APPLICATION OF FULL-SCALE FIRE TESTS TO CHARACTERIZE AND IMPROVE THE AIRCRAFT POSTCRASH FIRE ENVIRONMENT

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Abstract

The Federal Aviation Administration (FAA) has conducted numerous full-scale fire tests for the purpose of characterizing the postcrash cabin fire environment and developing improved fire test criteria for cabin materials. The tests consistently demonstrated the importance of cabin flashover on occupant survivability. Flashover is basically a sudden, very rapid spread of fire, generating large quantities of heat, smoke and toxic gases that quickly fill the cabin. Before flashover the cabin environment is largely survivable; after flashover, occupant survival becomes highly unlikely. Thermal incapacitation is more important near the fire origin and at higher elevations; whereas, toxic gas incapacitation is predominant away from the fire origin and at lower elevations. The FAA has developed and adopted improved fire test methods for seat cushions (fire blocking layers) and interior panels (low heat release). In both cases the fire test methods are consistent with full-scale test results and serve to improve occupant survivability be delaying the onset of flashover, which produces large quantities of toxic gases, providing substantially greater available time for occupant evacuation.

Keywords: Aircraft fire safety, flashover, toxic gases, full-scale fire tests, survivability

1. Introduction

Is there a need for a smoke toxicity test method for aircraft cabin materials? To attempt to answer this question it may be useful to review what information exists relative to the characteristics of aircraft fires, especially with respect to occupant survival. There are two primary sources for this knowledge - accident investigations and full-scale fire tests. This paper will focus on the latter, summarizing full-scale fire tests conducted by the Federal Aviation Administration (FAA). Also of interest is the application of full-scale fire tests by FAA to develop improved fire test methods and criteria for cabin materials; viz., seat cushions (fire blocking layers) and interior panels (low heat release).

Why are full-scale fire test so important? Basically, because full-scale fire tests furnish extensive data and information that cannot be obtained through the investigation of an accident, or by theoretical analysis, or by reduced scale experiments. Accidental aircraft fires produce grim evidence of the consequences of a tragedy (e.g., number of fatalities, location of bodies, cause of death). However, what transpired inside the airplane in time and space, especially with respect to the progression of the fire and occupant survivability, is impossible to reconstruct. Properly instrumented, controlled and realistic full-scale fire tests provide the most credible approach for defining or understanding a fire problem and developing design and operational improvements.

An aircraft fire can occur under two circumstances - during flight (in-flight fire) or following a crash (postcrash fire). A small number of fatal but catastrophic in-flight fires have occurred in the past. In all cases the fire originated in a hidden or inaccessible area of the airplane. Protection against in-flight fire is best achieved by early and reliable detection, following by rapid fire extinguishment or suppression/control. Aircraft material selection should be based on fire test methods that measure fire containment capability (e.g., burnthrough resistance of cargo liners) or ignition resistance. The aim of this design philosophy is to contain and control the fire, in order to isolate passengers and crew from the fire hazards and safeguard flight-critical systems, until the airplane can be safely landed at the nearest airport. Therefore, this paper will discuss the smoke toxicity issue within the context of a postcrash fire.

Over the past 15 year the FAA Technical Center conducted numerous full-scale aircraft fire tests. Different test article sizes, including wide body, narrow (standard) body and commuter, have been used. Most of the tests were conducted indoors in a special facility to assure controlled fire conditions, which is absolutely mandatory in developmental programs involving a series of fire tests. Several tests were also conducted outdoors. In most cases the interior was only partially furnished, since this was shown to be adequate to provide the desired data, although fully-furnished tests also were conducted. An external pool of burning jet fuel, usually adjacent to a fuselage opening (rupture or door), was the ignition source in all tests. This type of fire source (with a dominant radiation effect) is necessary because practically all postcrash aircraft fires are initiated by the ignition of jet fuel released from the damaged fuel system. During the full-scale tests designed to develop improved fire test criteria for cabin materials, the fuel fire was located adjacent to a fuselage opening with minimal fuel flame penetration through the opening, corresponding to a zero wind or downwind condition (Sarkos et al., 1982; Sarkos and Hill, 1982; Sarkos and Hill, 1985; Hill et al., 1985). Minimal fuel flame penetration assures that the fire hazards within the cabin will be governed by burning aircraft materials and not by the burning fuel fire hazards. More recent cabin water spray tests employed fuel fire conditions with significant flame penetration through the opening in order to create a more severe fire threat for evaluation of waterspray effectiveness (Hill, et al., 1991; Marker, 1993; Sarkos, et al., 1993). Tests have also been conducted with the fuel fire adjacent to an intact fuselage, to evaluate burnthrough resistance (Webster, 1994; Webster, 1995) or water spray effectiveness in suppressing a cabin fire following fuselage burnthrough (Hill, et al., 1991).

2. Characteristics of Postcrash Aircraft Cabin Fires

Test observation and data analysis of the early referenced full-scale fire tests provide the following description of the characteristics of a cabin fire. The seat closest to the fuel fire is the initial material ignited. As the seat burns its combustion products accumulate and spread along the ceiling. Later, the fire spreads to portions of the seats fore and aft of the initial seat ignited; ceiling and stowage bins above the burning seats also ignite and burn. The fire remains localized and confined to the outboard seats and overhead materials which flash intermittently in the black smoke layer. A distinct partitioning of the cabin is created - a hot overhead smoke layer clinging to the ceiling, approximately 2 or more feet thick, and a clear region below the smoke layer, largely at or near ambient conditions. The smoke layer spreads throughout the cabin. The observed fire below the smoke layer remains localized and the two zone effect persists until the occurrence of a flashover. Although definitions of flashover vary, it is basically a sudden, rapid spread of fire within a enclosure. The extent of the spread of the fire is dependent on the availability of oxygen, which is consumed in great quantities because of tremendous burning rates associated with the flashover. Flashover is a phenomenon that may occur in any enclosure fire, such as a bedroom, a warehouse, a bus, or an aircraft cabin.

Cabin flashover is clearly the critical factor affecting occupant survivability during a postcrash fire dominated by burning cabin materials (as opposed to a postcrash fire in which survival is governed by the fuel fire hazards). Cabin hazard history measurements taken during a full-scale fire test in a wide body test article are shown in figure 1 (Sarkos and Hill, 1985). Before the flashover, which occurred at approximately 150 seconds, the cabin environment was clearly survivable; after flashover, the conditions deteriorated to such a degree that survival would have been unlikely. As shown in figure 1, within 30 seconds visibility was reduced from clear to 3 feet, temperature increased from ambient to 400° F, carbon monoxide jumped from zero to 2500 parts per million (ppm) and oxygen dropped from 21 percent to 16 percent. Obviously, improvements in postcrash fire survivability, when burning cabin materials predominate, can best be achieved by taking measures that delay the onset of flashover. This will also delay the production of hazardous levels of toxic gases since before flashover the concentration of toxic gases (CO, HCN, HCl, and CO_2) was essentially zero (at the measurement location, 5.5 feet high and 40 feet away from the fire entry opening).

The early full-scale tests described above employed a cluster of materials about the fire opening. A later test outfitted a much larger area of the test article in a most realistic fashion and provided additional characterization of the cabin flashover phenomenon (Sarkos and Hill, 1989). In the "fully-furnished" C-133 test, the forward cabin was completely furnished over a length of 45 feet (see experimental arrangement in figure 2). Fourteen rows of seats, in a double-triple-double seating arrangement, and a triple seat in front of the galley, totaling 101 seats were used. Aircraft ceiling panels, stowage bins, sidewalls and carpeting were installed throughout the furnished cabin length. As in previous experiments, survivability was driven by cabin flashover and extreme fire hazard gradients were measured.

The thermal characteristics of the flashover was measured by thermocouples placed slightly above the center seat top at rows 5, 7, 9 and 15 (figure 3). Note that row 4 was at the fire entry point. The onset of flashover occurred at 210 seconds and, based on the separation between the rising portion of the profiles, propagated at above 60 feet per minute, or at a rate of one seat row about every 3 seconds. Before flashover, the seat top temperatures were near ambient values. The flashover caused peak temperatures of 1600° F to 1900° F. The trailing edge of the profile shows the fire self-extinguished and the cabin cooled down. Oxygen concentration measurements indicated that the fire became oxygen-starved; readings at the seat top level decreased to less than 5% throughout the test article.

In addition to flashover, another important characteristic of a cabin fire is the existence of pronounced fire hazard gradients. There are tremendous heat losses to interior surfaces; as much as 90% of the heat generated by a fire may be absorbed by interior surfaces. For example, ceiling temperature gradients of 1000° F were measured along a 60 foot cabin length (longitudinal direction). Large temperature gradients in the vertical direction were also measured. Figure 4 contains temperature histories on the symmetry plane at station 880, across from exit door, about 60 feet aft of the fire entry opening. The temperature varied considerably from floor to ceiling; e.g., the peak temperature at the ceiling exceeded 900° F, while at one foot above the floor the temperature was only about 125° F. Heat stratification occurred before and after flashover.

The most important toxic gas produced by a cabin fire is CO. Because CO losses are primarily by ventilation, CO reduction away from the fire origin is much less than that for temperature. Vertical CO gradient also exist because of buoyancy/ventilation effects, as shown in figure 5. The rapid increase in CO concentration at 240 seconds was caused by the flashover in the forward cabin. In the upper half of the aft cabin CO concentrations saturated the gas analyzer at a reading of 2%. Only near the floor were the concentrations low enough, due to cool air entrainment through the exit door, to perhaps allow for survival over a period of time, as discussed below.

In order to relate the measured hazards to survivability, a fractional effective dose (FED) model was employed (Speitel, 1995). Briefly, the model assumes that the effect of heat and each toxic gas on incapacitation is additive and that the increased respiratory rate due to elevated carbon dioxide levels is manifested by the enhanced uptake of other gases. Calculated FED profiles at the three measurement heights at station 880 are shown in figure 6. Incapacitation at all heights is caused by CO inhalation; the effect of heat is essentially zero. At three feet six inches incapacitation occurs about 25 seconds later than at 5 feet 6 inches, and occurs very quickly (as at 5 feet 6 inches)due to the extremely rapid increase in CO concentration caused by flashover. However, at 1 feet six inches, incapacitation is delayed by about 200 seconds. The practical implications of the latter are twofold. First, an individual may be able to crawl out of an airplane after flashover if adequately protected from the thermal hazard. Second, erect individuals who are capacitated and fall to the floor, may survive for relatively long periods of times if they are in close proximity to a fuselage opening.

Full-scale water spray tests conducted in recent years provide additional characterization data for postcrash cabin fires (Hill, et. al., 1991; Marker, 1993; Sarkos, et al., 1993). The results are consistent with earlier tests with respect to the dominant effect of flashover. In one baseline test (without water), the experiment was designed to cause fuel flames to penetrate into fuselage opening, simulating a moderate wind condition (Marker, 1993). An FED analysis of data taken at two heights at each of two fuselage stations is shown in figure 7. The graphs show the relative contribution of heat and toxic gases at the calculated time of incapacitation (FED = 1.0). Two trends are noteworthy. First, at a particular fuselage station, the relative importance of toxic gases on incapacitation increases the closer you are to the floor. Second, as the distance from the fire origin increases, the relative importance of toxic gases on incapacitation also becomes greater.

Pathological examination of aircraft fire victims and laboratory analysis of blood samples often lead to the conclusion that death was caused by "asphyxiation" or "elevated carboxyhemoglobin" levels in the blood. This finding is consistent with full-scale aircraft fire tests which have demonstrated over a wide range of test conditions the overriding effect of cabin flashover on occupant survivability. As discussed previously, when survivability is driven by flashover, thermal incapacitation dominates the nearer you are to the fire origin and the higher you are in the cabin (elevation). Conversely, toxic gas incapacitation becomes more important (and dominant) with increasing distance from the fire origin and as the elevation decreases. The latter trend would be the likely direction taken by passengers attempting to escape from the fire. Thus, under these circumstances the incapacitation of occupants unable to evacuate the aircraft before cabin flashover will be by exposure to toxic gases.

The trend outlined above was evidenced in a full-scale test reenactment of a past accident. The particular accident was the B-737 accident at Manchester in 1985, during which it was reported that an upwind fuel fire rapidly penetrated the rear of the aircraft, setting the cabin on fire and resulting in 55 fire fatalities (Air Accidents Investigation Branch, 1988). A CV-880 was employed in the full-scale test which incorporated many key elements of the Manchester accident including, but not limited to, timed door opening sequences, exterior pool fire size and location, wind speed and direction, and aircraft configuration (Webster, 1985).

Figure 8 shows gas concentration and temperature data taken in the first class cabin, approximately 60 feet forward of the location where the initial burnthrough was observed to occur. The peak and valleys exhibited by the gas and temperature profiles are similar to the variation in past full-scale fire test during cabin flashover. In the Manchester reenactment test, it appears that three flashovers, or flashover-like events, occurred. Because of the larger number of openings compared to previous tests, it may be that there was a more rapid replenishment of oxygen before the cabin cooled down, resulting in multiple flashovers.

A fractional effective dose analysis of the gas concentration and temperature data is shown in figure 9. Based on the FED model, incapacitation in the forward cabin was caused entirely by CO exposure. Thermal incapacitation was not a factor and lagged the toxic gas incapacitation by 4-5 minutes. As is previous tests, the onset of incapacitation is rather sudden, and incapacitation occurs practically instantly.

3. Development of Improved Fire Test Criteria for Cabin Materials

In the past the FAA has made extensive use of full-scale fire tests to develop improved fire test criteria for seat cushion fire blocking layers and low heat release panels (e.g., sidewalls, ceiling, stowage bins and partitions). The new material fire test were adopted as regulations through the rulemaking process to improve the fire safety design of commercial airliners. The fire blocking layer rule required a retrofit of all seats in the U.S. fleet with fire blocking layers (Final Rule, 1984). Installation of low heat release panels was required in aircraft manufactured after August 20, 1990 (Final Rule, 1988). The following is a brief summary of the development of these important fire test standards.

Early full-scale fire tests demonstrated the effectiveness of fire blocking layers against a postcrash fuel fire (Sarkos and Hill, 1982). The test aircraft was lined and furnished with actual cabin materials. The results of four tests with modified seat cushions, but with all other test features identical, is shown in figure 10. Norfab and Vonar fire blocking layers delay the onset of flashover and extend the FED-calculated survival time by a significant 42 and 60 seconds, respectively. Additional tests demonstrated that fire blocking layers could also prevent ramp and in-flight fires, originating at a seat, that would otherwise burn out of control if left unattended (Sarkos and Hill, 1982).

The seat cushion flammability test developed by FAA subjects seat back and bottom cushions to an intense burner flame that creates the heating conditions produced by a large fuel fire (Brown and Johnson, 1983, Final Rule, 1984). Unlike most flammability tests, the test specimen simulates the end-use seat geometry in order to take into account and measure important effects observed in full-scale tests. A good correlation was seen between seat cushion flammability and large-scale test results (Brown and Johnson, 1983). Acceptance criteria was selected to match the behavior of fire blocking layer materials proven effective in full-scale fire tests.

After the implementation of seat fire blocking layers, the next step in fire hardening of cabin was to improve the performance of large surface area interior panels. Again, full-scale tests demonstrated potential fire safety benefits by changes in the composition of the honeycomb panel components; e.g., facings resin, adhesive and cloth (Sarkos and Hill, 1985; Hill, et al., 1985). Figure 11 contains the FED histories of five types of honeycomb panels under full-scale fire test conditions. To realistically evaluate panel performance, the flat panels were in a typical configuration that included sidewall, stowage bins, ceiling and partitions. Fire blocked seats and carpet were also installed. Only the panel composition was varied from test to test. The results show that the phenolic/Kevlar and epoxy/fiberglass panels experienced the earliest flashovers, wheras the phenolic fiberglas panel delayed flashover by about 3 minutes.

Figure 11 also contains data for these same panels tested in the Ohio State University (OSU) rate-of-heat-release apparatus. An inverse relationship exists between OSU apparatus heat release measurements and full-scale survival times, which essentially reflect the time-to-flashover. The relationship between heat release and flashover in enclosure fires is well established and the subject of considerable theoretical and experimental evaluation. For example, one study at the National Bureau of Standards developed an expression between the heat generation rate causing flashover and a number of enclosure characteristics, including heat transfer coefficient, wall area and opening size

(McCaffrey, et. al., 1981). Final selection of the OSU apparatus by FAA was based on the established relationship between heat release and flashover along with a number of practical considerations. The phenolic/fiberglass panel that had performed so well in full-scale tests was used as a benchmark for setting performance criteria for OSU heat release testing (Hill, et. al., 1985).

4. Summary

Realistic and properly designed full-scale fire tests are required in any major endeavor to improve aircraft fire safety. FAA has conducted many full-scale fire tests that demonstrated the predominant role of cabin flashover with respect to occupant survivability during a postcrash fire. In these tests the toxic gas hazard at measurement locations some distance from the fire origin was essentially zero before the onset of flashover. Furthermore, incapacitation caused by exposure to toxic gases generated by flashover was shown to become more dominant as the distance from the fire origin increases and the closer you are to the floor. Thus, it is plausible that victims of aircraft fires whose death is attributed to asphyxiation or elevated blood carboxyhemoglobin levels were incapacitated by toxic gases generated by flashover. FAA has employed full-scale fire tests to demonstrate material fire safety benefits and develop improved fire test methods and criteria for seat cushions and cabin panels. A similar approach is required to guide the development of a toxicity test method for aircraft materials if it can be initially established that it is warranted.

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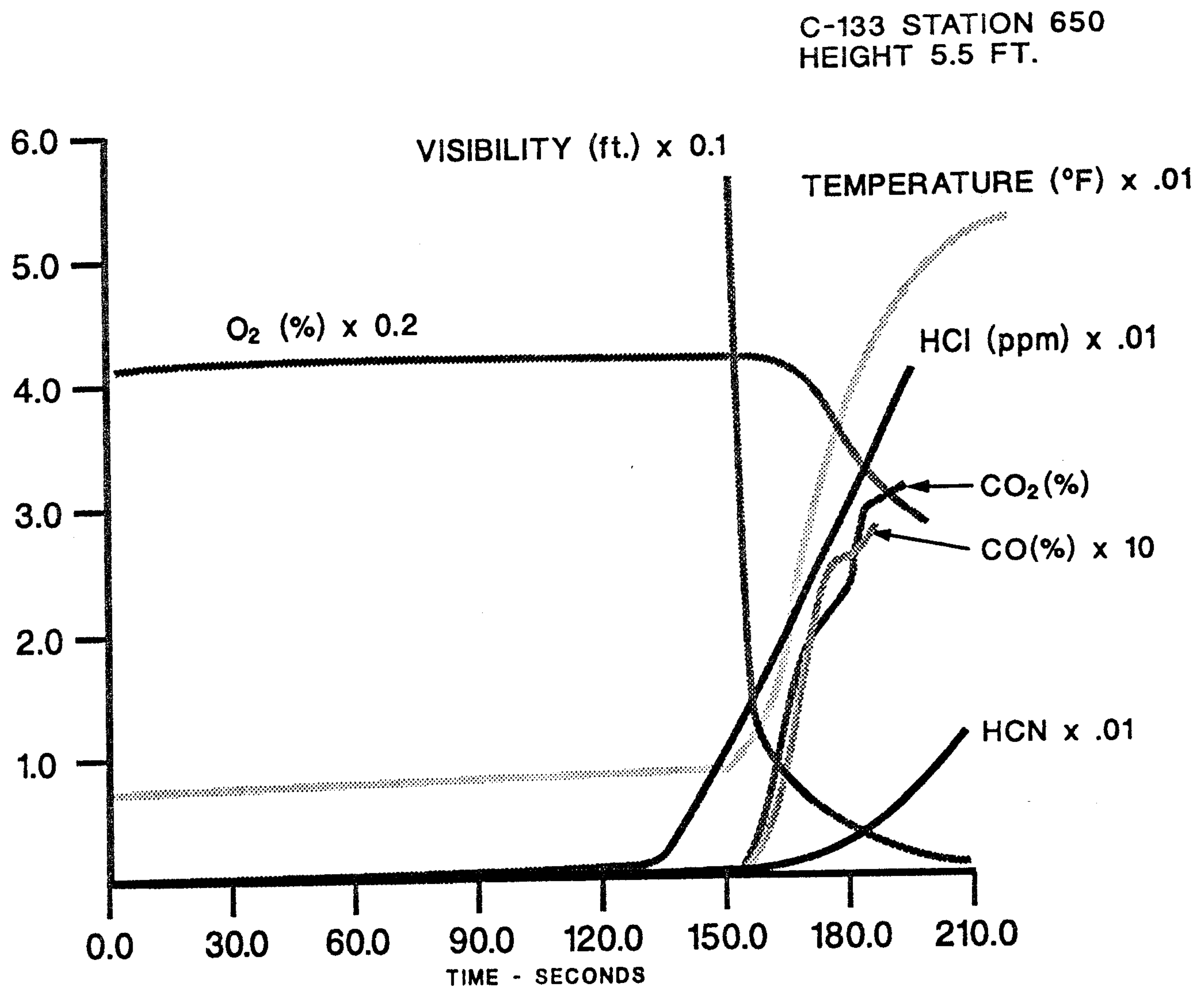

FIGURE 1. WIDE BODY CABIN HAZARD HISTORIES (C-133)

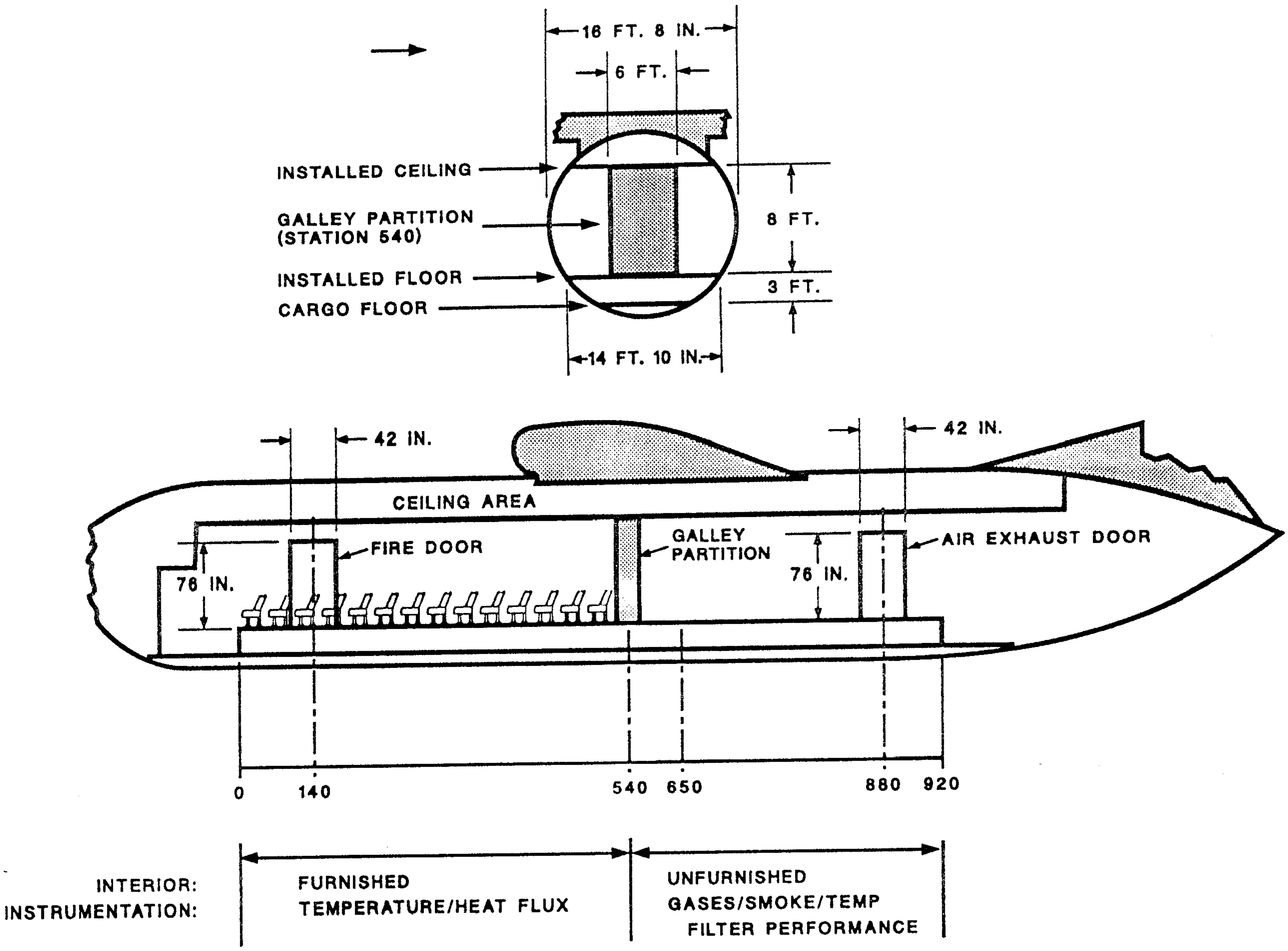

FIGURE 2. WIDE BODY FULLY-FURNISHED FULL-SCALE TEST ARRANGEMENT (C-133)

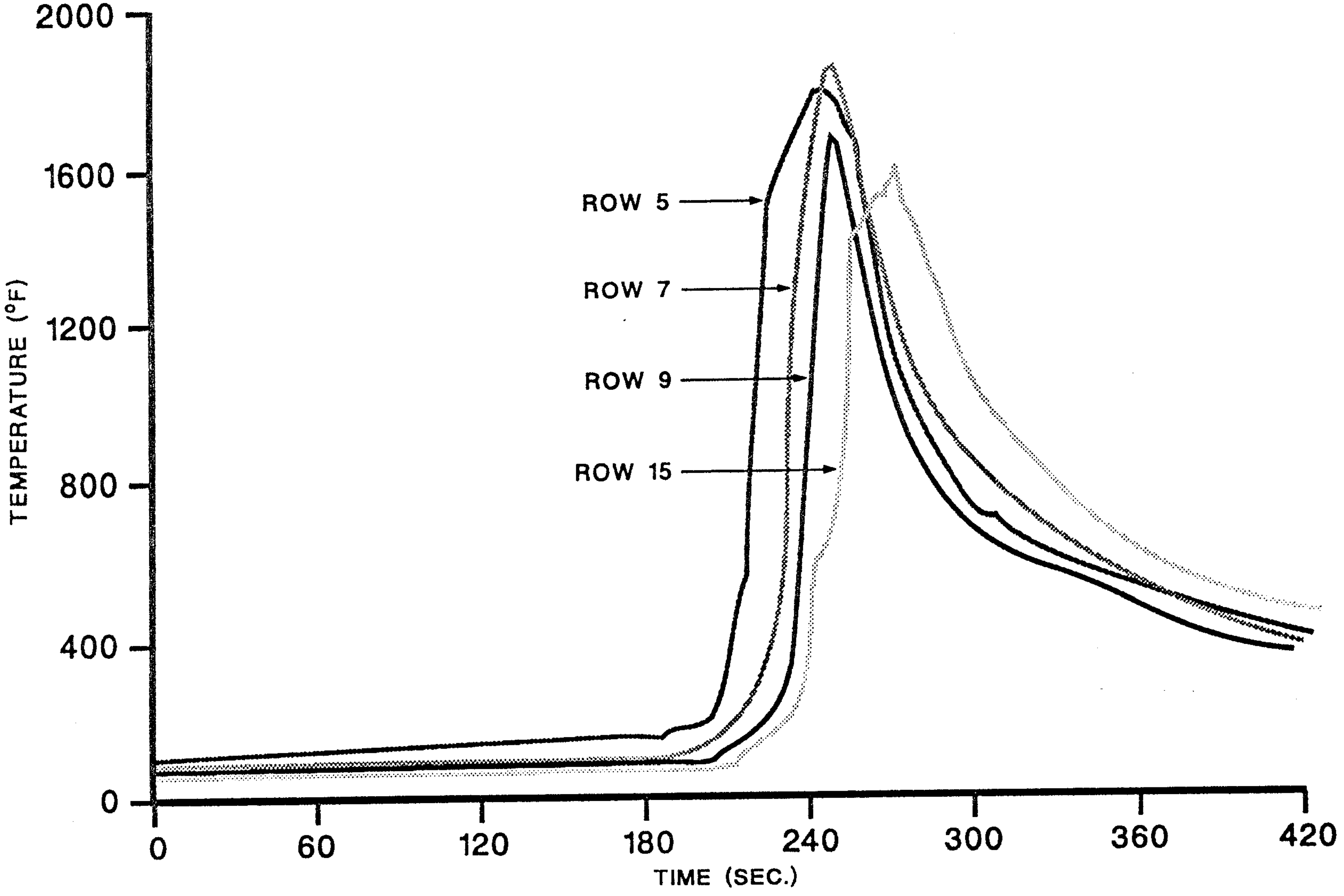

FIGURE 3. WIDE BODY FULLY-FURNISHED TEST SEAT TOP TEMPERATURES (C-133)

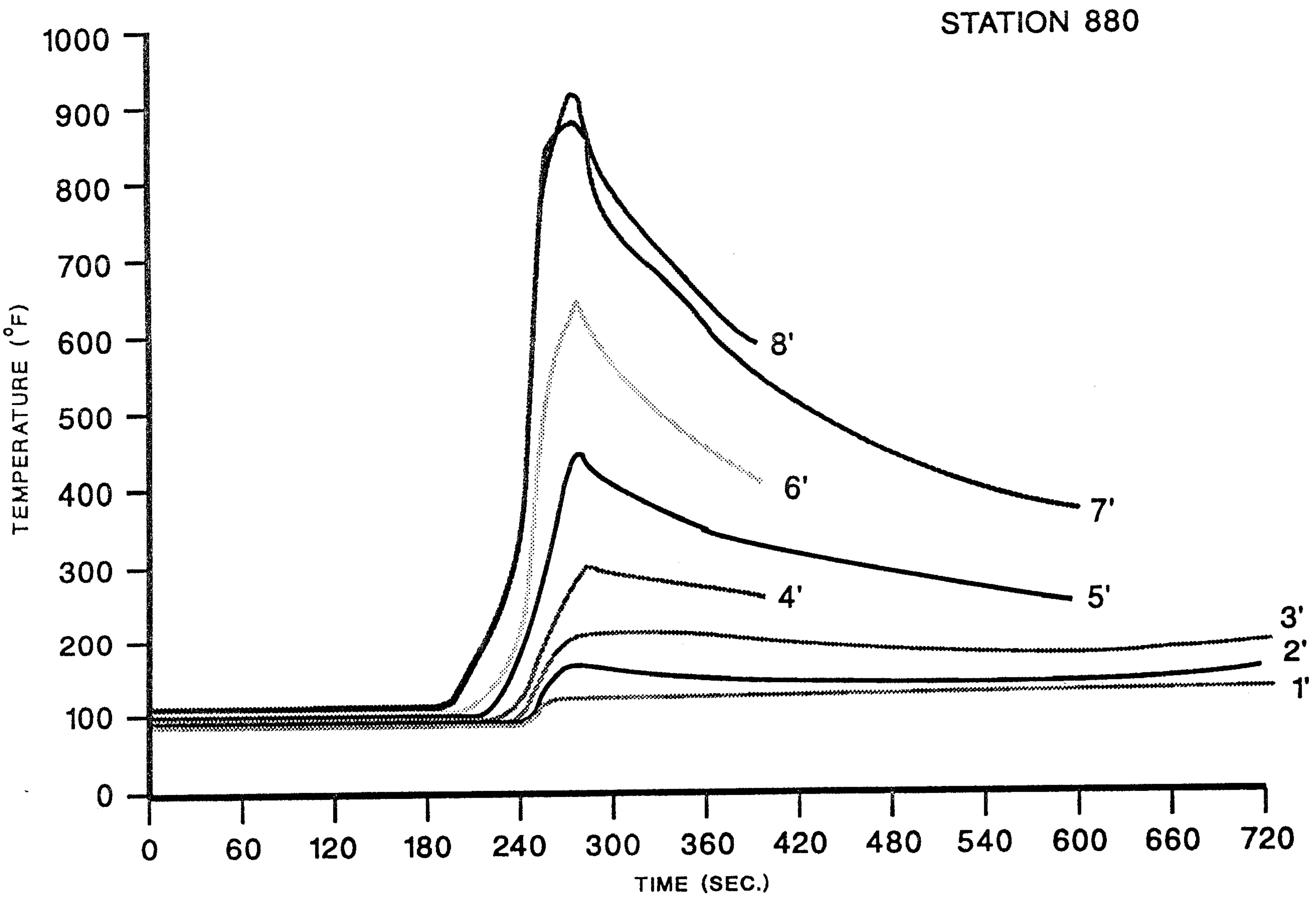

FIGURE 4. FULLY-FURNISHED TEST TEMPERATURE NEAR DOOR OPENING (C-133)

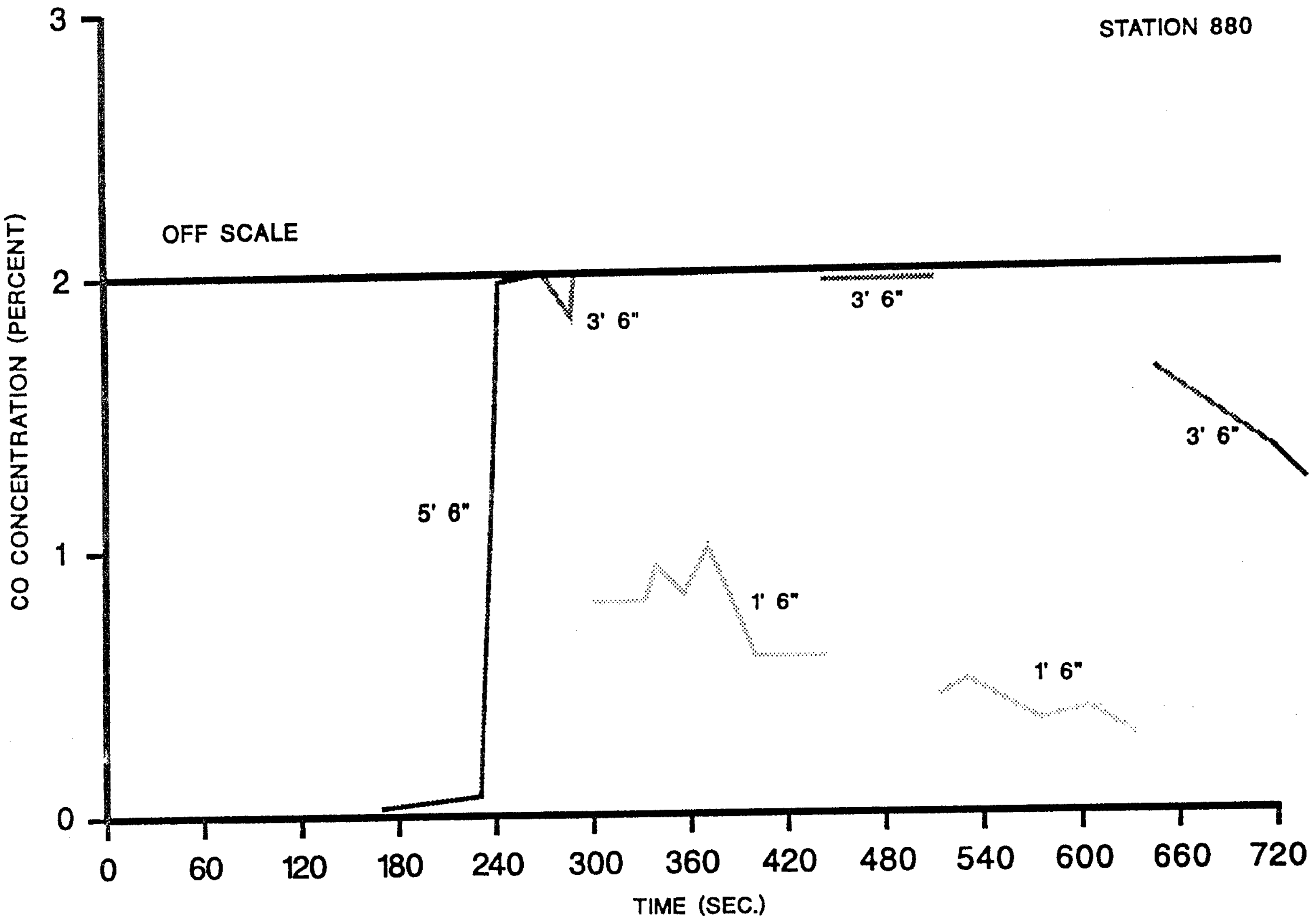

FIGURE 5. WIDE BODY FULLY-FURNISHED TEST CO LEVELS NEAR DOOR OPENING (C-133)

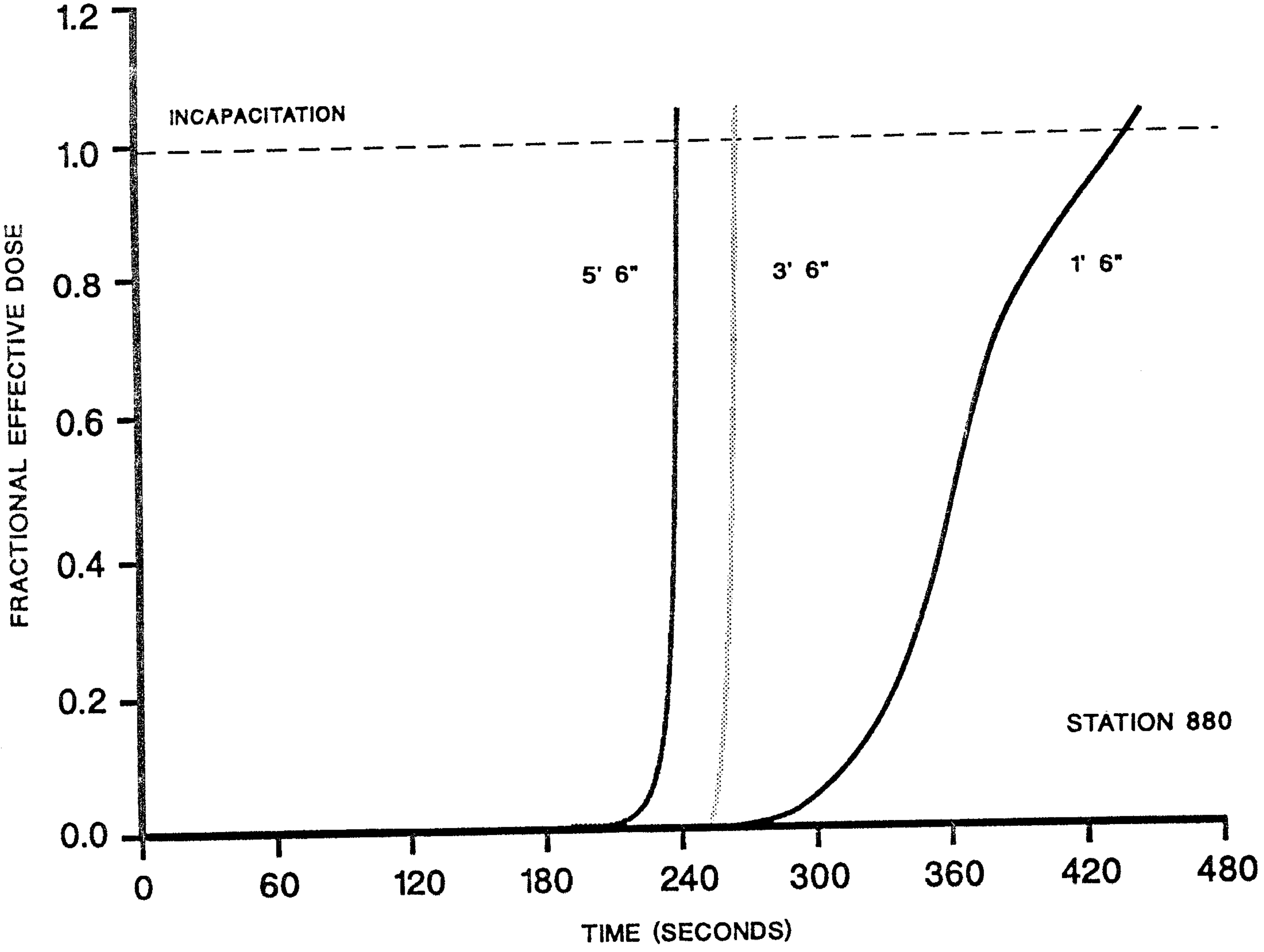

FIGURE 6. HEIGHT DEPENDENCY OF CALCULATED INCAPACITATION NEAR DOOR OPENING (C-133)

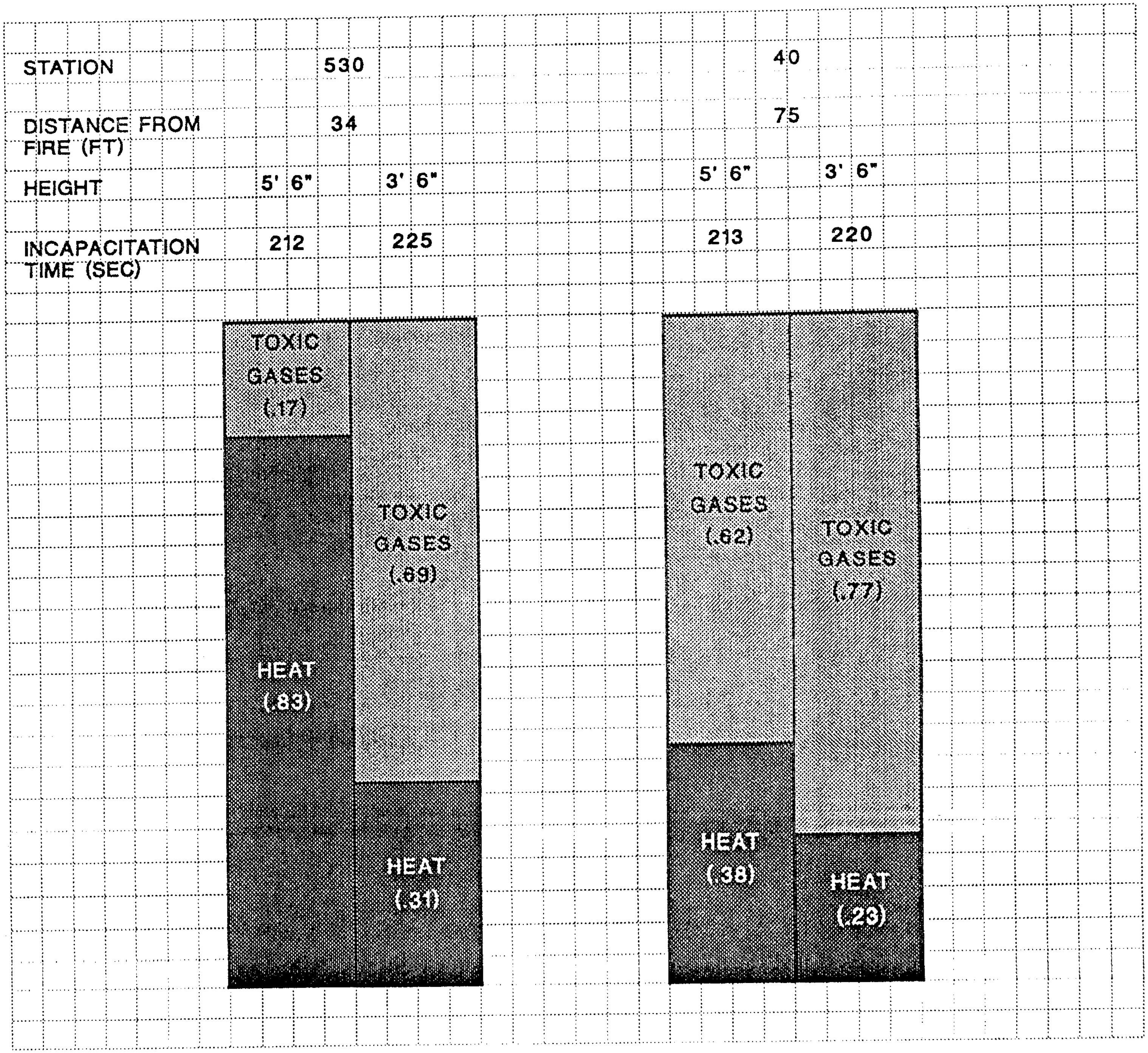

FIGURE 7. RELATIVE EFFECT OF HEAT AND TOXIC GASES AT CALCULATED TIME OF INCAPACITATION (TC-10)

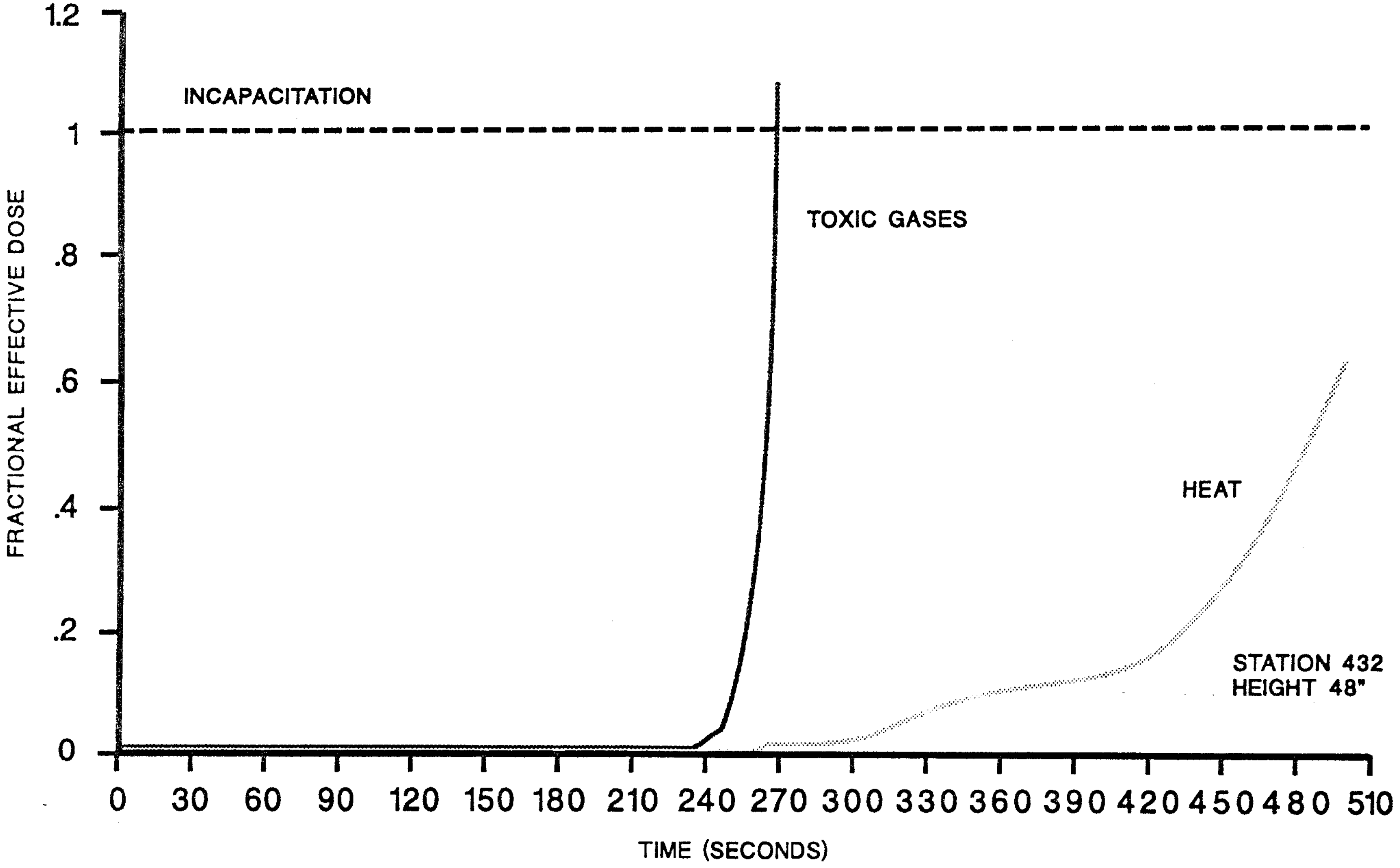

FIGURE 9. INCAPACITATION EFFECTS OF HEAT AND TOXIC GASES IN FIRST CLASS CABIN DURING ACCIDENT REENACTMENT TEST (CV-880)

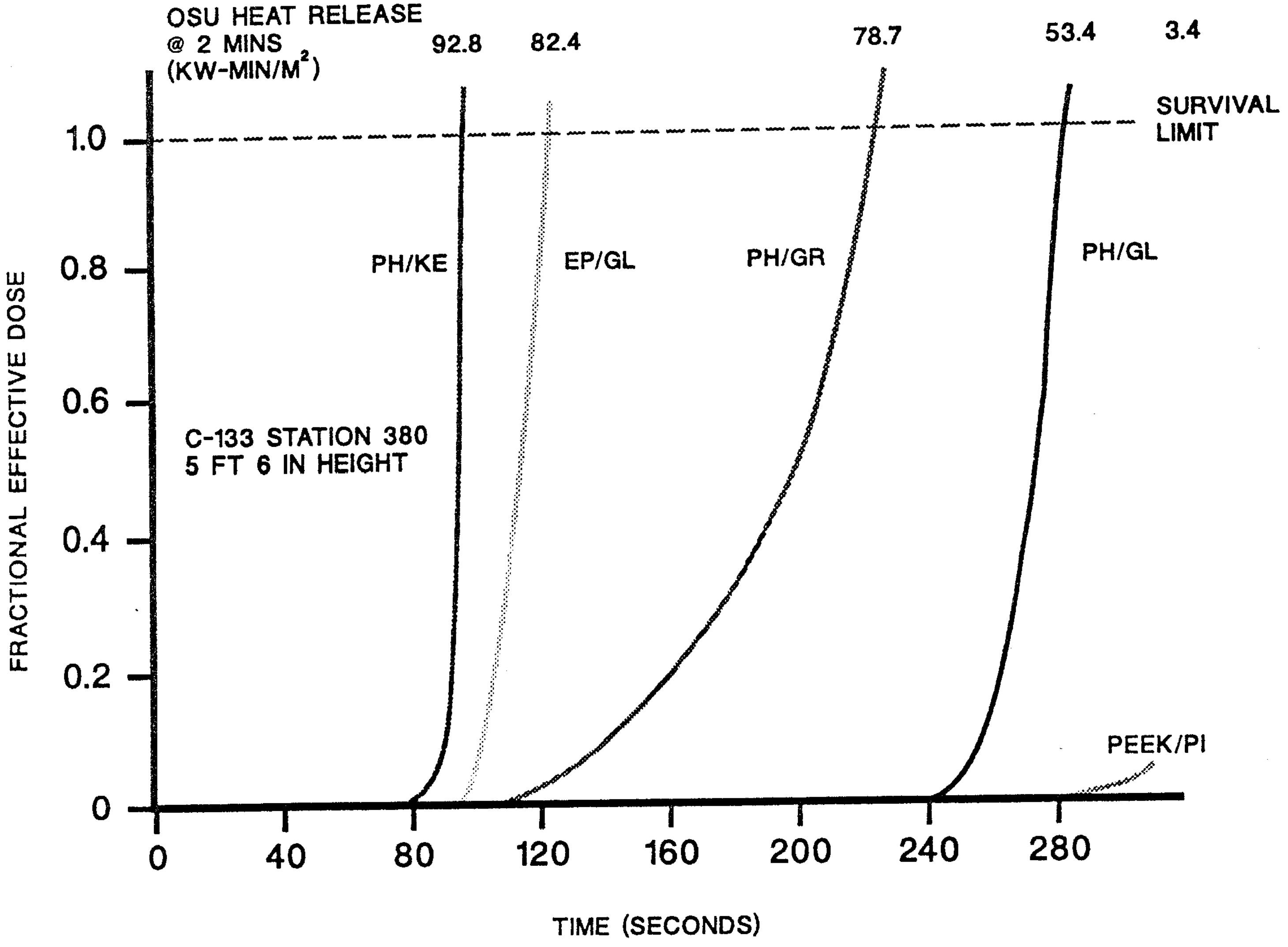

FIGURE 11. EFFECT OF COMPOSITE PANEL DESIGN ON FRACTIONAL EFFECTIVE DOSE (C-133)