Evaluation of Aircraft Interior Panels under Full-scale Cabin Fire Test Conditions

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ABSTRACT

Realistic full-scale fire tests demonstrated the potential safety benefits of
advanced interior panels in transport aircraft, and displayed the character-
istics of cabin fire hazards. The tests were conducted in a C-133 airplane,
modified to resemble a wide-body interior, under postcrash and in-flight fire
scenarios. The safety benefit of the advanced panel ranged from a 2-minute
delay in the onset of flashover when the cabin fire was initiated by a fuel
fire adjacent to a fuselage rupture, to the elimination of flashover when the
fuel fire was adjacent to a door opening or when an in-flight fire was started
from a seat drenched in gasoline. Analysis of the cabin hazards measured
during postcrash fire tests indicated that the greatest threat to passenger
survival was cabin flashover, and that toxic gases did not reach hazardous
levels unless flashover occurred.

INTRODUCTION

Objective

The primary objective of this paper is to describe the safety benefits of
advanced interior panels under realistic full-scale aircraft cabin fire test
conditions. A secondary objective is to characterize and analyze the hazards
affecting occupant survivability in cabin fires.

Background

Although the accident record of the airline industry is excellent, on rare
occasions accidents do occur with grave consequences. For the United States
(U.S.) airline industry, an average of 32 fatalities per year are attributable
to fire. [1] All of these fatalities have occurred in crash accidents which
are usually accompanied by the spillage and ignition of jet fuel. In spite of
the intensity and apparent dominance of a jet fuel fire, under certain acci-
dent conditions, the survivability of cabin occupants will be established by
the hazards of burnin interior materials. [2] The Federal Aviation Adminis-
tration (FAA) is supporting and conducting research, testing and development
to minimize the hazards of burning interior materials in the postcrash fire
environment. [3] Also, the in-flight fire problem is now receiving more

attention because of this type of accident experience with foreign carriers; e.g., Air Canada DC9 accident in Cincinnati. [4]

Improvements for two important types of cabin interior materials have been investigated — seat cushions and panels. Because of the flammable nature of urethane foam cushions, a fire blocking layer concept was developed that provides significant safety benefits for both postcrash and in-flight cabin fires. [5] The FAA has proposed more stringent flammability regulations for seat cushions. [6] The current emphasis by FAA is to develop improved test requirements and materials for interior panels, which constitute the side-walls, ceiling, stowage bins, and partitions of a contemporary transport cabin interior. The importance of panels during a cabin fire stems from their large surface area and location in the upper cabin (ceiling, stowage bins) where fire temperatures are highest.

Full-scale fire tests are necessary to determine the potential benefits of safety improvements in real fires and to corroborate the trends indicated by small-scale test results. During full-scale tests, important real-world conditions such as fire source, geometry, and scale are reasonably simulated. Another important application of full-scale fire tests, is for the analysis of the hazards affecting survivability during a cabin fire. These hazards are grouped into three categories: heat, smoke (visibility), and toxic gases. What is the relative importance of each of these hazards? What are the effects of different types of fire scenarios on the significance of each hazard category? Realistic full-scale tests can provide information which, at the very least, give insight for answering these complex and far-reaching questions.

DISCUSSION

Interior Panel Materials

Figure 1 describes the advanced and inservice panels evaluated in this paper.

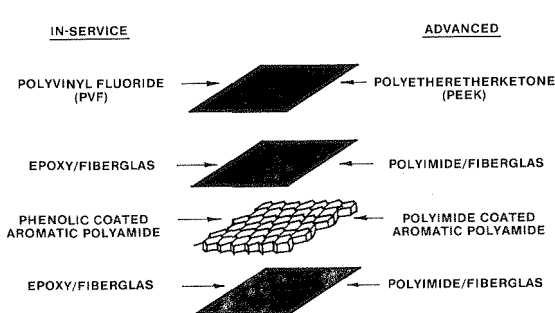| IN-SERVICE		ADVANCED
POLYVINYL FLUORIDE (PVF)		POLYETHERETHERKETONE (PEEK)
EPOXY/FIBERGLAS		POLYIMIDE/FIBERGLAS
PHENOLIC COATED AROMATIC POLYAMIDE		POLYIMIDE COATED AROMATIC POLYAMIDE
EPOXY/FIBERGLAS		POLYIMIDE/FIBERGLAS

Figure 1. Composition of Composite Panels

The in-service panel contained epoxy/fiberglass facings and represented the type of panel design employed in the earliest wide-body jet interiors. Polyimide was selected in the advanced panel design for resin and core coating because of its high degradation temperature. Polyetheretherketone (PEEK) was

the decorative film in the advanced panel design, primarily to eliminate the
production of hydrogen fluoride during thermal decomposition of the polyvinyl
fluoride film commonly used in contemporary panels. The superior thermal
stability of the advanced panel was evidenced alone by its cure temperature;
viz., 500° F for 16 hours vs. 350° F for approximately 2 hours for the in-
service panel.

Test Article

The full-scale test article was a C-133 aircraft, modified to resemble a
wide-body cabin interior, as shown in figure 2 and reference 2. It was
utilized to compare the performance of the advanced and in-service panels
installed in a representative cabin interior layout as sidewalls, stowage
bins, ceiling and partitions, under simulated postcrash and inflight fire
conditions. Under the postcrash scenarios, the interior was subjected to an
external fuel fire adjacent to an opening (door or fuselage rupture) in the
forward part of the fuselage (figure 2). For the in-flight fire scenario, the
fuselage openings were covered and a perforated ducting system simulated the
ceiling discharge of air into the cabin as occurs with the cabin environmental
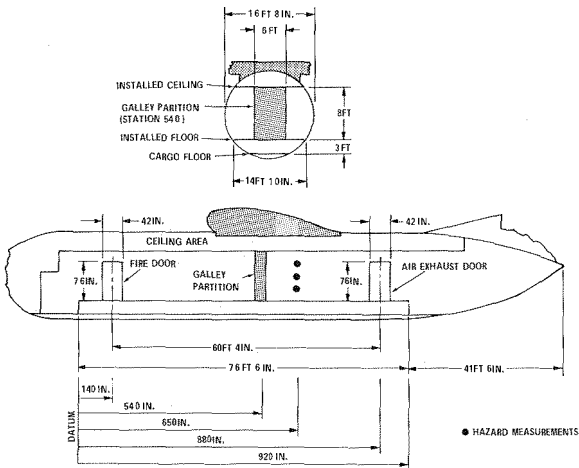control system (ECS).

Figure 2. Schematic of C-133 Wide-Body Cabin Fire Test Article

Fire Scenarios

Table 1 outlines the fire scenarios utilized in this study. In the postcrash
scenario, previous work had demonstrated that the size of the C-133 external
fuel fire produced 80 percent of the radiant heat flux into the interior
expected from an infinite fire. [7] Thus, the experimental fuel fire gave a
reasonable simulation of a large pool of burning fuel. With an unfurnished
C-133 interior and zero wind, there is virtually no accumulation of fuel fire
hazards (temperature, smoke, and gases) inside the test article. [7] For this
reason, the cabin hazards measured with interior materials installed and a
zero wind fuel fire are attributed to burning materials, although fuel fire

flames are drawn into the interior as the materials begin to ignite and burn.[8] The main role of the fuel fire is to subject the interior materials to intense radiant heat.

Table 1. Fire Scenarios

NO.	DESIGNATION	TYPE	IGNITION SOURCE	FUSELAGE CONFIGURATION	VENTILATION
1	FUEL FIRE/ RUPTURE	POSTCRASH	FUEL FIRE	INTACT, TWO OPENINGS: RUPTURE (FIRE) DOOR (AFT)	NATURAL ZERO WIND
2	FUEL FIRE/ OPEN DOOR	POSTCRASH	FUEL FIRE	INTACT, TWO OPENINGS: DOOR (FIRE) DOOR (AFT)	NATURAL ZERO WIND
3	GASOLINE/ SEAT	IN-FLIGHT	SPILLED GASOLINE ON SEAT	CLOSED	CONTROLLED

The in-flight fire scenario consisted of the ignition of a passenger seat doused with one quart of gasoline. It probably represented the most intense in-flight fire that is likely to occur out in the open (in contrast to a fire in a concealed area). The use of forced ventilation in a closed fuselage for the in-flight scenario was expected to affect the fire characteristics, compared to the postcrash case with fuselage openings and natural ventilation.

TEST RESULTS AND ANALYSIS

Postcrash Fuel Fire and Fuselage Rupture Scenario

The arrangement of materials with the postcrash fire scenario with a fuselage rupture adjacent to the fuel fire is shown in figure 3. Basically, a small area of the interior in the vicinity of the fuselage rupture was lined with the panels being examined and furnished with seats and carpet. The seats were surplus aircraft passenger seats protected with cushion fire blocking layers and the carpet was new, aircraft grade wool/nylon carpet. The quantity of materials employed was more than adequate to produce non-survivable conditions in the event of ignition and adequate fire growth. By using seats and carpet in addition to the panels being evaluated, the effect of panel flammability on the ignition and burning of other cabin materials used in large quantities, and vice-versa, was taken into consideration.
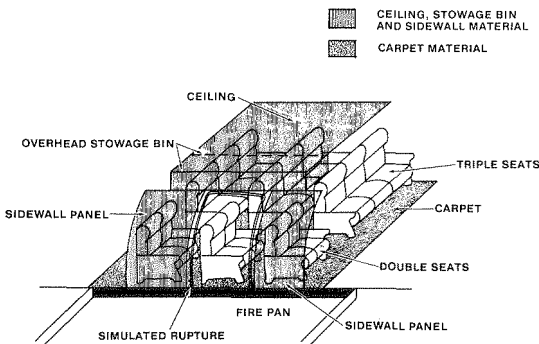
Figure 3. Postcrash Fuel Fire/Rupture Scenario

The postcrash fuel fire scenario with a fuselage rupture was the most severe
fire condition used, primarily because a seat was centered in the rupture and
exposed to high levels of radiant heat. A flashover — defined in this paper
as the sudden and rapid uncontrolled growth of the fire from an area in the
immediate vicinity of the fuel fire to the remaining materials — occurred
with both types of panels. However, the time to flashover was much earlier in
the test with in-service panels than in the test with advanced panels. As
shown in figure 4, the difference in flashover times was approximately 140
seconds. Since the occurrence of flashover is the event in a postcrash cabin
fire that creates nonsurvivable conditions, as discussed later in this paper
and in an earlier study (reference 2), the advanced panels also resulted in
140 seconds of additional time available for evacuation. This difference in
available evacuation time was clearly a significant benefit to be gained from
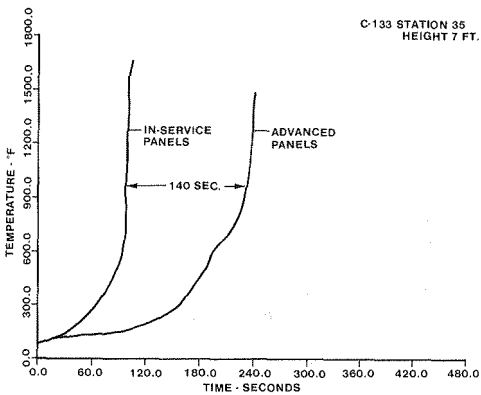the advanced panels.

Figure 4. Benefit of Advanced Composite Panels-External Fuel/Fuselage
Rupture Scenario

Postcrash Fuel Fire and Open Door Scenario

The arrangement of materials with the postcrash fire scenario with an opened
door adjacent to the fuel fire was similar to the fuselage rupture scenario
except that the center row of seats was eliminated and a box-like structure
representing a galley was installed. The resultant fire condition was less
severe than with the fuselage rupture scenario because of the removal of the
passenger seat next to the opening.

The superior fire performance of the advanced panels was even more evident
with the fuel fire/open door scenario. Under this scenario, the usage of
advanced panels eliminated flashover. This result is demonstrated in figure
5, which compares the temperature history inside the test article for both
types of panels. With in-service panels, flashover occurred in aproximately 2
1/2 minutes; however, with advanced panels, flashover did not occur over the
7-minute test duration. A comparison of the results with both types of
postcrash scenarios (see figures 4 and 5) demonstrates the consistency of the
data and illustrates that the rate of development of a cabin fire is largely
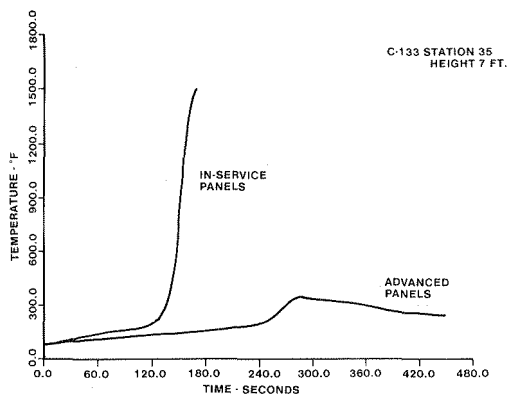dependent on fire scenario.

Figure 5. Benefit of Advanced Composite - External Fuel Fire/Open
Door Scenario

An analysis of the cabin hazards measured in the fuel fire/open door test with
in-service panels revealed the importance of flashover in dictating surviv-
ability during a postcrash cabin fire. This data is shown in figure 6, which
contains the hazard histories measured approximately 40 feet aft of the fire
door at an elevation of 5 feet 6 inches. Before the flashover which occurred
at approximately 150 seconds, the cabin environment was clearly survivable;
after flashover, the conditions very suddenly deteriorated to such a degree
that survival would have been highly unlikely. The suddeness of flashover,
and perhaps the fact that it occurs without any apparent warning, may make
passengers unaware of the imminent dangers that they face during a cabin fire.
For example, within 30 seconds, as shown in figure 6, visibility decreased
from about 30 feet to 3 feet, temperature measured from slightly above ambient
to over 400° F, CO increased from zero to over 2500 ppm, and oxygen decreased
from ambient to 16 percent. Therefore, it was concluded that improvements in
postcrash cabin fire safety, when burning interior materials are the dominant
factor, can be best attained by delaying the onset of flashover. If material
selection is on the basis of state-of-the-art small-scale fire tests, then
the use of an appropriate flammability test would seem to be far more benefi-
cial than the use of either smoke or toxicity tests.

Why were the hazards measured 40 feet aft of the fire door at an elevation of
5 feet 6 inches virtually zero for over 2 minutes in the fuel fire/open door
test with in-service panels? There are two likely reasons for this result.

First, the small mass burning rate before flashover and the large cabin volume
(13,200 cubic feet) made dilution and wall loss effects (heat transfer,
adsorption) dominant. Secondly, the hazards that are produced before flash-
over are largely contained in the hot "smoke layer" which clings to the
ceiling, above the measurement location and probably above the head of most
passengers. Previous C-133 tests [2], and the photographic/ video coverage
from the tests described in this paper, document the significant stratifica-
tion during a postcrash cabin fire with natural ventilation; i.e., with no
forced ventilation.

The in-flight fire scenario was the least severe of the three scenarios studied. Figure 8 compares the temperature history near the fire source for the in-service and advanced panels. As in the fuel fire/open door test, flashover did not occur with the advanced panels. The fire resistance of the more flammable in-service panels was also sufficient to delay the onset of flashover until 8 minutes. From a practical viewpoint, an in-flight fire of this kind with inservice panels would, under most circumstances, have been extinguished by crewmembers utilizing hand-held extinguishers before the fire became out ot control.
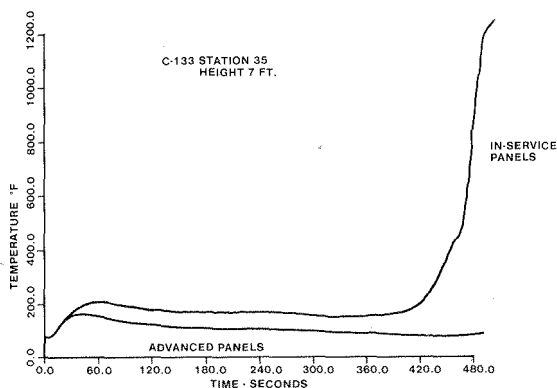

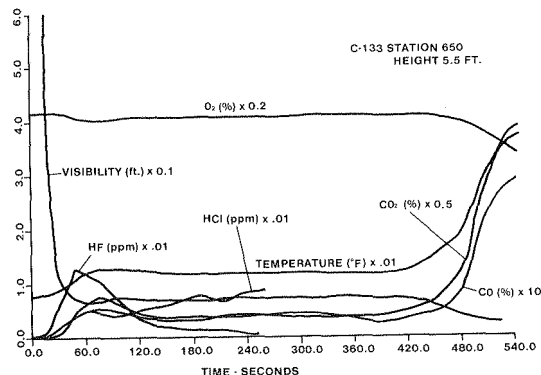Figure 8. Benefit of Advanced Composite Panels - In-Flight Fire Scenario

Figure 9. Hazard Time Profiles With In-Service Composite Panels - Flight Fire Scenario

The controlled ventilation in the in-flight scenario tended to distribute the seat fire hazards throughout the airplane. Figure 9 presents the measured hazard histories for the in-service panel test. Each of the measured hazards was detected before the onset of flashover, apparently because of the mixing action associated with the controlled ventilation. In contrast, for the postcrash tests where the cabin was ventilated naturally through fuselage openings, the hazards were primarily contained in the ceiling smoke layer, and remained virtually undetected at the 5-foot 6-inch sampling height until the

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C-133 STATION 650
HEIGHT 5.5 FT.

VISIBILITY (ft.) x 0.1   TEMPERATURE (°F) x .01

O₂ (%) x 0.2   HCl (ppm) x .01

CO₂(%)

CO(%) x 10

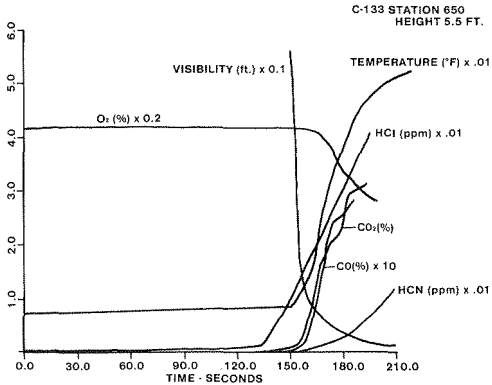HCN (ppm) x .01

TIME - SECONDS

Figure 6. Hazard Time Profiles With In-Service Composite Panel - External
Fuel Fire/Open Door Scenario

Figure 7 also demonstrates that the hazards over this 7-minute test were
clearly survivable. At 7 minutes, the temperature had only increased by 20° F
over ambient, the concentration of CO_2 was 2000 ppm, the concentration of
O_2 remained at ambient, and visibility had decreased to 50 feet. The toxic
gases CO, HCl, HCN, and HF were not detected. This data also supports the
conclusion that in a postcrash cabin fire, the hazards effecting survival are
created by a flashover. Also, smoke and toxic gas hazards affecting surviv-
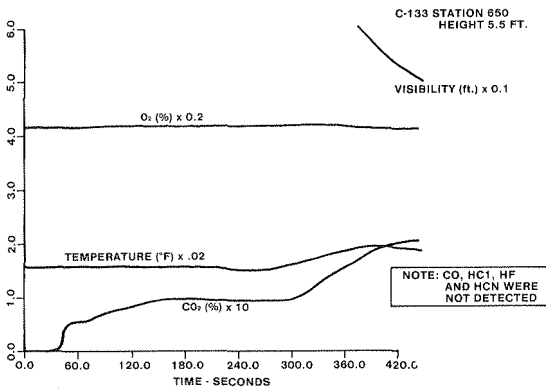ability did not materialize as a consequence of flashover being prevented.

C-133 STATION 650
HEIGHT 5.5 FT.

VISIBILITY (ft.) x 0.1

O₂ (%) x 0.2

TEMPERATURE (°F) x .02

NOTE: CO, HCl, HF
AND HCN WERE
NOT DETECTED

CO₂ (%) x 10

TIME - SECONDS

Figure 7. Hazard Time Profiles With Advanced Composite Panels External
Fuel Fire/Open Door Scenario

In-Flight Fire Scenario

For the in-flight scenario, the fuselage openings were covered and a perfora-
ted duct simulated air discharge from the cabin ECS. The seat next to the
covered door, doused with one quart of gasoline, served as the fire source.
This type of seat fire will burn for 2 mnutes, with a peak burning rate at
40 seconds before self-extinguishing because of the fire blocking layer. [9]

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cabin flashover (e.g., see figure 6). For the in-flight test, however, each measured hazard before flashover was well below its estimated incapacitation level. For example, at 8 minutes the calculated dose of CO was approximately 4000 ppm-minutes, which is significantly below the estimated human escape impairment dose of 30,000-40,000 ppm-minutes. [10] Also, the measured concentration of HCl, which was less than 100 ppm, would have been easily tolerated by passengers, based on recent primate studies. [10] The main peril before flashover was the dramatic loss in visibility due to smoke (calculated visibility was less than 10 feet at 30 seconds). It is interesting to note that significant smoke obscuration can occur without hazardous levels of toxic gases or elevated temperatures.

SUMMARY OF SIGNIFICANT FINDINGS

Based on the realistic, full-scale cabin fire tests and analysis described in this paper, and on the composite panel materials evaluated and the types of fire scenarios employed, the following are the significant findings:

1. Advanced interior panels can provide a significant safety improvement during postcrash and in-flight cabin fires.

2. The greatest threat to passenger survival during postcrash cabin fires dominated by burning interior materials, is cabin flashover.

3. Toxic gases produced during postcrash cabin fires consisting of a fuel fire adjacent to a fuselage opening or in-flight fires initiated by a gasoline-drenched seat fire do not reach hazardous levels unless flashover occurs.

4. During an in-flight fire, the cabin environmental control system has a major effect on the distribution and dissipation of hazards.

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