The importance and role of cabin materials on survivability from fuel-fed fires and cabin-fire hazards arising solely from external fuel fires have been investigated...

Full-scale wide-body test article employed to study post crash fuel fires

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A NUMBER of tests have been carried out by the U.S. Federal Aviation Administration to study aircraft cabin fire hazards. Testing involved an external fuel fire adjacent to a large fuselage opening in an otherwise intact fuselage. The test set-up assured minimal fuel-fire flame penetration but intense radiation into the cabin. The test article employed was constructed from a surplus McDonnell Douglas C-133 Cargomaster.

In summary, there were five significant findings:

- Burning cabin interior materials can be the primary factor affecting occupant survivability in certain types of postcrash fires, despite the presence of a large fuel fire.
- Uncontrolled postcrash fires in an intact fuselage will produce a flashover condition, which will be followed by a loss in survivability throughout the cabin.
- The only fire hazards of significance measured before the onset of flashover were the irritant gases, HF and HCl, and smoke produced by burning composite panels and, possibly, seats.
- In tests with zero wind and the cabin interior realistically furnished and lined with interior materials, application of a Vonar fire-blocking layer on seat cushions improved the calculated survival time in the aft cabin by 60 seconds.
- Potential benefits to cabin fire safety beyond those provided by seat cushion blocking layers may be realized from improvements made to the remaining interior materials; however, it is presently unclear if effective and practical alternative materials are available.

Over the past 20 years, all fatalities attributable to fire in United States air carrier accidents have occurred during survivable crashes (versus in-flight fire accidents). In almost all of these cases, the postcrash cabin fire was initiated by a large fuel fire external to the aircraft. Under these conditions, the importance and role of cabin materials on survivability, in the context of and in contrast to a large fuel fire, are difficult to assess.

Small-scale fire tests on cabin materials — by themselves — do not treat the dynamic range of conditions and important parameters present in a real cabin fire. Therefore, over the last 5 years, the Federal Aviation Administration (FAA) has placed increasingly more emphasis on large-scale and full-scale fire tests and on fire modeling to understand and demonstrate the behaviour of cabin materials in a postcrash fuel-fed fire.

Aircraft accident investigations, in most instances, do not furnish the detailed information required to identify the primary physical factors contributing to those fatalities resulting from fire. This lack of information is due, in part, to the infrequent occurrence of aircraft accidents and the usual destruction of evidence by the fire, but, more importantly, to the complex nature of the fire dynamics and hazards ultimately responsible for preventing escape by passengers and crewmembers.

Therefore, although the outcome of an accident investigation may suggest the existence of a design deficiency leading to fire fatalities in a particular case, some form of controlled and well-instrumented experimentation is needed to validate the conclusions reached and the benefits of proposed improvements. The type of testing which is most convincing is that which most closely replicates the actual fire environment and aircraft geometry configuration — *i.e.*, what has been termed a full-scale test.

A number of organizations, including the U.S. National Transportation Safety Board (NTSB), which has the responsibility for investigating civil aviation accidents in the United States, have analyzed the incidence of aircraft accidents accompanied by fire. A study of NTSB for the period 1965-1974 estimated that 15 per cent of all fatalities in U.S. air carrier accidents were attributable to the effects of fire. In all instances, the cause of the fire was the result of aircraft crash impact with the ground. Moreover, in most cases, the fire originated from the ignition of jet fuel released from fuel tanks damaged by the crash impact.

A much smaller number of fatal accidents have occurred in U.S. manufactured aircraft operated by foreign carriers as a result of accidental fire erupting inside the fuselage while the aircraft was in-flight. These in-flight fatal fires consist of a Varig B-707 in 1974, a Pakistani B-707 in 1979, and a Saudia L-1011 in 1980, combining for a total of over 500 fatalities. As a consequence of the two more recent accidents, particularly the Saudia L-1011 which resulted in 301 fire fatalities, more emphasis is now being placed within the FAA's Cabin Fire Safety Programme on in-flight fire problems.

Factors in postcrash fatalities

It is generally agreed that ignition of jet fuel represents the greatest potential danger in aircraft crash accidents. No other conclusion seems possible when one considers that jet fuel is extremely flammable and is carried in large quantities in modern jet transports — *e.g.*, the fuel tanks capacity of an L-1011 is 23,000 gallons.

In accidents where large quantities of fuel are released and ignited, and where the integrity of the fuselage is damaged to a degree that enables major portions of the cabin to be directly subjected to the fuel fire, the dominance of the fuel fire is clear. However, accidents do occur with relatively small quantities of fuel spillage, or none at all, and with the fuselage primarily intact, that result in a cabin fire leading to fire fatalities. These accidents are part of a classification of accidents defined as survivable — those accidents in which one or more of the occupants survive the impact. In an FAA study for the period 1964 to 1974, it was estimated that 39 per cent of the fatalities were attributable to fire in survivable accidents.

It is difficult, if not impossible, to assess the role of a particular interior material, or materials, in general, on the number of fatalities in crash accidents accompanied by fire. Numerous factors are known to affect the behaviour of a material in a fire; however, the present status of fire technology does not allow for the prediction of the combined effect of each factor on the overall threat to cabin occupants under a given fire condition. Nevertheless, there does exist both direct and indirect data of the importance of interior materials on survivability during a postcrash cabin fire.

Of a direct nature, is the measurement of high levels of blood cyanide in some accident victims. These measurements have been incorporated into U.S. accident investigations since 1970. However, the relationship between cyanide levels in blood samples taken from accident victims to the concentration of cyanide to which the victim was exposed to during the fire has been questioned.

Another form of direct data is the fact that although most crash accidents are accompanied by fuel spillage, several fatal accidents have occurred with insignificant or no fuel release. For example, at Salt Lake City in 1965, a 727 crashed and caught on fire as the result of a severed fuel line beneath the cabin floor. The initial fire consisting of a relatively small quantity of spilled fuel was probably not life threatening in itself, but was of sufficient intensity to ignite the cabin interior, which resulted in 43 fatalities. More recently, a B-747 crashed in Seoul, Korea, in 1980, without any fuel spillage, yet the ensuing fire killed 15 people.

More of an indirect nature of data is the recognition that an aircraft cabin is an enclosure with limited egress, high loading of plastic and synthetic interior materials, and high occupancy density. Past large-scale tests conducted in the United States on simulated cabin interiors or mockups have demonstrated that hazardous and fatal conditions will arise from ignition of interior materials with the development of a self-sustaining fire.

In the laboratory, a wide range of heat, smoke and toxic gas levels has been measured during testing of in-service materials subjected to intense fire exposure. These test data gathered under specific and, perhaps, not completely realistic conditions indicate the potential dangers of burning interior materials.

Complexity of cabin design is one of the many factors that make it difficult to determine the importance of interior materials on postcrash cabin fire survivability. The cabin interior is completely lined with multi-layered materials and furnished with hundreds of seats. Each component is selected with due consideration given to fire safety, functionality, durability, processability, cleanability, economics, and, of increasing importance, weight.

Current FAA regulations specify that all major components "self-extinguish" after a prescribed exposure to a small flame. Moreover, at their own initiative, the airframe manufacturers strive to select materials with low-smoke emissions and low-flame spread rate. One manufacturer also screens materials for emissions of specified toxic gases.

Despite apparent differences in design goals and philosophy, the cabin materials used by the three major U.S. airframe manufacturers are very similar. The composite panels which constitute the bulk of the sidewalls, stowage bins, ceilings and partitions are basically composed of a Nomex (aramid) honeycomb core with glass-fibre facings impregnated with epoxy or phenolic resin and a decorative laminate composed of Tedlar (polyvinyl fluoride) layers or Tedlar and polyvinyl chloride layers.

A greater variety of materials are used for floor coverings and seat cushions, which are selected by the airlines, but are typically wool pile carpet and cushioning composed of flame retardant (FR) urethane with a wool (90 per cent) / nylon (10 per cent) upholstery cover.

A full-scale test configuration should include, at least, the major cabin usage categories — *i.e.*, carpet, seats, sidewall panels, stowage bins and ceiling panels.

Why full-scale tests?

From a practical necessity, aircraft materials are and should be selected based on the results of small-scale fire tests. However, it is generally recognized that small-scale test results do not reflect the behaviour of a material in its end-use application under realistic fire conditions.

Therefore, until more realistic and meanigful small-scale tests are developed, the FAA, as well as many other organizations engaged in fire testing, is relying more heavily on large-scale tests and, to a much lesser degree, full-scale tests for materials evaluation. Full-scale tests are usually performed for more far-reaching reasons — namely, to define the nature of a perceived fire problem, identify governing parameters, bracket fire conditions, examine the relevency of small-scale test results, and demonstrate the benefit of improved material or fire management systems.

In the past, the number of fire tests consisting of exposure of a realistically-furnished cabin test article to a fuel fire has been small. Each of these tests programmes was deficient in one or more of the following:

- instrumentation incomplete or improper (*e.g.*, absence of smoke measurements or test animals, improper sampling of reactive acid gases);
- the test article not fully protected to allow for multiple tests, causing the results to be inconclusive or unconvincing;
- the fuel fire unrealistic in terms of size (too small) and position (placement was inside the fuselage), exaggerating the contribution of fuel-fire smoke to the cabin environment and subjecting the interior materials to unrepresentative low levels of radiant heat;
- ineffective precautions taken to negate the effect of random ambient wind, which has a pronounced and sometimes dominant effect on external fuel fire penetration through a fuselage opening, thus the effect of the fuel fire with regard to heat exposure of the interior and its contribution to cabin hazard levels was not identical from test to test; and
- protection of the test article interior with sheet metal probably created higher wall heat losses than would have been encountered with a real interior, thus the wall losses could have far exceeded the levels measured in enclosure fires (*i.e.*, 50-95 per cent of the total energy released by the fire).

None of the test articles simulated a wide-body cabin. In the development of the cabin fire test article described herein, an attempt has been made to rectify the problems enumerated above.

The FAA convened the Special Aviation Fire and Explosion Reduction (SAFER) Advisory Committee to "examine the factors effecting the ability of aircraft cabin occupants to survive in the postcrash environment and the range of solutions available." The Committee approved the objectives set forth by FAA in its programme plan for full-scale cabin fire testing. After examination of the contemporary makeup of aircraft cabin interiors, the Committee concluded that a near-term solution was available to protect or replace the FR urethane used in seat cushions, which was believed to be the most flammable of all the interior materials used in large quantities.

Cushions represent another problem. Although the potential flammability of flexible urethane foam has been recognized for 10 years, it has only been until the last several years that more fire-safe and practical alternatives have emerged. While neoprene foam has always possessed excellent flame resistance, earlier formulations were extremely smokey and heavy.

The development of LS-200 represented a marked improvement in neoprene technology, by reducing smoke emissions and weight and improving physical properties. Nevertheless, the reduction of neoprene foam density to the 112-128 kg/m^3 range was still prohibitively high for the aviation market. To retain the cushion properties of urethane without the weight penalty of a full neoprene cushion, the concept of a fire-blocking layer encasement was developed.

By design, the blocking layer encasement inhibits or prevents the fire involvement of the flammable urethane foam underneath. A commercial foam fire blocking layer was developed in the mid-1970s and given the trade name Vonar. Extensively evaluated by FAA and others, Vonar is a thin neoprene foam layer that is heavily treated with flame retardants (approximately 40 per cent by weight).

A number of mechanisms contribute to

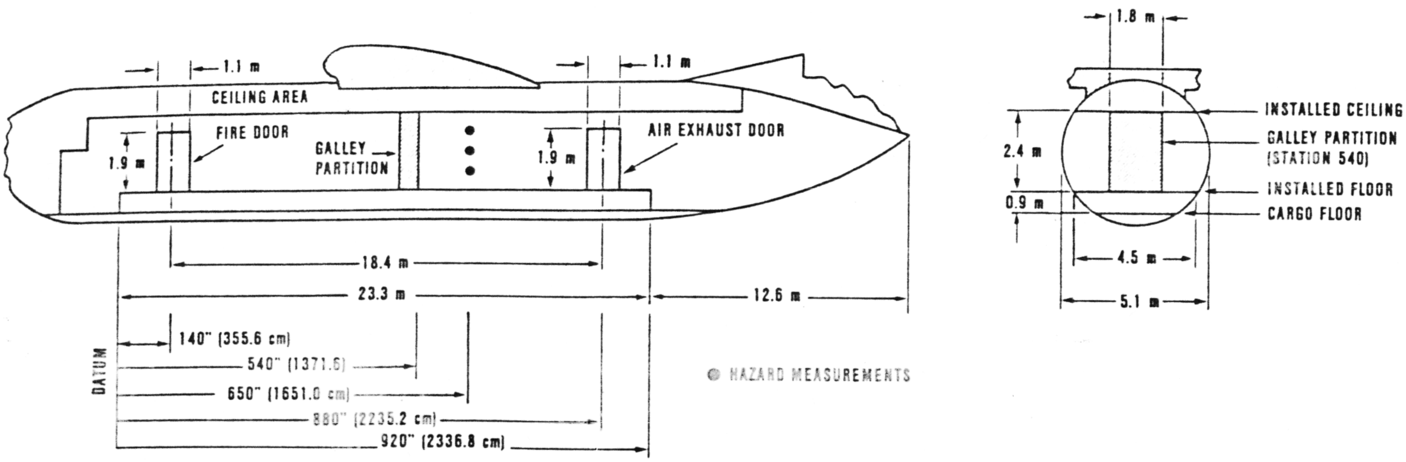


Figure 1. Layout and dimensions of C-133 wide-body cabin fire-test article.

its fire-blocking behaviour, but, most important, is the formation of a stabile and strong char when it is exposed to heat or flame. The insulative properties of the char, of course, significantly reduce the rate of heat transfer to the urethane foam sublayer.

Although Vonar had been demonstrated to be highly effective against moderate ignition sources, such as newspaper or wastebasket fires, or fires likely to occur in rapid transit vehicles, the FAA test programme was the first to subject the material realistically to the intense radiant heat produced by a large fuel fire.

Design of test article

The survivable postcrash fire scenario selected for study consisted of an intact fuselage with open doors, as might exist during evacuation, and an external fuel fire adjacent to an opening. Selection of the scenario was based on creating a realistic postcrash condition with an external fuel fire rather than a fuel fire within the cabin, which is an easier test to perform but is less realistic. Moreover, it was believed that placement of the fire outside the fuselage would more properly balance the cabin hazards from the fuel fire and burning interior materials. Another important aspect was to develop a test fire that would recreate the intense radiant heat produced by a large fuel spill fire.

(An accident occurred after the fire scenario was conceived which was a near duplicate, attesting to the realism of the scenario.)

The full-scale test article was a modified surplus C-133 aircraft. The important dimensions and overall layout are shown in Figure 1. The cross-sectional area is similar to, although slightly smaller than, a wide-body jet cabin. An interior volume of 374 m^3 is representative of a wide-body jet.

The test article was designed for fire durability to allow for the conduct of numerous tests. This was accomplished by stripping the interior of all combustibles, lining the inside surfaces with non-combustible ceramic and bonded glass fibre materials, and installing a CO$_2$ total-flooding fire protection system. It was believed that the ceramic glass fibre materials provided for more realistic wall heat transfer than sheet metal. The test article has withstood approximately 150 tests, although on several occasions extensive repairs had to be made.

The opening adjacent to the fire was a wide-body type-A door opening. However, the opening was treated as a rupture rather than a door (*i.e.*, seats are placed in the opening). This size opening was selected because descriptive information on fuselage rupture size from actual accidents was found to be lacking.

A full-scale fire test facility houses the test article. A specially designed ceiling allows for the setting of large fuel fires inside the test bay. The facility provides an environment that is basically isolated from fluctuating ambient winds, which can destroy test repeatability and make test results analysis very difficult, and allows for testing throughout the year under all weather conditions. A large fan can simulate a range of wind speeds at the fire door, providing the flexibility of varying, as desired, the degree of fuel-fire flame penetration into the cabin.

The C-133 test article is extensively instrumented to measure the major hazards produced by a cabin fire at various cabin locations as a function of time. The most extensive measurement is that of air temperature; a series of thermocouple poles on the fuselage center line is located throughout the cabin. Gardon gage-type calorimeters, primarily clustered around the fire door, measure the radiant and convective heat flux from the jet fuel fire and ensuing cabin fire.

Smoke density is measured by light transmissometers, consisting essentially of a light source and photoelectric cell receiver.

Gas concentrations are measured by continuous analyzers and from post-test analysis of batch samples taken at regular intervals during the test. The gases analyzed continuously at four cabin locations include carbon dioxide (CO$_2$), carbon monoxide (CO) and oxygen (O$_2$). The remaining gases analyzed from batch samples consist of two classes: acid gases, such as hydrogen fluoride (HF) or hydrogen chloride (HCl), and organic gases, like hydrogen cyanide (HCN).

The acid gases, particularly HF and HCl, are analyzed by ion chromatography of samples collected on Tenax tubes.

Exclusive of the gases analyzed from batch samples, the cabin hazard measurements are recorded on a computer data acquisition system, converted into engineering units and plotted after completion of a test. Cabin fire growth is monitored during a test by video coverage. Colour-photography documentation includes 35-mm sequential photographs at 5-second intervals, and 16-mm movies.

Fuel fire test conditions

Since the quantities of jet fuel potentially involved in a postcrash fire are enormous, the realism of past full-scale fire tests utilizing small amounts of fuel was questionable. An important design goal for the C-133 test article was to derive a test fuel fire of intensity representative of a large fuel fire.

Past studies of the burning behaviour of pool fires indicated the dominance of thermal radiation, as compared to convection, for pool fires above 1 metre (3 feet) in diameter; radiation was relatively invariant at approximately 14 British Thermal Units per square foot per second (Btu / ft^2-sec). Of concern, however, was the amount of radiation into a cabin interior from a large fuel fire adjacent to a type A door opening. Therefore, a study

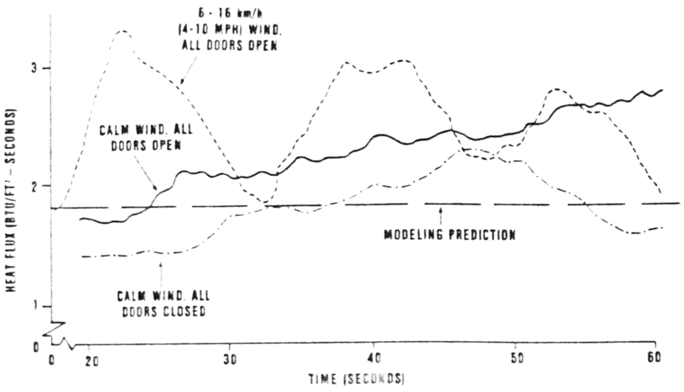


Figure 2. DC-7 symmetry plane heat flux.

was performed using models of the C-133 test article of various diameters, subjected to a fuel fire of width equal to or greater than the model diameter. The study was performed indoors to eliminate wind as a factor.

It was determined that the radiant heat flux on the fuselage symmetry plane at the fire door station at an elevation of one half the door height was 1.8 Btu / ft^2-sec for an infinite fire and zero wind conditions. In addition to establishing a design goal for the C-133 test fire, the model tests in conjunction with a mathematical analysis of the radiant field inside the fuselage, demonstrated the presence of severe radiant heat gradients within the fuselage enclosure. Thus, it became evident that, during its initial stages, an interior fire would be highly localized, and that at relatively small distances away from the fire the radiant heat flux would be virtually zero.

To validate the above modeling results, a surplus DC-7 aircraft with a fuselage opening scaled to the C-133 opening was subjected to a 30-foot-square pool fire. Figure 2 contains a comparison of the symmetry plane heat flux measured during three tests with the modeling value of 1.8 Btu / ft^2-sec.

As shown, a reasonable agreement was achieved between the two tests performed under calm wind conditions and the modeling prediction for zero wind. With a wind fluctuating from 6-16 kilometres per hour (4-10 mph), the measured radiant heat flux undulated above the modeling prediction because of the intermittent penetration of flames into the cabin caused by the winds. The increase in radiation is due both to the larger flame surface emitting heat and the smaller distance between the flame surface and measuring calorimeter.

In the C-133 test article, the fuel pan was located at the bottom edge of the opening, rather than on the ground, to best assure that a solid flame surface would cover the entire opening, as would result from a large ground fire. Initial tests with a 1.2-m-square (4-ft-square) pan, which was slightly wider than the opening, proved that this pan size was inadequate due to incomplete flame coverage over the opening, resulting from "necking" of the fuel fire. Subsequent tests were performed with progressively larger pan sizes, and adequacy of the pan size was rated in terms of the completeness of flame coverage over the opening and closeness of the cabin symmetry plane radiation to the modeling prediction for an infinite fire.

A pan that was 2.4 x 3m (8 x 10 ft) completely covered the opening with flames and produced a symmetry plane heat flux of 1.5 Btu / ft^2-sec. Although this pan size produced radiation at the symmetry plane which was slightly less than the level expected from an infinite fuel fire, it was obviously representative of a large fuel fire and was thus selected for the "stan-

feared that a larger fuel fire might jeopardize the safety of the facility housing the test article or, perhaps, cause the early destruction of the test article itself.

In a typical fire test, 50 gallons of fuel are placed in the fuel pan atop a water base to assure uniform fuel depth throughout the pan. This fuel quantity assures an unwavering fire for at least 4$^1/_2$ minutes, which is the usual test duration.

A protective covering of steel sheeting over a fibrous ceramic matting prevents melting of the C-133 aluminium fuselage skin adjacent to the fuel fire. This protective measure, which provides an opening of unchanging area for fuel fire penetration into the interior, does not detract from the realism of the test article.

During an actual wide-body accident, a major fuel fire burned for an estimated 2-3 minutes, before extinguishment, without fuel fire penetration into the cabin. Therefore, for a wide-body aircraft exposed to a major fuel fire for 3-4 minutes, it is likely that the fuel fire hazards passing through an initial opening will far exceed the increase in hazards as the opening enlarges.

Cabin hazards created by fuel

To understand the role of interior materials in a cabin fire arising from an external fuel fire, it is necessary to first examine the effects of the fuel fire alone. This was accomplished by setting a large series of fuel-fire tests with the C-133 interior completely devoid of interior materials. The tests were performed outdoors with the test article configuration shown in Figure 1 and the primary variables were ambient wind velocity (uncontrolled) and fuel-fire size.

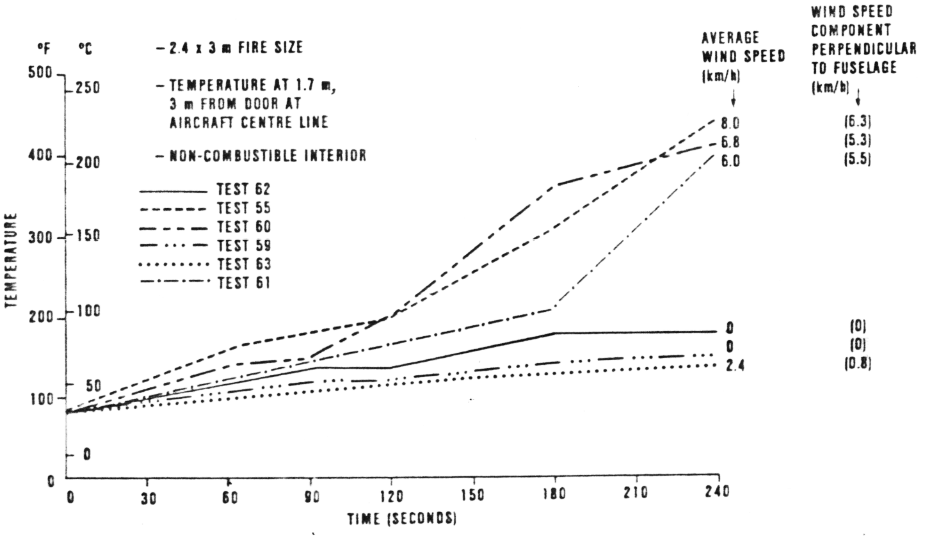
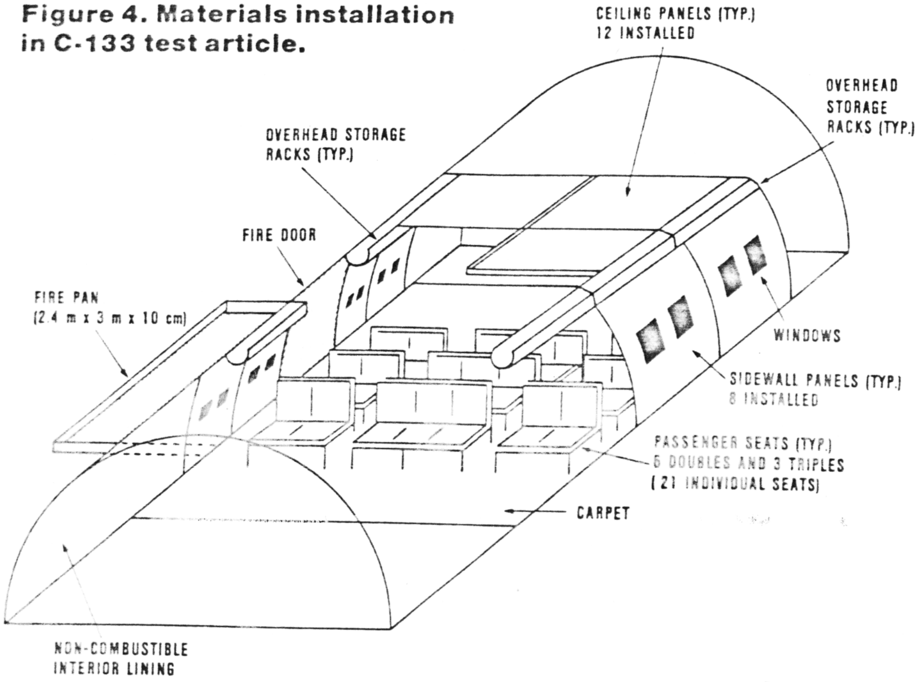


Figure 3. Effects of wind speeds on cabin temperature with fuselage downwind of fire.

Figure 4. Materials installation in C-133 test article.



To examine the wind conditions of interest, which were winds of a relatively low speed (0-8 km/h) and in a direction to cause flame penetration into the interior, tests were run in the early morning when weather conditions were favourable.

Wind conditions were found to have a dominant effect on the rate of hazard development inside the cabin. This conclusion was also reached in related studies where the effect of door opening locations away from the fire, relative to the wind direction, were also found to be an important factor. The effect of wind speed on cabin temperature is shown in Figure 3 when the C-133 test article was subjected to a 2.4 x 3-m fire upwind of the fuselage.

Except for the low wind test (2.4 km/h), the trend for the most part was to have higher cabin temperatures as the wind speed increased. The principal implications of this finding are twofold: (1) for a specific aircraft/fuel-spill crash configuration, the cabin hazards caused by burning fuel vis-à-vis burning interior materials are highly dependent on ambient wind and cabin draft conditions; and (2) for the C-133 test configuration, the degree of fuel flame penetration into the cabin, and the resultant fire exposure of interior materials near the fire opening, can be adjusted over a wide range of values by utilizing an artificial wind (fan).

The small increase in cabin temperature shown in Figure 3 under zero wind is the result of a significant portion of the fuel fire products, entering the cabin, becoming entrained back into the fire. The insignificant temperature rise for the zero wind case is also indicative of the results when the fuel fire is downstream of the fuselage — *i.e.*, minimal cabin hazard accumulation even though the radiation into the cabin is intense.

The relationship between convective heating (and smoke and gas accumulation) within the cabin and radiative heating for a given wind speed was found to be dependent on fuel-fire size. Because flame bending increases with decreasing fire size for a given wind speed, a small fire size (*e.g.*, 1.2 x 1.8 m) will create greater heat and smoke accumulation inside the cabin but less radiative heating than a larger fire size (*e.g.*, 2.4 x 3 m).

Beginning with this experimental finding, the subsequent discussion is an analysis of the possible ramifications of the utilization of small fuel pan fires in full-scale tests. Since the amount of heat and smoke produced by interior materials increases with the level of radiation, rather than of convection inside the cabin, the proportion of heat and smoke accumulation inside the cabin from burning fuel vis-à-vis burning interior materials is greater for smaller fuel fires.

Thus, the use of unrealistically small fuel fires for test purposes because of their ease of handling may produce misleading results. A small fuel fire will create higher cabin hazards from the fuel fire than might exist from larger fires, but will not cause the interior materials to burn as extensively as might a larger fire.

Tests performed with the C-133 test article devoid of interior materials indicated the prominence of certain cabin hazards over others when the fuel fire is the dominant threat. In tests with significant flame penetration into the cabin, elevated temperature exceeded human tolerance limits and smoke obscured visibility; however, CO concentrations were extremely low and clearly nonhazardous.

Since high levels of carboxyhemoglobin are often measured in blood samples taken from aircraft fire victimes, in light of the C-133 test results, and without consideration of other scenarios, it appears as if this finding cannot be explained in terms of a dominant fuel fire. The source of high levels of carboxyhemoglobin in some fire accident victims may have been CO produced by burning interior materials.

Hazards from interior materials

To study and measure the full-scale hazard of cabin interior materials subjected to an external fuel fire, a section of the C-133 test article, centred at the opening adjacent to the fuel pan, was lined and furnished with wide-body type materials. Samples of the various materials were tested and determined to be, as required, compliant with FAA flammability regulations prescribed in Federal Aviation Regulation (FAR) 25.853. As shown in the cutaway isometric drawing in Figure 4, the materials were arranged in a realistic fashion.

The following summarizes the materials' loading: (1) 12 flat, honeycomb composite panels, each 1.2 x 1.8 m, comprised a 7.3-m-long drop ceiling; (2) 6 lengths of honeycomb composite overhead stowage bins were mounted on both sides of the cabin; (3) 8 contoured honeycomb composite sidewall panels with window reveals, each 1 x 1.7 m, were fastened to the insulated inner fuselage; (4) a total of 21 seats, including 6 doubles and 3 triples, composed of wool (90 per cent)/nylon (10 per cent) upholstery covers and FR urethane cushions, were arranged into 3 rows to form a dual aisle interior; and (5) a wool (100 per cent) pile carpet was placed over the aluminium-faced cabin floor. The ceiling panels and carpet were new, while the sidewall panels, stowage bins, and seats were obtained from refurbished wide-body aircraft.

The materials were subjected to a zero wind fuel fire. This condition was selected because the cabin hazards solely arising from the fuel fire would be minimal and clearly survivable as shown in previous test (see Figure 3). In this manner, the cabin hazards with materials installed in the test article would be unmistakably produced by the burning materials and not by the fuel fire.

A revealing account of the fire growth inside the cabin was obtained from the colour photographic coverage, including 35-mm motorized stills and 16-mm movies. Examination of these films demonstrated that for approximately 2 minutes, the cabin fire was limited to the area in the immediate vicinity of the fuselage opening adjacent to the fuel fire.

The outboard double seat at the fire opening was almost completely engulfed in flames, as was the back of the outboard seat forward of the opening and the front of the seat behind. Fire had not progressed to the triple seats comprising the centre section, although some smouldering was evident. Also in evidence was intermittent flashing in the smoke layer under the ceiling by the opening.

Although the heavy smoke obscured the upper cabin, the high temperatures recorded in this area and the existence of flashes indicated that ceiling and stowage bins near the opening were pyrolyzing and, perhaps, burning. At approximately 2 minutes, within a matter of 10 seconds or less, the remaining interior materials were suddenly set aflame or underwent pyrolysis. This event has been observed in many types of enclosure fire tests and has been given the name "flashover."

The major hazards produced by the cabin fire, aft of the galley partition, are shown plotted as a function of time in Figure 5. The survivability is of interest in this section of the cabin because (1) the evacuation process is usually in a direction away from the fire origin and (2) in some past accidents victims have been found clustered near exits.

The occurrence of flashover indicates that conditions throughout the cabin will become nonsurvivable within a matter of seconds. Of concern, thus, is whether any of the preflashover hazards were at a level to impair or prevent escape.

An examination of Figure 5 indicates that the acid gases HF and HCl accumulated in the aft cabin at least one minute before any of the remaining hazards. These gases were produced by the burning honeycomb composite panels which comprise the ceiling, stowage bins, and hatrack. The somewhat similar shape of the curves is a clue that the two gases emanated from the same source.

Moreover, a past study of thermal degradation products from aircraft materials indicated that HF and HCl, the latter in higher yields, are produced by some panels. The source of HF was the 3-mil Tedlar polyvinyl fluoride decorative film which covers the panels. The source of HCl is probably the flame retardants used in the epoxy resin which impregnates the fibre glass facings and adheres the panel components together. Another source of HCl was the polyvinylchloride (PVC) seat components (armrest covers, side panels) and those components containing chlorinated fire retardants (cushions).

It appears as if the initial gas peak was caused by the rapid thermal degradation of the decorative film and fibre glass facing resulting from the intense radiant heat from the fuel fire at the beginning of the test. The second gas peak was caused by the rapid fire involvement associated with flashover of all the interior materials.

The early concentrations of acid gases [*e.g.*, 300 parts per million (ppm) and 140 ppm for HCl and HF, respectively, at 60 seconds] are considered to be significant levels. Composite panel lining materials — the source of these gases — are important potential contributors to cabin fire hazards because of their large surface area and, in many cases, vulnerable location in the upper cabin area.

Elevated temperature, smoke and HCN were the remaining hazards detected before the onset of flashover. Flaming conditions during a postcrash cabin fire, as opposed to a smouldering fire, make the presence of high temperatures to be expected. More unexpected was the low concentration of HCN, considering that wool is used for seat upholstery and carpet, and that wool produces high yields of HCN, approximately 40 milligrams per gram (mg/g), when pyrolyzed oxidatively.

A number of explanations for the low HCN concentrations are plausible, in-

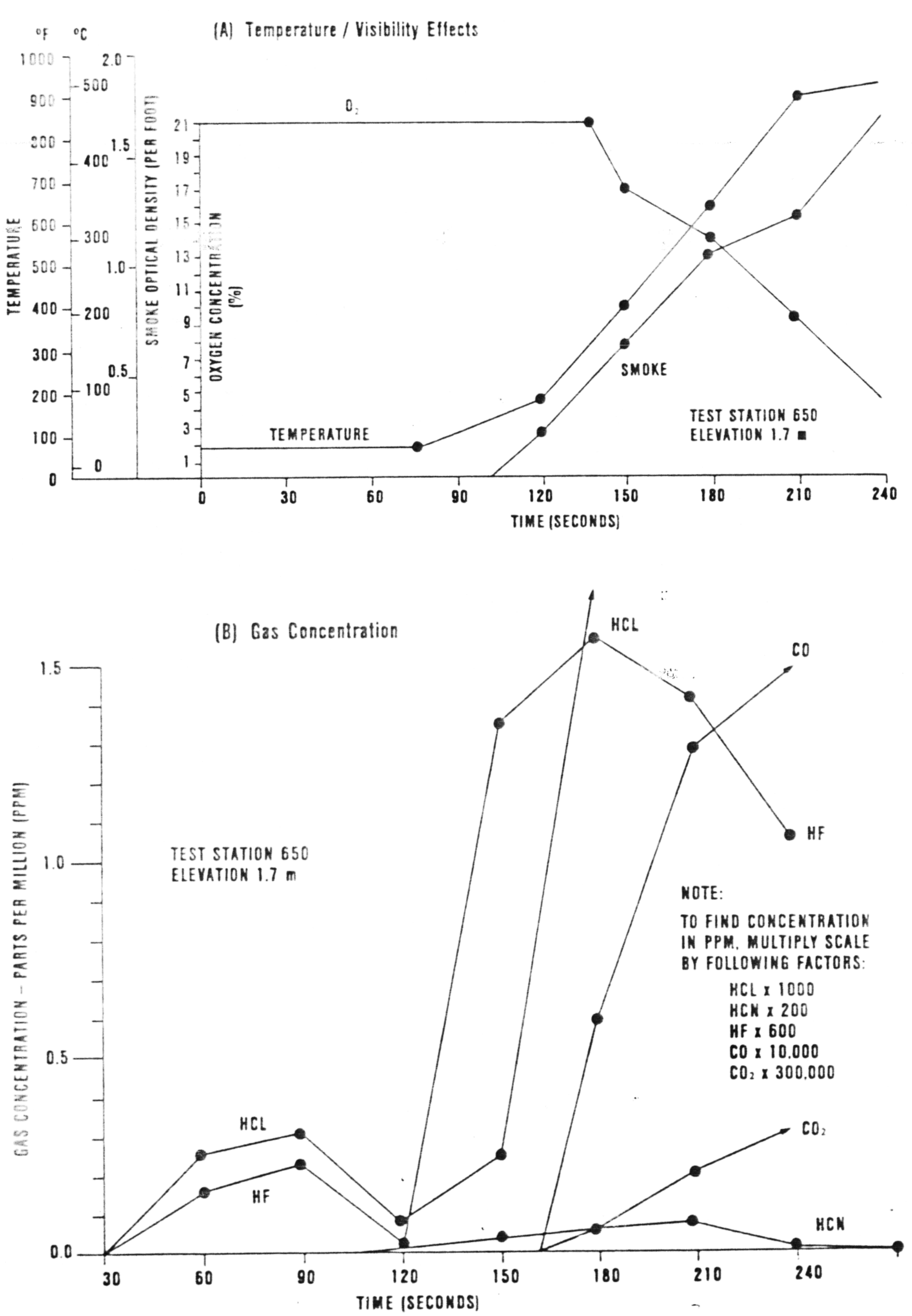


Figure 5. Aft cabin hazards resulting from burning interior materials.

cluding (1) burning of the HCN during flashover, (2) because of the prominence of flaming, production of nitrogen oxides by the wool rather than HCN, or (3) insufficient fire involvement of the wool due to relatively low loading and to location in the lower cabin. An interesting result was the late detection of smoke at approximately 100 seconds, in contrast to HF and HCl which were detected much earlier into the test.

To assess the relative importance of each cabin fire hazard, a hypothetical human survival model was formulated. Its main purpose is to provide a means of predicting the time- of-incapacitation within a fire enclosure, based on measurement of elevated temperature and toxic gases concentrations which change, in some cases substantially, with time. Thus, it is a tool for reducing a fairly large number of somewhat abstract measurements into a single, cogent parameter: time-of-incapacitation, or the hypothetical time at which an individual can no longer escape from a fire environment.

How well the model relates to actual escape potential is unknown and, realistically, cannot be determined. It is known that segments of the model are deficient for lack of available information. For example, no data exists on the effect of irritant gases (*e.g.*, HCl, HF) on acute human escape potential. (FAA has sponsored new research at Southwest Research Institute to determine "the threshold concentration for escape impairment by irritant gases (HCl and acrolein, initially) using a nonhuman primate model and a relevant behavioural task that can be extrapolated to man.")

Thus, the HCl and HF incapacitation doses utilized in the model are simply based upon extrapolation from threshold limit values (TLV's) for an 8-hour work environment. Confidence in the model is greater for the prediction of the relative escape time between tests on different material systems than on the prediction of absolute escape times.

The human survival model was applied to predict the survivability in the aft cabin based on the hazard measurements taken at the location plotted in Figure 5. As shown in Figure 6, the hypothetical survival time was 159 seconds when wide-body materials were installed in the cabin. Conversely, when no materials were installed in the cabin, corresponding to an idealistic and unrealistic completely non-combustible interior, there was no detectable loss in survivability.

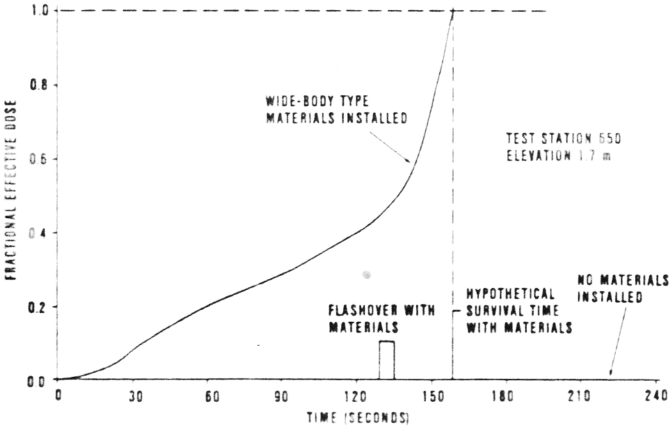
The slope of the survival curve with wide-body materials installed in the cabin increased drastically shortly after the flashover because of the rapid increase in hazards caused by the flashover. Until this test time, the survival curve was entirely driven by HF and HCl. As discussed earlier, the incapacitation doses of these irritant gases are unknown and the values used in the survival model are calculated estimates. If one ignores the hazards of HF and HCl, the survival curve becomes driven primarily by temperature and, to a lesser degree, CO.

Also, the fractional effective dose will not increase above zero until 135 seconds, and will exhibit a much steeper slope than when the irritant gases are included.

Four of the six hazards considered in the model eventually exceeded their incapacitation dose, as follows: temperature at 180 seconds, HF at 210 seconds, CO at 237 seconds, and HCl at 248 seconds. The fractional effective doses of the remaining hazards, CO_2 and HCN, were comparatively insignificant (0.2 and 0.04 at 240 seconds, respectively).

It has long been recognized that a margin of safety exists near the floor inside an enclosure fire. The wisdom of this advice was examined by measuring the major hazards at three elevations at test station 650 and calculating the survival time at each elevation. These survival curves are plotted in Figure 7(a) and verify that survivability is possible for a longer period, the closer one is to the floor. A 34-second improvement was calculated between 1.7 and 1.1 m (5.5 and 3.5 ft), but the improvement was only 9 seconds between 1.1 and 0.5 m (3.5 and 1.5 ft).

Figure 6. Hypothetical survival curve in aft cabin.



In Figure 7(b) the relative importance of each hazard at the calculated survival time is graphed. The irritant gases HF and HCl again drove the survivability calculation at all three elevations. Although a contributing factor at 1.7 m, heat (elevated temperature) became negligible at the two lower elevations. Instead, CO was found to be a more important factor although this is not adequately shown in Figure 7(b).

This is more apparent when the survivability calculation is extended beyond the survival time; within several minutes CO will become the dominant hazard at the two lower elevations. Thus, if it is assumed that the HCl and HF incapacitation doses utilized in the model are low, and, if they are raised (*i.e.*, the incapacitating effect of these irritant gases is made less potent in the model), the CO will be the dominant factor affecting incapacitation. Also, since CO is a more lethal agent than either HF or HCl, it may be argued that CO would be primarily responsible for any fatalities caused by inhalation of gases near the floor. It may also then be argued that a plausible scenario for demise of an individual during a cabin fire is incapacitation, while standing, from exposure to irritant gases and heat, and, after collapsing to the floor, death from CO asphyxiation.

The most striking feature of a cabin fire is the smoke layer which because of buoyancy appears to cling to the ceiling. Figure 8 is a graph of the vertical temperature profile at various test times at test station 270, which was the first thermocouple pole station aft of the last seat row. The inflection point in the temperature profile defines the smoke layer thickness.

Figure 8 illustrates that the cabin environment may be approximately described by two zones — a hot zone at the ceiling, which thickens as the fire progresses, with a linear temperature profile, and a much cooler zone in the lower cabin with a uniform, but above ambient, temperature. The temperature differential between the ceiling and lower cabin was very large — *e.g.*, at $2^1/_2$ minutes the differential was higher than 538°C (1000°F). This finding has a bearing on the relevance of small-scale tests (ceiling materials are exposed to higher convective heat fluxes than are carpets, for instance).

The existence of a hot zone also has a bearing on evacuation. For example, at a station only 3.6 m aft of the fire (Figure 8), conditions would be clearly survivable from convective thermal exposure, as late as 2 minutes (10 to 15 seconds before flashover), for an individual who crouches in order to avoid exposure to the

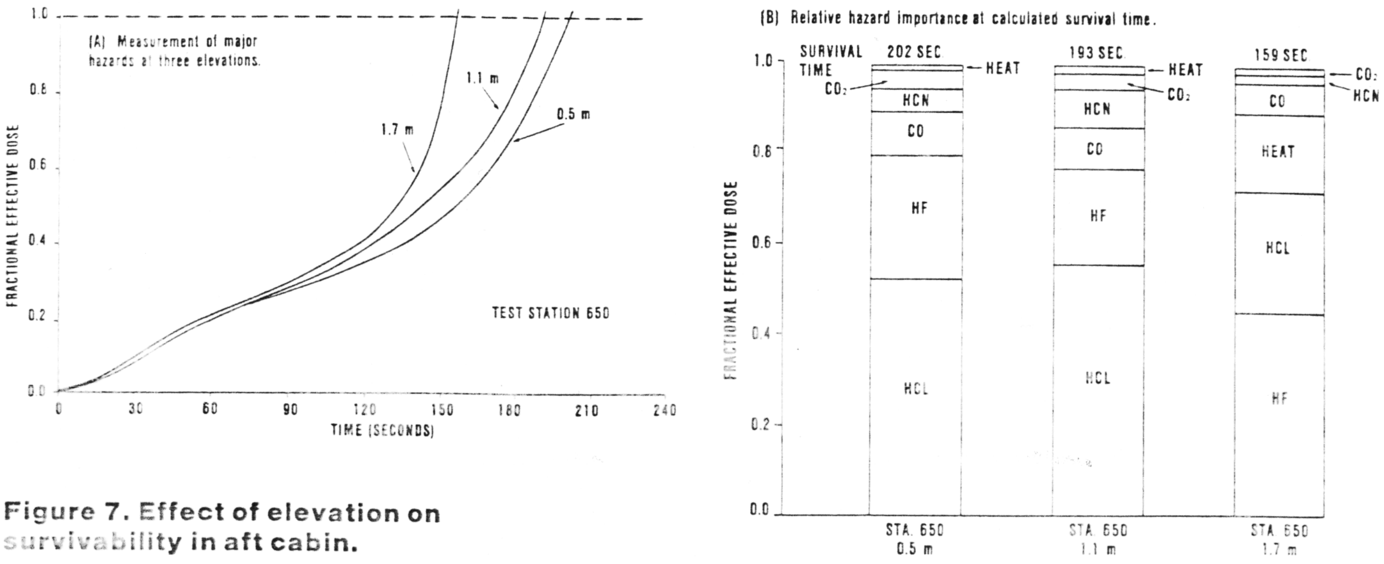


Figure 7. Effect of elevation on survivability in aft cabin.

hot smoke layer. Moreover, a hot, smoky layer can nullify the benefit of ceiling-mounted emergency lighting, possibly by causing thermal failure in the units, or by obscuring exit signs or blocking illumination.

The existence of large heat losses into the walls of an enclosure during a fire and the entrainment of lower zone cool air into the hot smoke layer creates corresponding losses in the heat content, or temperature, of the smoke layer gases as they are transported away from the fire origin. Figure 9 is a graph of the symmetry plane air temperature at the ceiling throughout the cabin at various times into the test.

Because of the aforementioned heat losses, the ceiling temperature decreased significantly with distance away from the fire. Although measurements near the fire were off-scale at 1800°F (980°C) after 2$^1/_2$ to 3 minutes into the test, because the thermocouples were not shielded from radiation these readings may be higher than the actual air temperature. The temperature profile at 2 minutes indicates that a large area of the ceiling was subjected to temperatures in excess of the thermal decomposition temperature of the composite panels, approximately 200 to 350°C, before the occurrence of flashover.

Examination of Figure 9 illustrates that the galley partition tended to confine much of the heat to the cabin section forward of the partition. A related observation has been made in accident aircraft where fire damage was more extensive on the fire origin side of a class divider than on the protective side. It is of interest to note that the ceiling temperature aft of the galley partition is more uniform than the ceiling temperature in the forward cabin. This apparent uniformity may have resulted from more active mixing in the smoke layer caused by the partition openings and by entrainment of fresh air through the exhaust door.

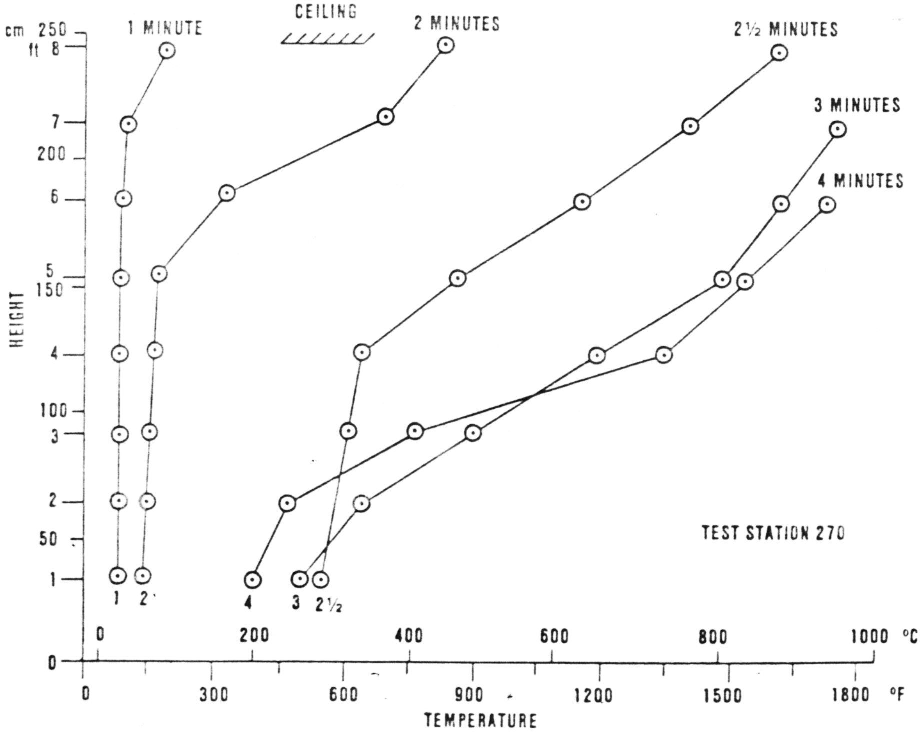


Figure 8. Heat stratification in forward cabin.

Evaluation of seat cushion layers

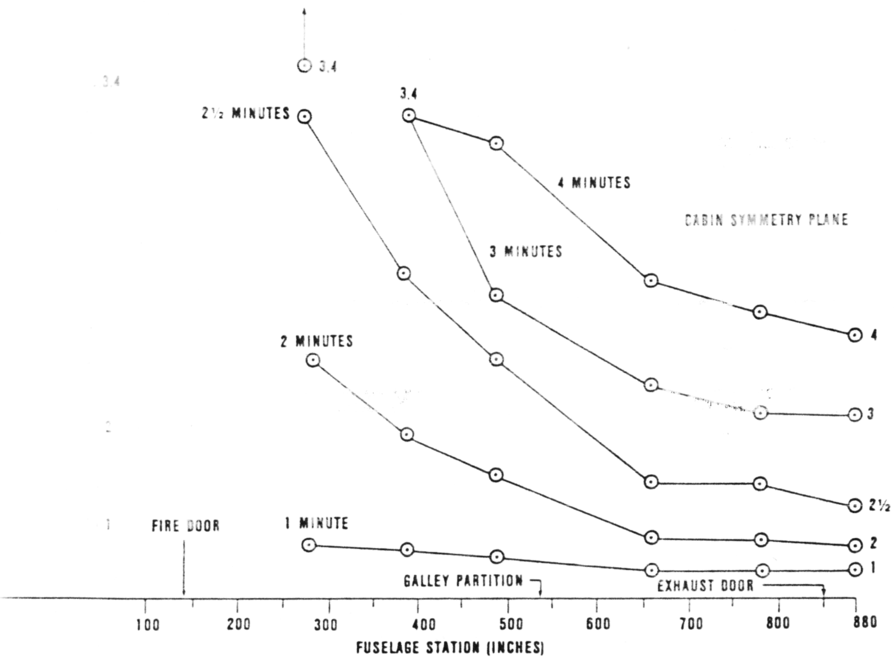
The C-133 test article was utilized to evaluate the effectiveness of aircraft seat cushion fireblocking layer materials. This work was undertaken in response to the SAFER Advisory Committee recommendation pertaining to cushioning fire blocking layers. Because of the high work priority, general interest in these materials and lack of data under postcrash fire exposure, the evaluation was performed under both large- and full-scale conditions to assure highest confidence in the test results.

Here, we will be limited to the initial work on foam blocking layers (Vonar and LS-200) to demonstrate the effectiveness of the concept. More recently, aluminized fabrics such as Preox and Norfab have exhibited promising fireblocking characteristics at less weight than the foams.

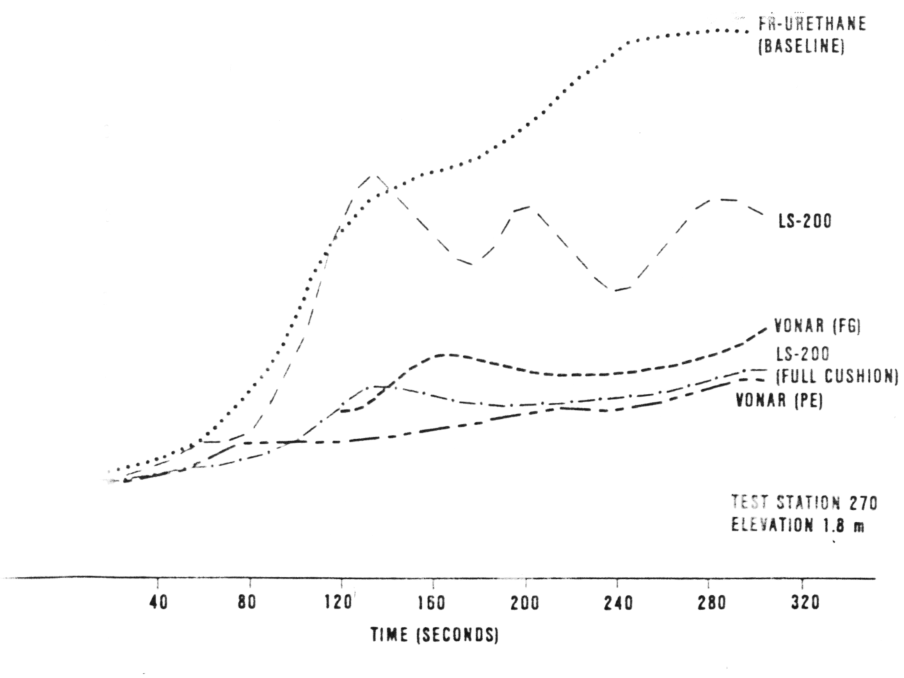
The fire blocking layer materials were evaluated at a number of seating conand test conditions, each with bjective. The bulk of the tests ormed on single or multiple sed to the fuel fire at the pening without any other in- rials installed in the cabin.

ries of tests was on double seat pported by a metal frame. In r, performance benefits pro- locking layers could be determined without contributions and possible confusion from the fire involvement of other materials.

Subsequent tests were performed on real seats to examine the benefit in the context of remaining seating materials. Multiple seats were evaluated to study the effect of blocking layers on seat-to-seat fire growth. To examine the effect of the primary test configuration (193 x 107-cm) opening, seat adjacent to opening, a series of tests were run with a smaller opening (61-cm square), and another series treating the opening as a doorway (with appropriate rearrangement of seating). Finally, tests were performed with a section of the cabin completely installed with interior materials in order to determine fire-blocking layer benefits under the most realistic conditions achievable.



. Longitudinal temperature profile at ceiling.



0. Blocking layer results on double seat cushioning on ame.

The forward cabin temperature history is plotted in Figure 10 for the initial test series on cushioning mounted on a double seat, metal frame. In this test, as throughout the programme, the seat upholstery fabric was a wool (90 per cent)/nylon (10 per cent) blend. The results were very encouraging in that each concept exhibited a significant improvement over the baseline cushion, FR urethane.

Two Vonar types, each 0.48-cm thick, were evaluated — polyester (PE) scrim and fibre glass (FG) scrim. Both Vonar materials produced results similar to the LS-200 full cushion, which is considered to be the premium flexible foam cushion in terms of fire safety. The Vonar results were considerably better than the results with LS-200 as a blocking layer (at double the thickness of Vonar). The superiority in fire performance of seat cushions protected with Vonar, as compared to unprotected cushions, was consistently demonstrated throughout the programme for each of the aforementioned series of tests.

What is the safety benefit of seat cushion fire blocking layers during a postcrash cabin fire within the context of the remaining interior materials? This question was answered by performing a test with a section of the C-133 test articles completely lined and furnished with interior materials (see Figure 4), and with the FR urethane cushions encased in Vonar PE blocking layers. The difference in survivability between the full-scale test with Vonar and the full-scale test with unprotected cushions was the safety benefit.

Figure 11 is a graph of the calculated fractional effective dose history for each of these tests. The calculation does not include the effect of HCl in any of the tests because of a malfunction in the analysis of HCl in the test with Vonar. The calculated safety benefit provided by Vonar was 60 seconds for the particular fire scenario that was simulated.

To compare the performance of Vonar protected cushions with the ultimate protection — noncombustible cushions — a full-scale test was conducted with the seat upholstery covers stuffed with Kaowool, ceramic fibrous insulation. Surprisingly, the increase in safety provided by the noncombustible cushions over that pro-

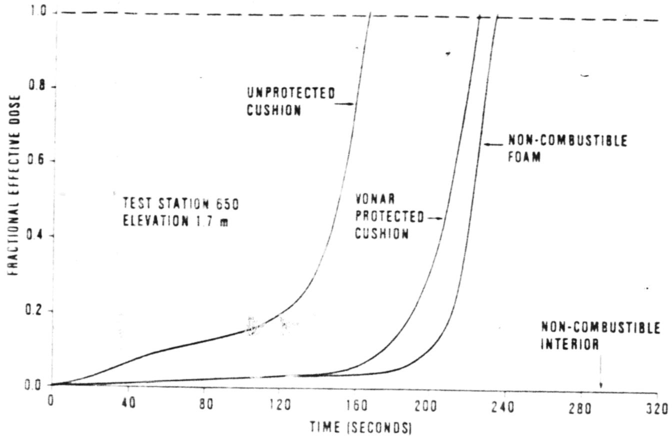


Figure 11. Effect of cushioning protection and materials on calculated survival time.

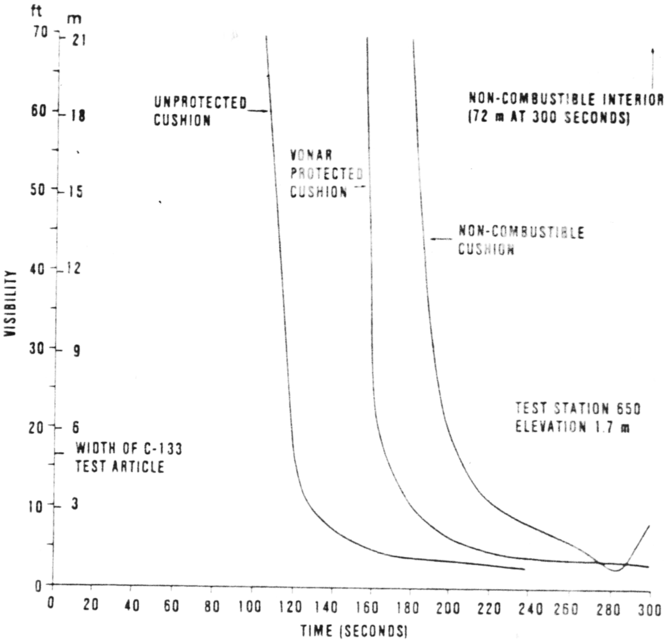


Figure 12. Effect of cushioning protection and materials on calculated visibility through smoke.

vided by the Vonar protected cushions was only 8 seconds. This comparison indicated that the fire protection offered by Vonar was nearly equivalent to a noncombustible cushion. Thus, if not a practical solution in itself, Vonar, by its excellent performance in full-scale fire tests, provided a lofty and achievable fire performance goal for seat cushion blocking layer materials under consideration for aircraft usage.

Figure 11 also indicates that, in the test conducted with a noncombustible interior, there was no detectable detriment to survival. Thus, major potential improvements in cabin fire safety may exist, beyond that provided by seat cushion blocking layers, from an upgrading of the fire performance of the remainder of the cabin interior (*e.g.*, ceiling panels, stowage bins, *etc.*). Whether there exists materials with enhanced fire performance, as well as acceptable functionality, durability, processability and weight, remains to be determined.

Smoke was not a component of the human survival model discussed earlier. Aside from possible physiological and psychological effects which are presently beyond mathematical description, the major impact of smoke is to obscure visibility and, thereby, increase the time required to evacuate an airplane. Thus, the net effect from the existence of dense smoke will be prolonged exposure of cabin occupants to fire hazards, which may ultimately cause incapacitation of some occupants before they are able to escape.

The most striking feature of the curves in Figure 12 is the rapidity by which visibility became obscured — *e.g.*, in some cases visibility was reduced from the length of the cabin to less than the width of the cabin in approximately 15 seconds. Also, by comparing Figures 11 and 12, it is apparent that smoke became an important factor well before survival was no longer theoretically possible. For example, visibility was reduced to less than the width of the test article at 30 to 60 seconds before the hypothetical survival time for each of the three full-scale tests with interior materials.

The ranking of results for visibility was identical to the rankings for hypothetical survival time, although the time increments between the curves were not equal. For example, the application of Vonar to aircraft seats increased the hypothetical survival time by 60 seconds (Figure 11), whereas the improvement in visibility from reduced smoke levels was 48 seconds (when visibility was reduced to the cabin width).

There are a number of planned projects with the C-133 test article, which are continuations of the initial work described herein, with the overall goal to better understand and characterize the role of cabin interior materials in postcrash cabin fire survivability.

Examination of the effect of fire scenario and material application (*e.g.*, ceiling panelling, sidewalls, carpeting, *etc.*) on cabin fire hazard development is planned. Also, advanced interior materials to be developed and identified by the U.S. National Aeronautics and Space Administration will be tested in realistic manner to determine if significant improvements in survivability can be realized. Finally, the C-133 test article will be utilized in a study designed to determine which small-scale test results give the best correlation with the hazards of burning interior materials during a postcrash cabin fire.

A considerable amount of work has been performed on seat cushion blocking layers beyond that described herein. Tests by the FAA have demonstrated that potentially destructive in-flight and ramp fires can be prevented by the application of cushion blocking layers.

Because the weight penalty of Vonar PE appears excessive, approximately 0.9-1.4 kg per seat, FAA has entered into an interagency agreement with NASA to develop effective lower weight blocking layer materials. An important finding under this agreement is the apparent effectiveness of aluminized fabrics encasing untreated urethane cushions, resulting in minimal, if any, weight penalty. FAA plans to evaluate this configuration under full-scale postcrash fire conditions in the C-133 test article. Tests completed by the FAA have demonstrated that untreated urethane cushions encased in an aluminized fabric are superior to unlayered FR urethane cushions when sujected to small ignition sources.

Other efforts under the interagency agreement include development of a cost/weight computer programme, evaluation of the durability of candidate blocking layer materials and large- and small-scale fire tests on candidate materials.

Finally, FAA, NASA, Boeing, Lockheed, and McDonnell Douglas are participating in a round-robin evaluation of their respective small-scale fire test methods for seat cushion blocking layers. Eleven material configurations are being evaluated in the round-robin test series as well as under large-scale fire test conditions.