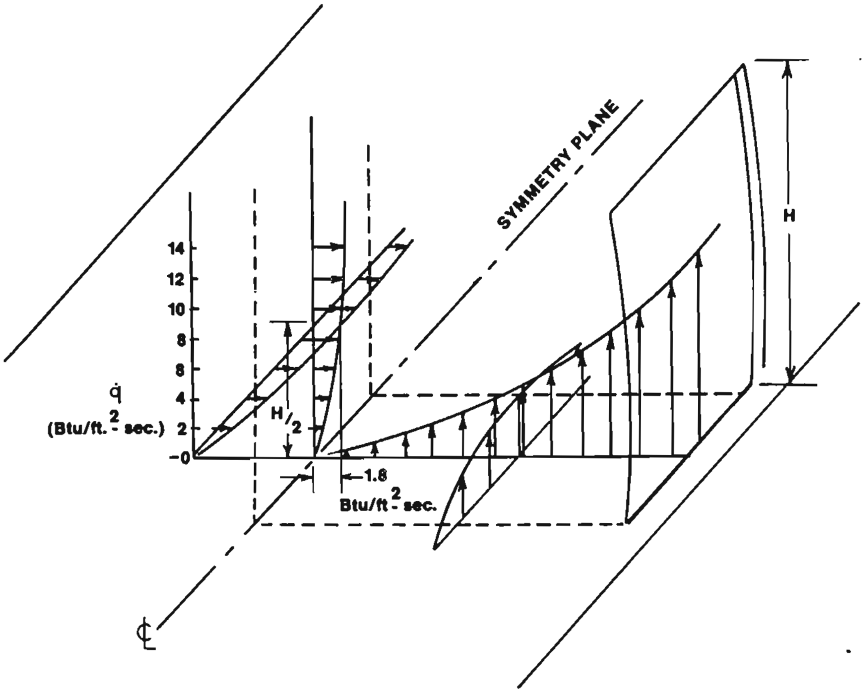

FIGURE 1. THEORETICAL THERMAL RADIATION PROFILES

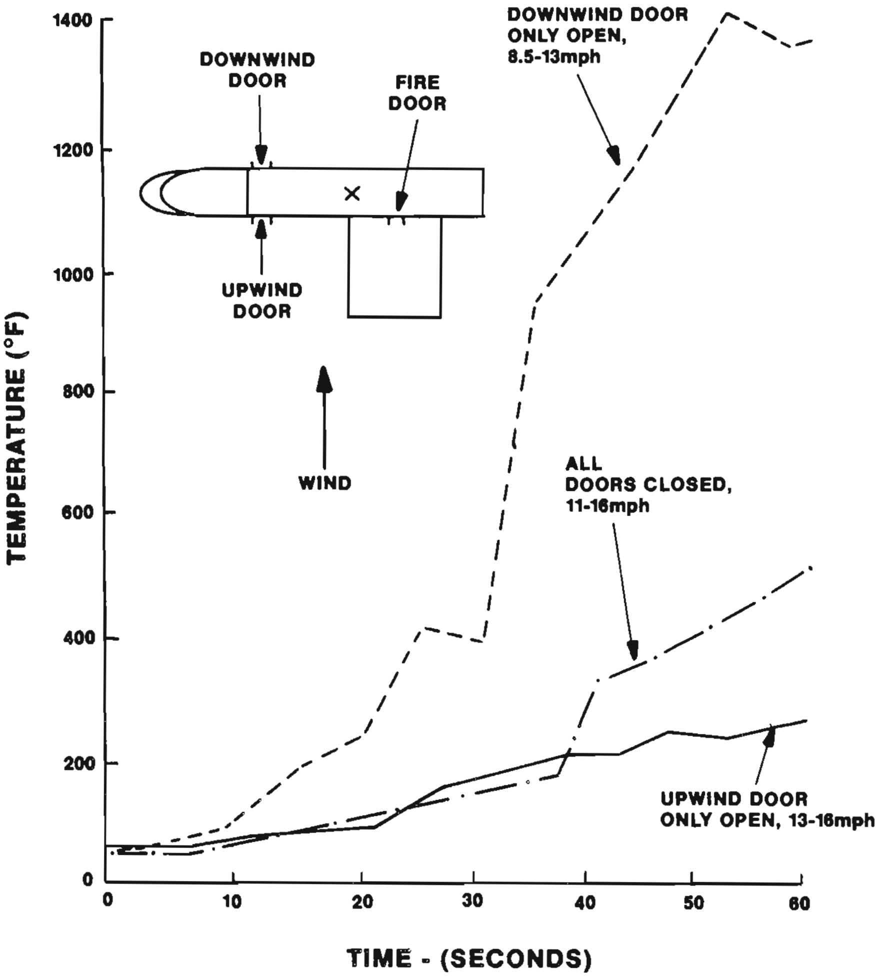

FIGURE 2. EFFECT OF WIND AND DOOR OPENINGS ON CEILING TEMPERATURE

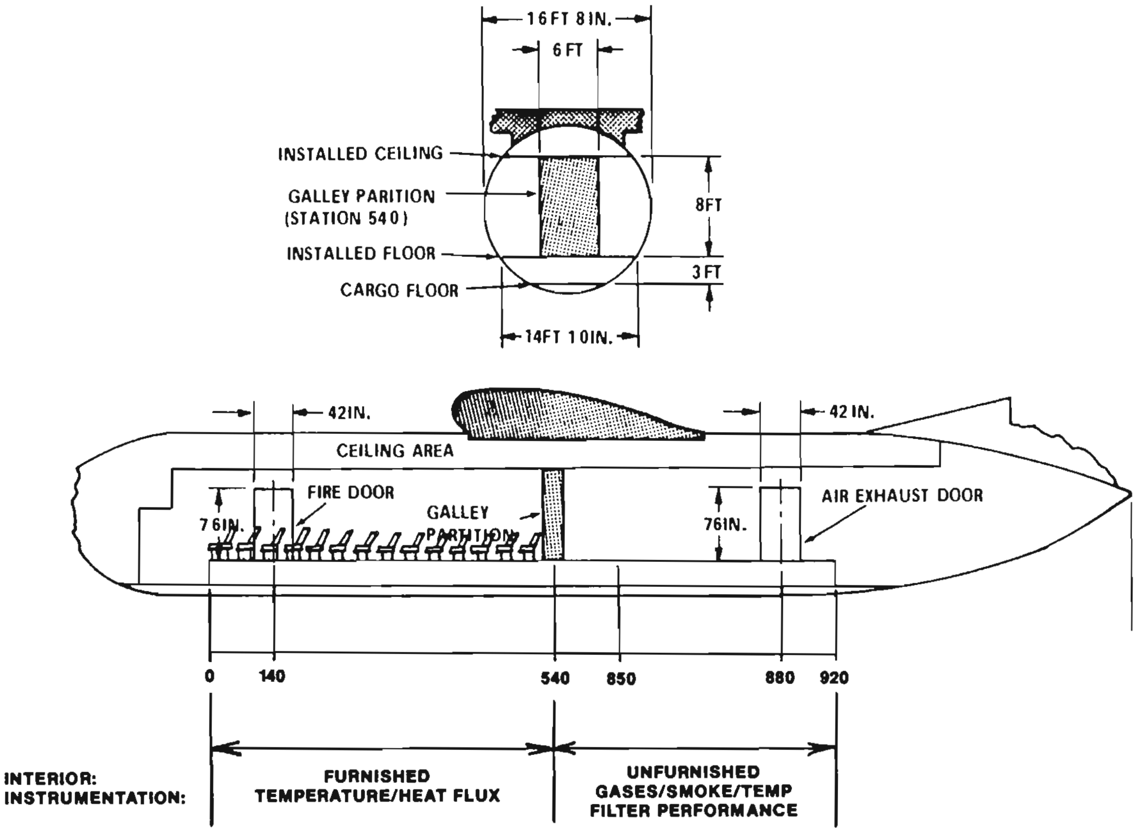

FIGURE 3. FULLY-FURNISHED FULL-SCALE TEST ARRANGEMENT

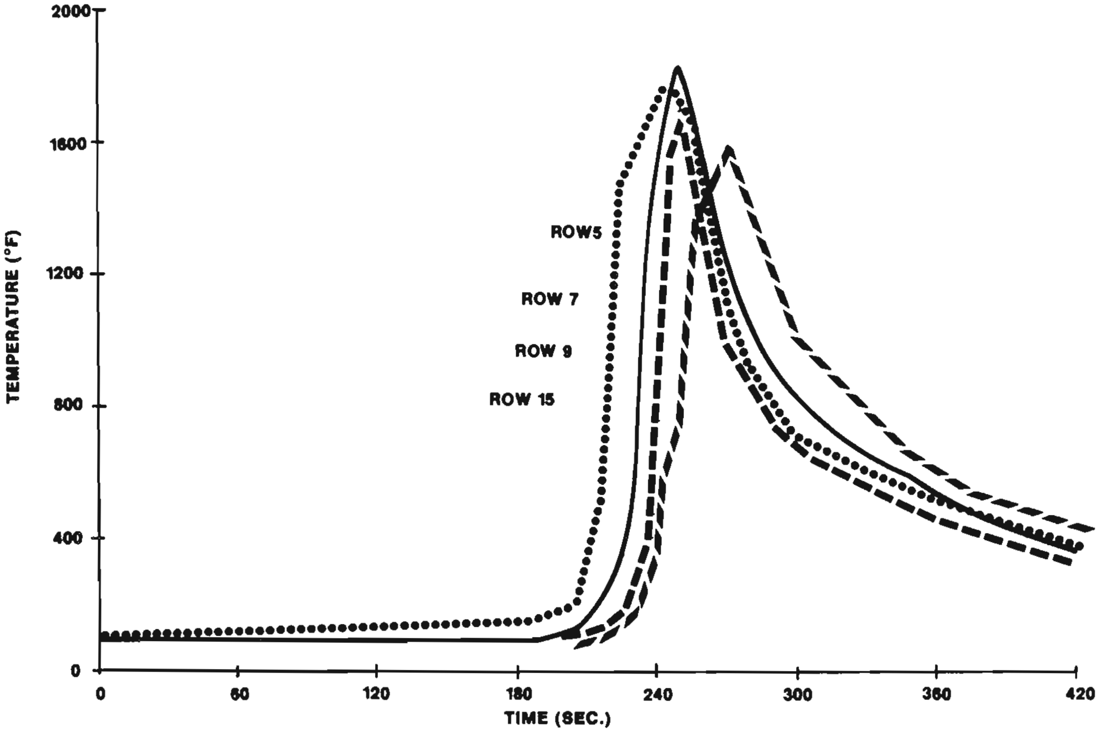

FIGURE 4. SEAT TOP TEMPERATURES

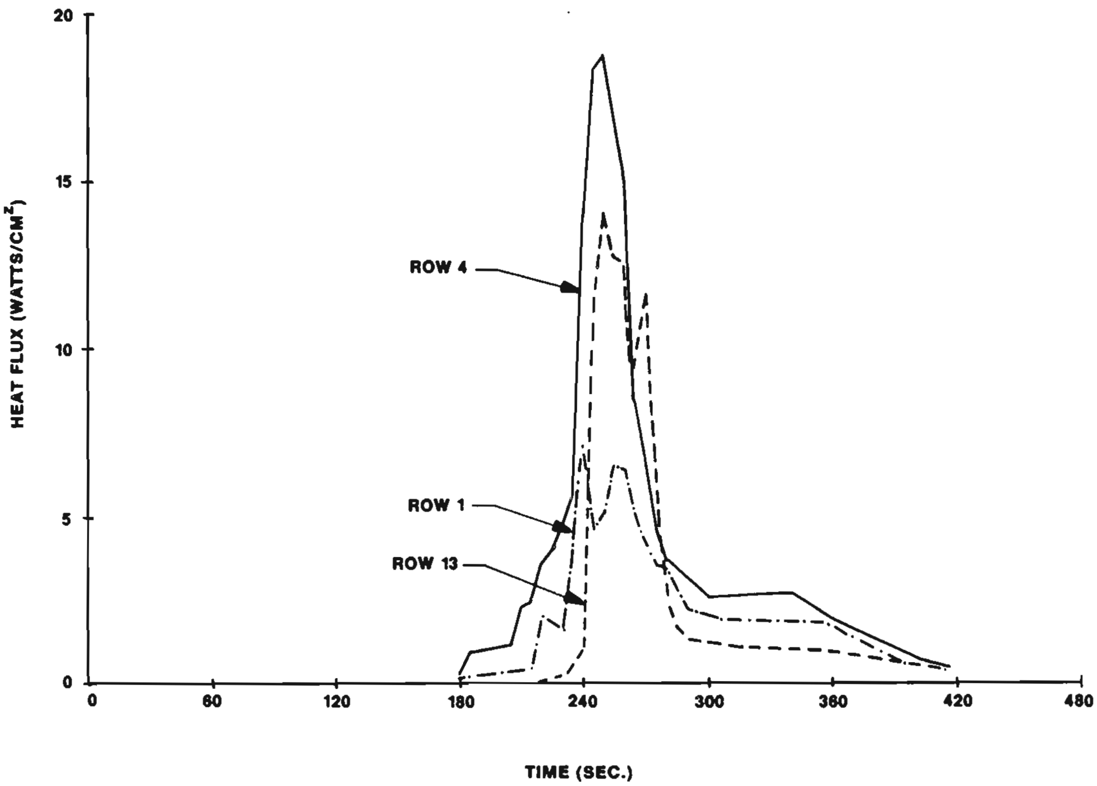

FIGURE 5. UPPER CABIN HEAT FLUX MEASURED AT SEAT TOP

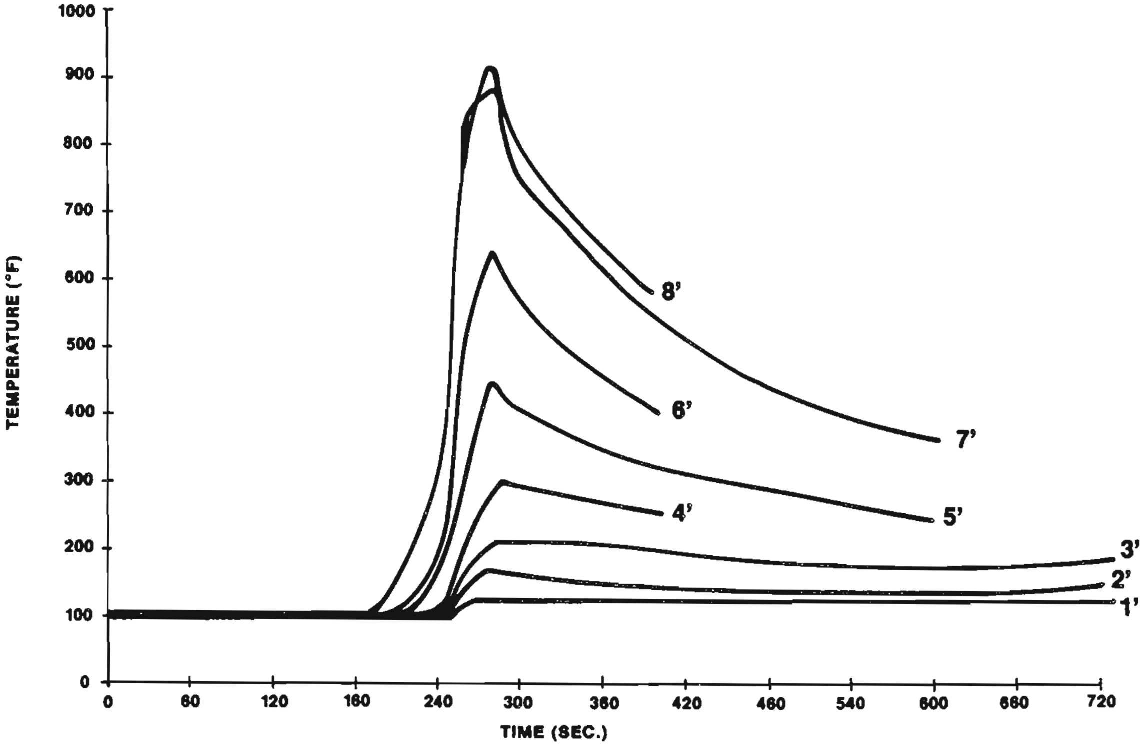

FIGURE 6. TEMPERATURES AT STATION 860

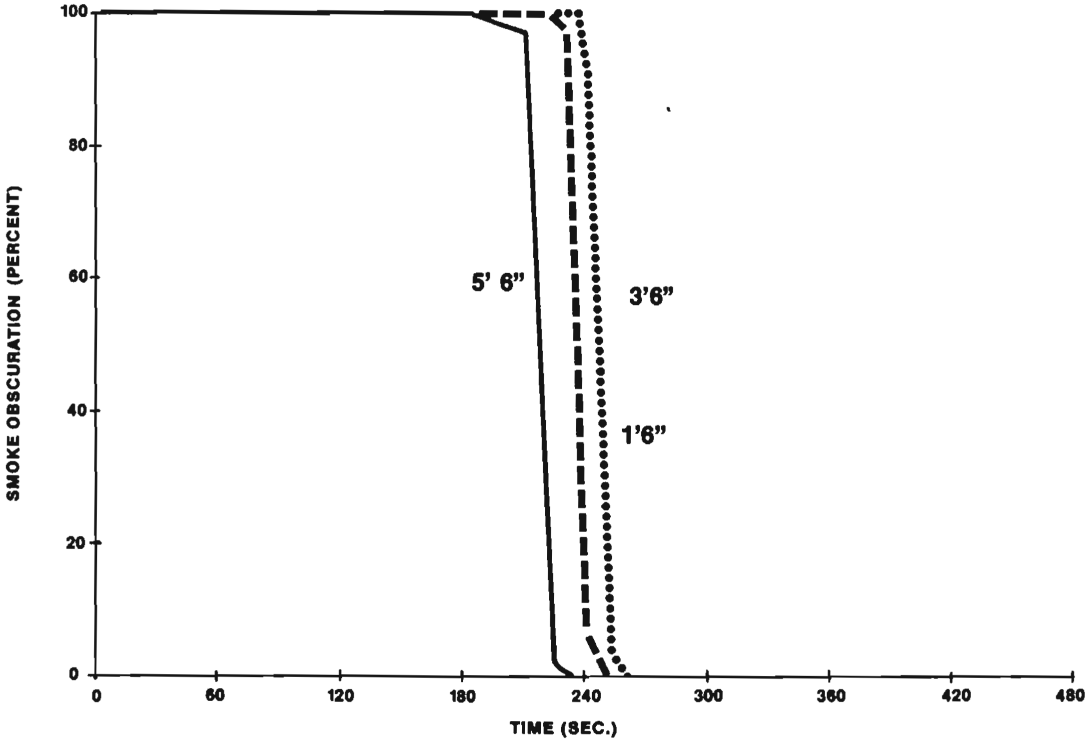

FIGURE 7. SMOKE LIGHT TRANSMISSIONS AT STATION 880

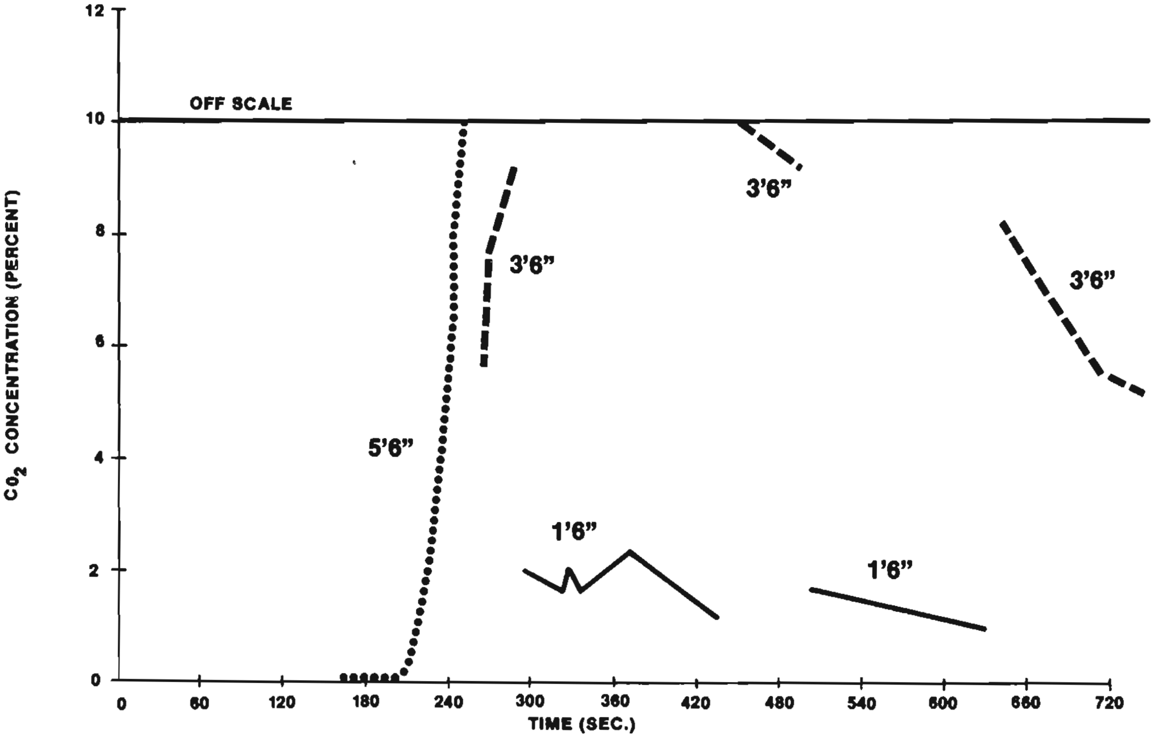

FIGURE 8. CARBON DIOXIDE CONCENTRATIONS AT STATION 880

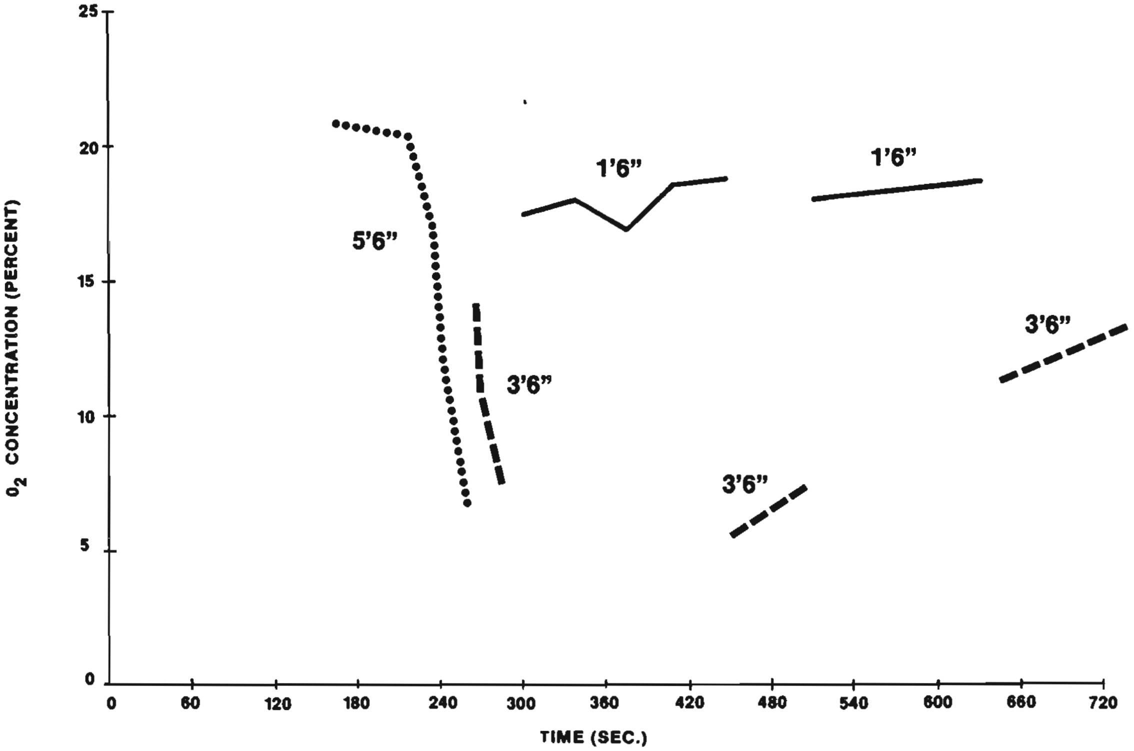

FIGURE 9. OXYGEN CONCENTRATIONS AT STATION 880

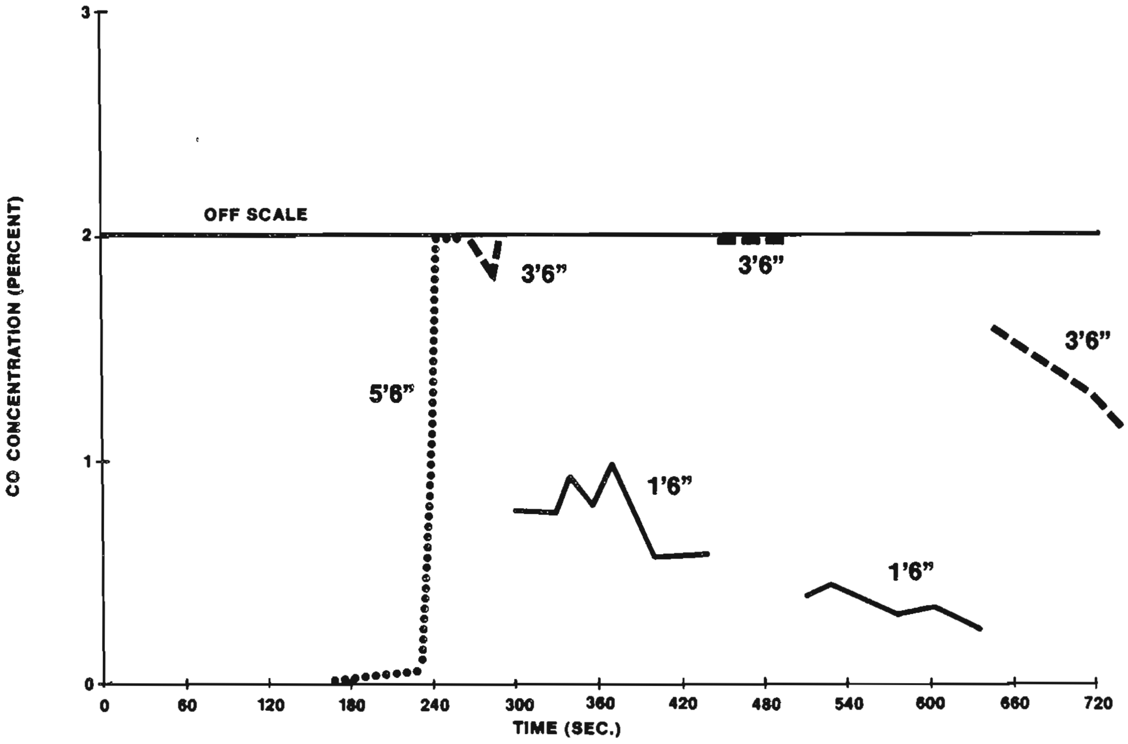

FIGURE 10. CARBON MONOXIDE CONCENTRATIONS AT STATION 880

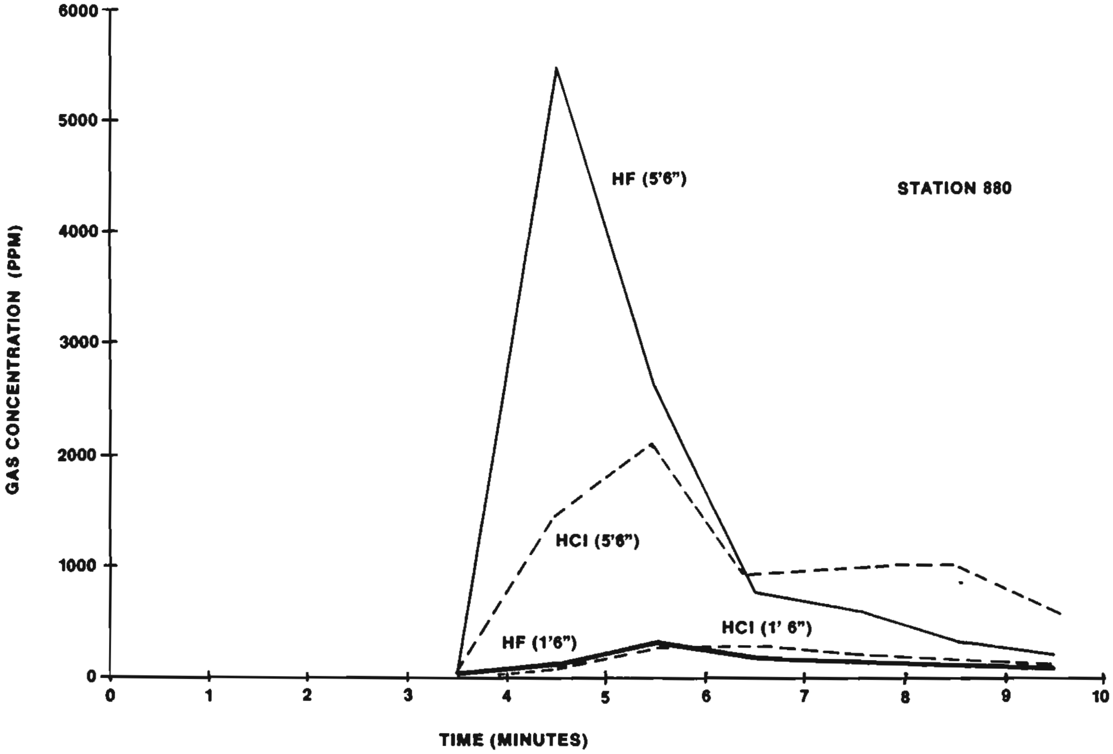

FIGURE 11. ACID GAS CONCENTRATIONS AT STATION 880

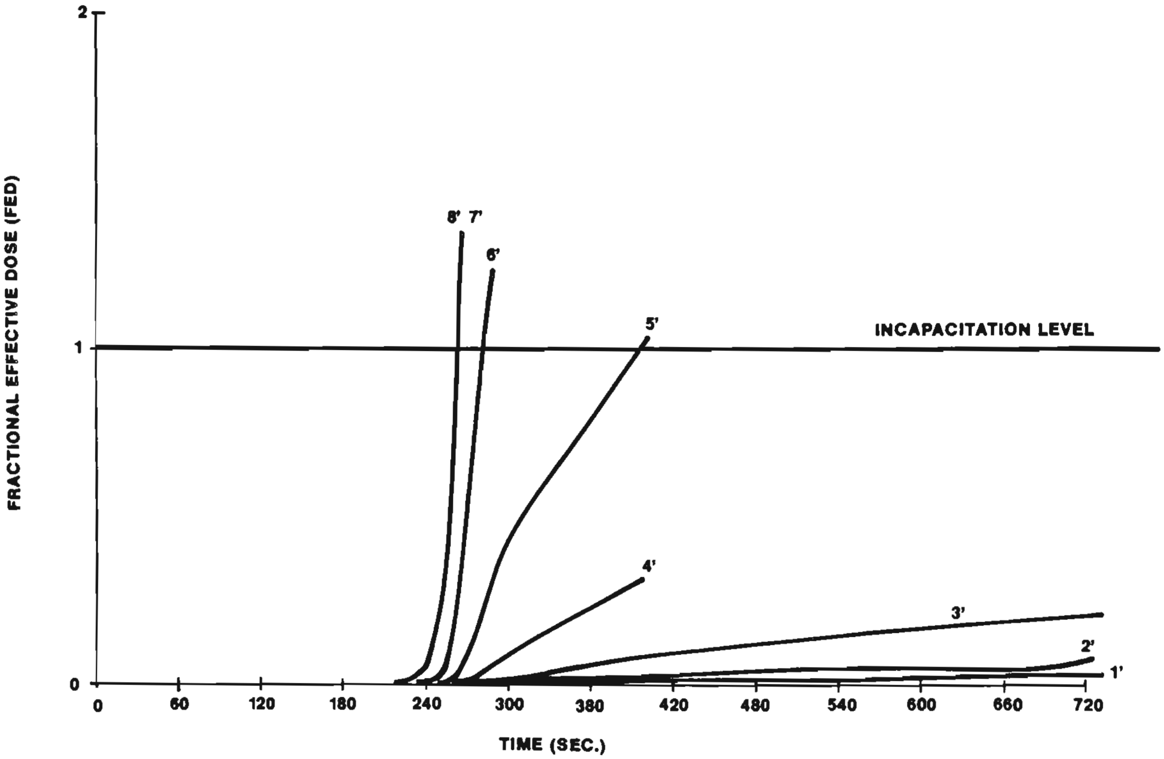

FIGURE 12. THERMAL FRACTIONAL EFFECTIVE DOSES AT STATION 880

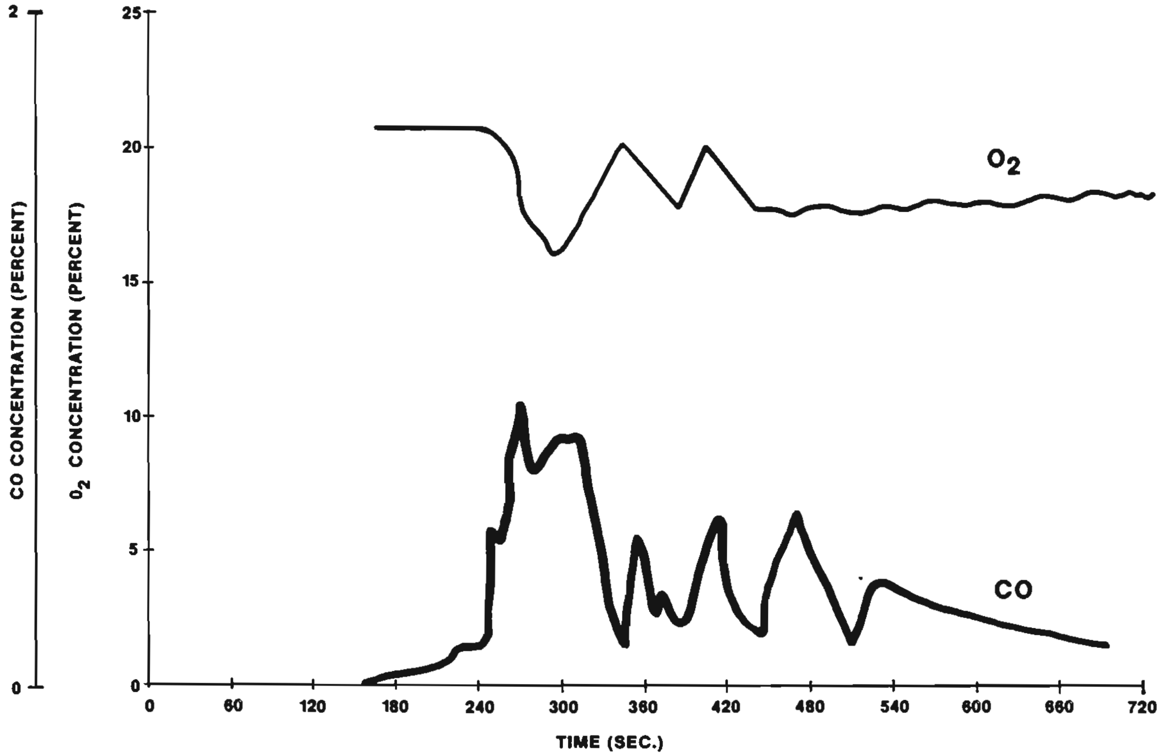

FIGURE 13. CARBON MONOXIDE & OXYGEN CONCENTRATIONS NEAR EXIT DOOR OPENING

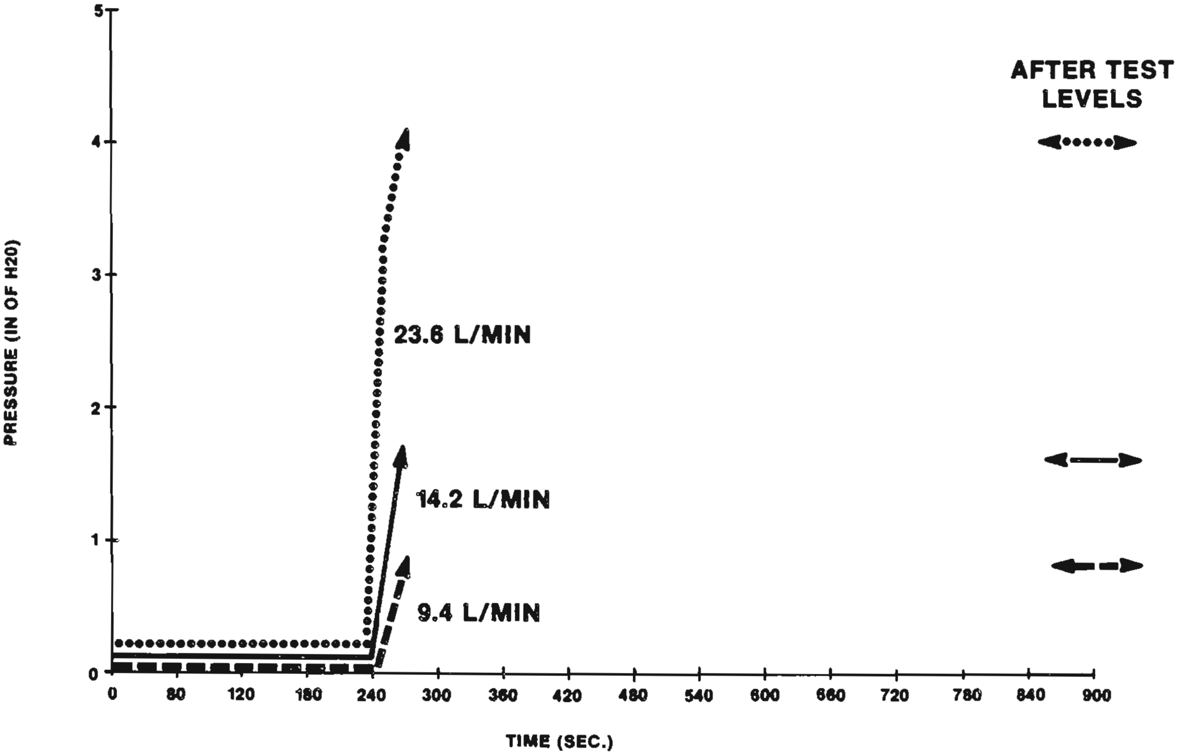

FIGURE 14. PRESSURE DROP ACROSS MASK FILTERS

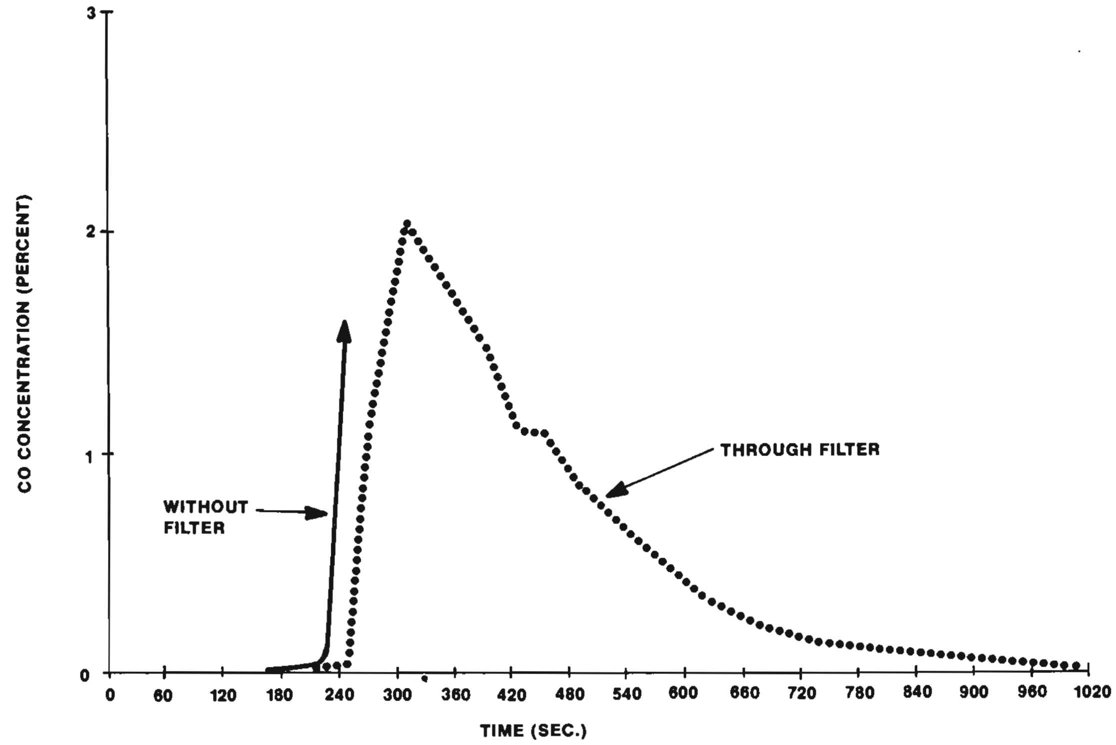

FIGURE 15. REMOVAL OF CARBON MONOXIDE BY MASK FILTER

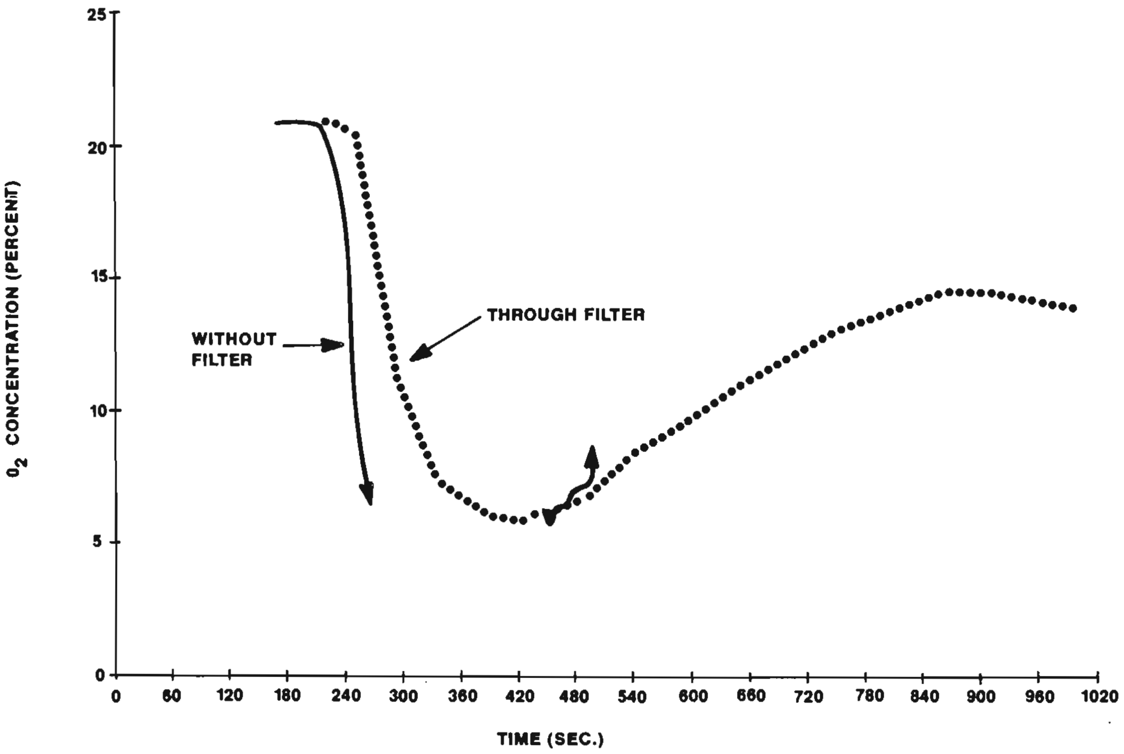

FIGURE 16. OXYGEN CONCENTRATION UPSTREAM & DOWNSTREAM OF MASK FILTER

DISCUSSION

M. DE LA PENA

What is the FAA view on the mandatory provision of passenger smoke protection hoods as we the industry have proved that they can be made to meet most performance requirements.

AUTHOR's REPLY:

The FAA supports the CAA decision, announced in december 1987, that passenger smoke hoods should not be mandated for the airlines. Although smoke hoods can or will be designed to meet specific standards, my belief is that more work needs to be done to study scenarios where the availability of smoke hoods may possibly become a safety hazard rather than a safety benefit.

E.R. GALEA

Bearing in mind the detailed informations required by field modellers in order to validate their models, can you provide them and if not do you have future plans to do so.

AUTHOR's REPLY:

As discussed in the paper, full-scale fire tests may be conducted to validate fire models. Usually, the purpose is to evaluate under realistic fire conditions the effectiveness of a fire safety concept. We have the capability of recording over 100 channels of data, including heat flux, temperature, smoke density, and various gas concentrations as a function of time at different cabin locations. In the near future we may be able to conduct a test with a steady-state fuel fire in order to assist you in validating your model.

K.W. SMITH

Is it possible to conduct future experiments with known and controllable winds generated, say by wind machines.

AUTHOR's REPLY:

We have conducted experiments in the past, referenced in the paper, using a DC-7 fuselage and with ¼-scale models, to examine the effect of wind and door openings on fuel fire penetration into a fuselage door opening. The few slides I showed at the end of my presentation were from a current activity to study fuselage burnthrough by an external fuel fire. Wind caused a more severe fire and higher skin heating conditions when the test article was above the ground (landing gear extended) than during tests with the test article resting on the ground (collapsed landing gear). I believe to properly account for the effects of wind on an airplane fire there are two options: 1/ conduct full-scale tests outdoors and make best with the variable wind, and 2/ use a realistic model and large enough fan to create steady airflow over the entire model. A third option may be to study the problem with a 3-D mathematical field model to compute aerothermodynamic conditions.

A.F. TAYLOR

Does your definition of flashover include flash ignitions, or do you agree that flash over is inevitable?

AUTHOR's REPLY:

The flashover observed in full-scale tests does contain flash ignitions of combustible gases accumulated in the ceiling smoke layer. At Manchester the scenario was markedly different at least in the follow ways: 1/early accumulation of thick black fuel smoke, 2/ 3 exit openings were employed, 3/the fire burned through the fuselage into the cabin and 4/the rear fuselage section dropped causing a large circumferential break. Conditions (2),(3) and (4) would tend to delay the onset of flashover. It is not clear to me how the presence of fuel smoke at the ceiling effects flashover. Although the Manchester accident report concluded that a fully-developed flashover did not occur, the burn damage to the Manchester 737 interior is strikingly similar to a full-scale test interior after flashover. Nevertheless, I do not believe that flashover is inevitable in every aircraft fire scenario, but it is clearly the dominant event affecting passenger survival when it does occur.

J.S.S. STEWART

It is impossible to reconcile the earlier full-scale test model with the pathological and toxicological evidence obtained from real accidents. Does the new model help to reconcile the different types of evidence?

AUTHOR's REPLY:

I do not agree that the earlier full-scale test model is inconsistent with pathological and toxicological evidence obtained from real accidents. The "new model" as you call it, or the full-scale fire test with more extensive furnishings and data-gathering in the post-flashover time period, produced consistent results with our previous tests; i.e. survivability is dominated by flashover. The data indicate that the primary hazards caused by flashover are elevated temperatures and oxygen depletion at locations closer to the fire origin and in the upper cabin; by contrast, at locations further away from the fire origin and closer to the floor, the dominant hazards are toxic gases.