Measurements of the Response of Transport Aircraft Ceiling Panels to Fuel Fires

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An experimental study has been carried out to investigate the response of five transport aircraft ceiling panel composites to conditions simulating a postcrash fuel fire. The panels were 80 × 58 × 0.635 cm thick and consisted of front and back fibrous, laminate facesheets co-cured to a 0.6 cm Nomex honeycomb core. The exposed side was also covered with a thin, decorative, polyvinyl fluoride film. The facesheet compositions were: epoxy-fiberglass, epoxy-Kevlar, phenolic-fiberglass, phenolic-Kevlar, and phenolic-graphite laminates. The epoxy-fiberglass composition is the most widely used in transport aircraft and is taken as the baseline composition. Of the remaining four compositions, the phenolic-graphite is a new composition being considered for future use, while the other three are currently in limited use for some cabin interior applications. In the pool fire and flame spread test facility at Jet Propulsion Laboratory, the panels were exposed to heat fluxes of 5 W/cm^2 and gas temperatures near 800 K from 0.23 m^2 fuel fires. The objective was to determine the relative ability of the various facesheet compositions to prevent or delay significant damage to the panel core. The results show that the phenolic-fiberglass and phenolic-graphite panels sustained the least damage of the five tested. Normalized mass loss data show that those two panels also underwent the least mass loss and, thus, are less likely to contribute fuel as decomposition products to the cabin enclosure. Decomposition products may contribute to the onset of flashover. Time-dependent temperature measurements at several locations in the panels are also presented. These data further describe the detailed thermal response of the panels. The excellent performance of the phenolic-fiberglass and phenolic-graphite panels is attributed to the charring tendency of the phenolic and the relative inertness of the two fibrous materials for the conditions studied. The remaining two panels provided no improvement over the baseline epoxy-fiberglass composition.

Nomenclature

m_f	= final panel mass, g
m_i	= initial panel mass, g
Δm	= total panel mass loss during test $(m_i - m_f)$, g
$\dot{q}_{conv}$	= convective heat flux to panel surface, kW/m^2
$\dot{q}_r$	= radiative heat flux to panel surface, kW/m^2
$\dot{q}_s$	= imposed heat flux at the (hot) surface of the panel, kW/m^2
$\dot{Q}$	= pool fire heat release rate, kW
t	= time, s
T	= temperature, K
T_{max}	= maximum measured panel surface temperature, K
T_r	= nominal panel surface temperature in reradiation term of Eq. (1), K
ΔT	= temperature difference across panel thickness, K
ΔT_{max}	= maximum measured temperature difference across panel thickness, K
x	= coordinate in the ventilation flow direction, cm
x_1	= char front progression through honeycomb core at the hot surface of the panel, cm
x_2	= char front progression through honeycomb core at the back (cold) surface of the panel, cm
y	= coordinate in the vertical direction, cm
α	= panel surface absorptivity, -
δ	= panel thickness, 0.635 cm
ϵ	= panel surface emissivity, -
Λ	= normalized panel mass loss parameter, $(\Delta m/m_i)/\dot{Q}$, 1/kW
σ	= Stefan-Boltzmann constant, 5.67×10^{-8} W/m^2-K^4

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Introduction

THE postcrash fire scenario has been the subject of considerable experimental and analytical study with regard to transport aircraft fire safety. This scenario is characterized by the penetration, usually enhanced by wind, of a large fuel pool fire through an opening (such as a door) into the aircraft cabin.[1,2] The subsequent response of cabin interior materials to the fire and the resulting hazards to the passengers are of special interest. This paper presents the results of an experimental study to characterize the response of cabin interior ceiling panels under conditions simulating the postcrash fire scenario.

Initial full-scale tests in the Federal Aviation Administration Technical Center's (FAATC) C-133 test article have demonstrated two ways ceiling panels contribute to postcrash fire hazards[3,4]: 1) During the initial stages of the fire, the thin layer of decorative laminate applied to the facing surface of the panel sheets ignites and drops to the floor as flaming debris. This then accelerates the spread of the fire to the seats below that have not already been ignited directly by the pool fire. 2) The remainder of the panel consisting of front and back facesheets and honeycomb core thermally decomposes and adds fuel to the cabin environment. This is presumed to contribute to the onset of flashover.

These previous studies have pointed out a need to improve the fire response characteristics of currently used materials. At Jet Propulsion Laboratory (JPL), five ceiling panel materials have been tested in a pool fire and flame spread test facility to evaluate a range of facesheet compositions, and they have been compared with the most widely used material (epoxy-fiberglass). Another objective of this research has been to better understand the detailed response characteristics of such panels. The experimental setup is approximately one-third the scale of a wide-body transport interior (Fig. 1), and the ceiling panel test specimens are subjected to a 0.23 m^2 Jet-A fuel fire at the floor.

Experimental Setup

The test facility is illustrated in Fig. 1 and has been described in detail in Ref. 5. The test section, 0.76 m high by 1.52 m wide, consists of four modular, interchangeable subsections of welded, 3.2-mm-thick steel construction. The total test section length is 3.4 m and its exterior is covered with fiberboard insulation. Ventilating airflow is provided by a centrifugal blower that supplies a maximum airflow of approximately 48 m^3/min (1700 ft^3/min). A damper upstream of the blower inlet controls the flow rate, and pitot and static pressure probes immediately upstream of the blower inlet are used to measure the flow rate. After exiting the blower outlet, the flow is turned 180 deg and passes through two layers of 20 mesh screen and 10 cm of honeycomb upstream of the test section to smooth the flow. The contraction section then accelerates the flow to the test section inlet condition. After making a 90-deg turn at the end of the test section, the exhaust products exit through a 61-cm-diam stack.

For the ceiling panel tests, a water-cooled fuel pan measuring 30 cm in the streamwise direction by 75 cm in the spanwise direction is located 1.12 m downstream of the test section inlet. It was estimated that this pan size would produce a pool fire flame height approximately equal to the height of the test section under quiescent conditions (without crossflow) based on correlations presented by Thomas.[6] The fuel pan is recessed in the floor 5 cm and centered on the test section centerline. Turbojet-A fuel is used in all tests and a 2.5-cm-thick ceramic fiber wick placed in the fuel pan produces a relatively uniform burning surface. An electrical resistance heater preheats the surface layer of fuel to give rapid ignition by an inserted pilot flame at the start of the tests.

In addition, a sheet metal "fence" 38 cm high by 91 cm in the spanwise direction was located on the center of the floor of the test section 15 cm downstream of the fuel pan. Previously reported experiments[5] have shown that, if the fuel pan spans the entire width of the test section and if no downstream fence is employed, the pool fire is blown over to such an extent that heat flux and temperature conditions at the ceiling are not severe enough to represent the postcrash fire situation. The downstream fence gives a more vertical orientation to the fire plume and the shorter fuel pan allows part of the core flow to be diverted around the fire plume. The fence could also represent the presence of a row of seats adjacent to the fire. The resulting test conditions at the panel location are discussed below.

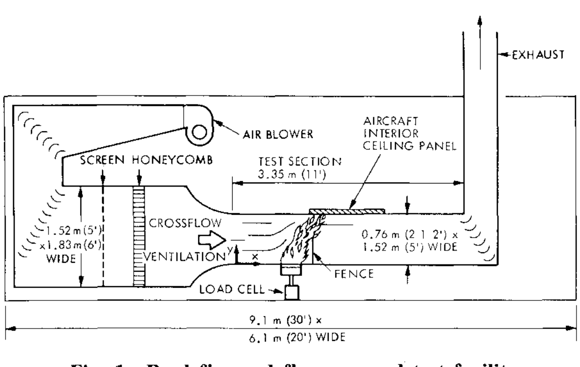


Fig. 1 Pool fire and flame spread test facility.

Temperature data are provided by 60 chromel-alumel (type K) thermocouples located on probes in the gas phase and mounted on the panel test specimen for materials temperatures. Temperature data were recorded sequentially on a 60 channel data logger sampling at 0.5 s/channel. Two water-cooled radiometer and calorimeter pairs were mounted in the ceiling along the centerline of the test section 25 cm and 71 cm downstream of the back edge of the fuel pan for system calibration runs prior to panel tests. Heat flux data were recorded continuously on strip chart recorders. Oxygen concentration measurements made in the exhaust stack were utilized to calculate energy release rates during tests by oxygen consumption calorimetry.[7] Finally, 12 viewports are provided for visual and photographic observations along the test section. In particular, these observations include data from five flow direction indicators spaced along the length of the test section.[5]

Experimental Conditions

Several calibration tests were conducted in the facility to establish appropriate conditions for panel testing. A range of characteristic temperature, flow, and heat flux conditions was identified in consultation with FAATC personnel to be consistent with the postcrash scenario and test conditions used there. Typical conditions under which panels were subsequently tested are shown in Figs. 2 and 3. Pool fire heat release rates are typically in the 100-150 kW range and the nominal cross-flow velocity of the incoming ventilating airflow is approximately 0.2 m/s. Heat release rates could be controlled somewhat by the fuel pan water-cooling rate and by varying fuel loading on the wick. However, the degree of fuel saturation in the large wick was difficult to measure accurately, leading to variations in heat release rate among the panel tests.

Temperature isotherms (Fig. 2) are taken from test section centerline averages during the period of most steady burning (0 min-20 s to 1 min-50 s). Calibration tests as well as all panel tests were 3 min in duration. The heat fluxes indicated in Fig. 2 are the mean total (convective plus radiative) fluxes during the stable period of the tests. That is, sustained fluxes of 4-5 W/cm^2 (40-50 kW/m^2) were observed 10 cm downstream of the leading edge of the panel. The peak gas phase temperature measured in this region was 766 K (see Fig. 2). At the downstream station (56 cm) heat fluxes were significantly less. Throughout the test period, incident radiative and convective heat fluxes were approximately equal.

Flow characteristics in the test section are illustrated in Fig. 3. Note the occurrence of a strong reverse-flow ceiling

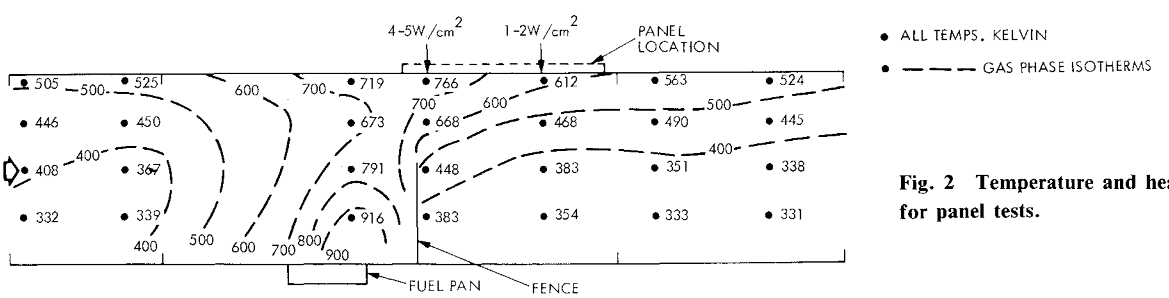


Fig. 2 Temperature and heat flux conditions for panel tests.

jet upstream of the fire. This reverse-flow region has been characterized for a number of inlet flow conditions and exists even when the visible flame region is blown over significantly in the direction of the ventilation.[5] Its effect is to transport smoke and hot combustion products to regions upstream of the fire, where they are eventually entrained into the incoming flow and transported back in the streamwise direction. Thus, smoke is quickly spread to both upstream and downstream regions and the test section interior is obscured in 30-45 s. The implication of these observations in the evaluation of hazards during postcrash evacuation has been discussed previously by the authors.[5] It should also be noted that a thick smoke layer occurs in the full-scale C-133 tests.[3]

Ceiling panels supplied by the FAATC were mounted in the test section ceiling 16.5 cm downstream of the back edge of the fuel pan (Fig. 1). The 6.35-mm-thick specimens measured 58 cm in the spanwise direction and 80 cm in the streamwise direction, and were mounted flush with the ceiling on the test section centerline. The edges of the panels were sealed with aluminum tape. Twelve thermocouples were mounted in the panels for the front and back surface and in-core temperature measurements, as shown in Fig. 4. Table 1 lists the compositions tested and illustrates the composite structure. All panels have a flame-retardant Nomex honeycomb core. The front and back surface sheets are a single-ply fiber mesh imbedded in a polymer substrate. The exposed (front) side facesheet is covered with a 0.05-mm white decorative Tedlar (polyvinyl fluoride) film. Panel 1 has been the most commonly used composition in the transport aircraft fleet in recent years. Thus, panel 1 was considered as the baseline composition for this study. Panel 3 is a composition that has been utilized to an increasing extent in recent years. Panels 4 and 5 are currently used to a limited extent in some applications. Panel 2 is an advanced composition being evaluated for possible future use.

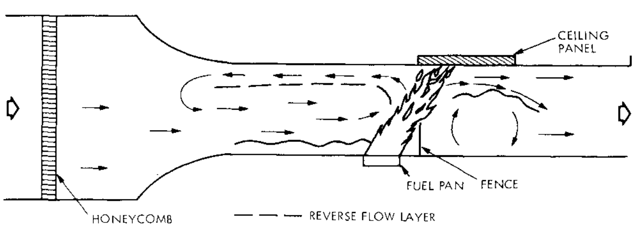


Fig. 3 Test section centerline flow characteristics.

The detailed thermal and chemical characteristics of the panel materials were not available. However, general characteristics of the constituent resins are well known. Epoxy resins are specialty thermosetting resins used frequently in reinforced laminates. Although normally flammable, flammability can be reduced considerably by flame-retardant additives.[8] Depending upon the epoxy compound and hardener (crosslinker) used, epoxy resins can be formulated to provide a wide variety of wear-resistant properties. Phenolics are thermosetting resins produced by the condensation of phenol and formaldehyde. They possess excellent thermal stability and are naturally resistant to combustion due to their high charring tendency.[8] The anaerobic char yield of phenolics is near 60%, while for epoxies it is about 20%. This typically results in improved flammability for phenolics over epoxies by a factor of 2-4 as measured by Limiting Oxygen Index (LOI) tests of aircraft-type formulations.[9]

Nomex and Kevlar are both polyaramid fibrous polymers that have similar thermal characteristics. Kevlar is characterized by high modulus fibers specifically developed for reinforcement of laminate sheets.[8] Nomex is woven into a "paperlike" material which comprises the honeycomb core with a high strength-to-weight ratio. The flammability of Nomex andd Kevlar is equal to, or somewhat better than, the most flame-resistant epoxies,[9,10] and their anaerobic char yields are in the 30-35% range.

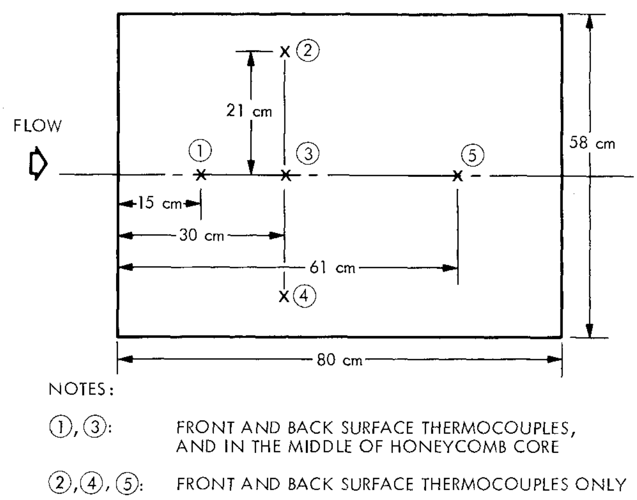
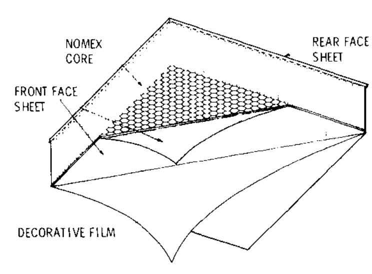


Fig. 4 Panel thermocouple locations.

Table 1 Aircraft ceiling panel construction

Facesheets	Core	Decorative film
1. Single-ply, 7781 woven fiberglass impregnated with fire-retardant epoxy resin, 0.3 mm thick	Nomex honeycomb, 3.2 mm cell, 1.8 lb. typical all panels	0.05 mm white Tedlar, typical all panels
2. Single-ply, 8 harness satin, 3 K fiber, T-300 woven graphite impregnated with modified phenolic resin, 0.4 mm thick		
3. Single-ply, 7781 woven fiberglass impregnated with a modified phenolic resin, 0.3 mm thick		
4. Single-ply, 385 woven Kevlar impregnated with fire-retardant epoxy resin, 0.2 mm thick		
5. Single-ply, 285 woven Kevlar impregnated with a modified phenolic resin 0.4 mm thick		



Fibrous composite sheets are generally 50-60% fiber-filled by volume. Thus, their properties are also highly dependent on the characteristics of the fiber reinforcement material. For the present test conditions, the glass and graphite fiber reinforcement materials are expected to be relatively inert. The Kevlar fibers would be expected to respond in a manner similar to Nomex, as discussed in the preceding paragraph.

The experiments described herein were designed to determine panel response under conditions severe enough to cause significant damage, but not so severe that the relative performance among the different panels could not be assessed. Also, we are interested in the response of the panels during the first 3-4 min to determine the effectiveness of panel *facesheet* materials in delaying or preventing significant decomposition of the remainder of the panel (honeycomb) structure.

Results and Discussion

A summary of results for the five panels tested is given in Table 2. In all tests, burning was characterized by initial ignition of the white Tedlar decorative sheet that dropped to the floor of the test section (usually while still burning) in pieces less than about 10 cm^2 in area. Flames from the pool fire were seen impinging directly on the panel over one-third to one-half of the panel surface before being obscured by smoke buildup after approximately 30 s. This is the region in which heat fluxes were near 5 W/cm^2. T_{max} and ΔT_{max} in Table 2 were measured at the 15 cm streamwise location closest to the fire (Fig. 4). Occasionally, small flamelets were observed flaring at the panel surface prior to smoke obscuration, but after the Tedlar sheet had burned away.

The results in Table 2 show 10-20% panel mass losses during the tests. Char front progression on the hot side (x_1) extended over halfway down the length of the epoxy-fiberglass panel (No. 1). The facesheets on both sides of panel 1 were separated from the core over about one-half of the panel surface and the Nomex core was buckled somewhat. For the phenolic-graphite panel (No. 2), the first 15 cm of the facesheet on the hot side was separated from the honeycomb, but there was no buckling of the Nomex core. This performance was excellent considering the higher fire intensity during this test. Panel 3 sustained relatively little damage. Panels 4 and 5 sustained physical damage comparable to or greater than reference panel 1, where both were tested at the lowest fire intensity. Frequently, delamination of the facesheet was characterized by a bubblelike appearance, as if it was at least partially caused by a pressure buildup from the decomposition product gases in the core. For all panels, the char front formed a wedge shape through the panel thickness beginning on the hot side at x_1 and extending back to the cold side at x_2, as illustrated diagrammatically in Fig. 5.

The ratio $\Lambda = (\Delta m/m_i)/\dot{Q}$ in Table 2 was defined for the purpose of comparing the relative performance of the panels and measures the degree of decomposition for a given fire intensity. Significant decomposition, especially during early stages of the fire, is an important factor in establishing the contribution of a panel to gas phase fuel loading. We estimate that these panels have a potential heating value of 15-20 MJ/m^2, or approximately 15-20 MJ/kg. The char progression distances x_1 and x_2 may also be used for comparison. They indicate the extent of charring and the relative amount of outgassing of fuel from the honeycomb core, which comprises 75-80% of the panel mass. This provides another measure of the ability of a given facesheet composition to protect the core. In this regard, we have estimated facesheet thermal conductivities based on literature data[11-15] and found them to be in the same range for all panels (0.4-0.5 W/m-K in the direction perpendicular to the plane of the sheet, and 0.8-0.9 W/m-K in the plane of the facesheet), *except* for panel 2. Thermal conductivities of

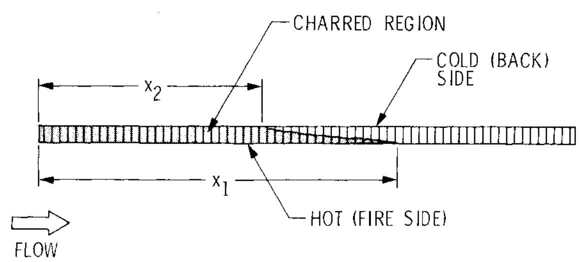


Fig. 5 Panel char progression distances.

Table 2 Summary of aircraft ceiling panel tests

Panel	Pool fire heat release rate, $\dot{Q}$, kW	T_{max}, K	ΔT_{max}, K	Mass fraction lost $\Delta m/m_i$	$\Lambda = \Delta m/m_i\dot{Q}$, 1/kW	Char progression, cm x_1	x_2	Physical condition: Facesheet	Nomex core
1. Epoxy fiberglass facesheet	115	711	175	0.19	1.6×10^{-3}	56	30	Delaminated over $\cong 1/2$ sheet area	Brittle in charred area; buckled and cracked
2. Phenolic-graphite facesheet	150	758	193	0.15	1.0×10^{-3}	43	25	Delaminated over forward 15 cm on hot side only	Brittle in charred area
3. Phenolic-fiberglass facesheet	115	716	130	0.10	0.9×10^{-3}	25	18	Slight delamination along forward edge of hot side	Brittle in charred area
4. Epoxy-Kevlar facesheet	100	705	230	0.16	1.6×10^{-3}	35	26	Delaminated over 40% on hot side and 30% on cold side	Brittle in charred area (33% sheet area); buckled and cracked
5. Phenolic-Kevlar facesheet	100	678	172	0.17	1.7×10^{-3}	36	32	Delaminated over 60% on hot side and 33% on cold side	Brittle in charred area (~40% sheet area); buckled and cracked

graphite-reinforced laminates are much higher by factors of 3-5. These data are for the uncharred material; char thermal conductivities are usually slightly higher. Thermal conductivities are higher in the plane of the facesheet laminate because the fiber axes are oriented in the plane of the sheet. Note also that since fibrous laminates are usually greater than 50% fiber by volume, the reinforcing material strongly affects the thermal characteristics of the facesheets.

Comparison of the results for Λ, x_1 and x_2, shows that panels 2 and 3 performed best among the five panels studied. This is consistent with the observations of physical damage. Λ is lowest and nearly the same for panels 2 and 3, and highest and almost equal for panels 1, 4, and 5. In comparing x_1 and x_2, we find that the phenolic-fiberglass panel (No. 3) underwent the least char progression, while the epoxy-fiberglass panel (No. 1) sustained the most charring. The Kevlar-reinforced panels (Nos. 4 and 5) both performed about the same on the basis of char progression: somewhat less charring than panel 1 but more than 3. Although the phenolic-graphite panel (No. 2) sustained significant charring, it was subjected to a 30-50% more intense fire. When this is considered, its char progression appears to be comparable to or better than panels 4 and 5. This is confirmed by the mass loss data.

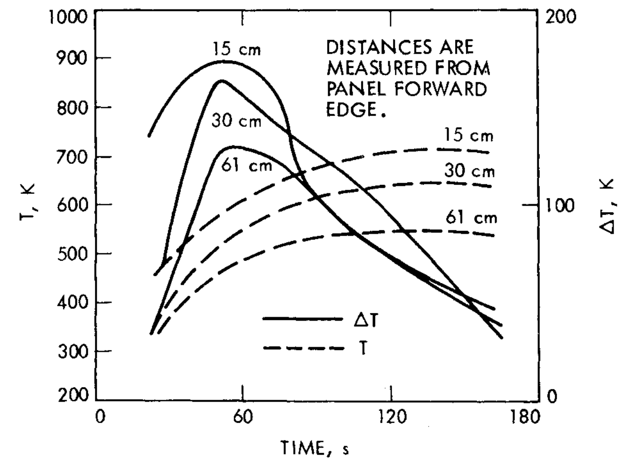


Fig. 6 Hot side panel surface temperatures and temperature differences across panel thickness vs elapsed time; panel 1, epoxy-fiberglass facesheet.

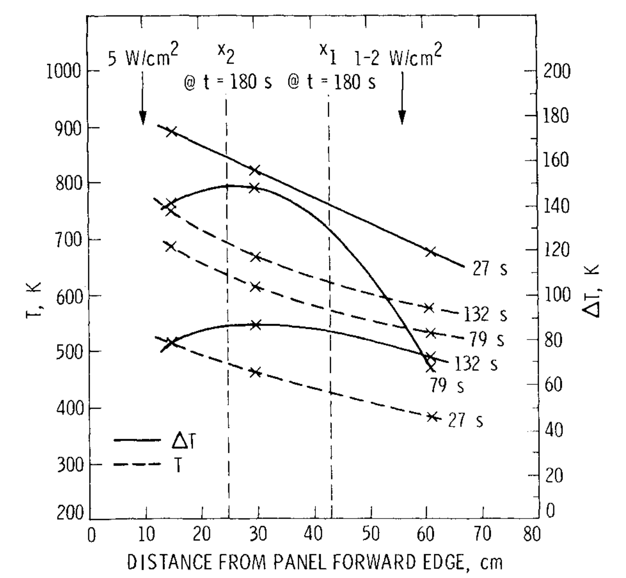


Fig. 7 Hot side panel surface temperatures and temperature differences across panel thickness vs distance from forward edge at three elapsed times; panel 2, phenolic-graphite facesheet.

Figure 6 shows the temperature-time histories for the epoxy-fiberglass panel (No. 1) at three positions along the centerline of the panel in the streamwise direction. Temperatures on the exposed surface increased steadily before leveling off after about 140 s. Temperature differences across the 6.35 mm thickness of the panel peaked near 1 min and decreased thereafter. These peaks correspond to the period of maximum heat fluxes as measured during the calibration tests and indicate peak heat transfer into the panel core. The subsequent decrease in heat fluxes may be due to the buildup of the thick, insulating smoke layer, a slight measured decrease in fire intensity, and complete heating of the panel across its thickness. These curves are typical for each of the panels tested.

Temperatures along the panel centerline in the streamwise direction are plotted in Fig. 7 at different times for panel 2. Also plotted is the total temperature difference vs distance. It shows movement of the peak temperature difference along the panel length with time from the leading edge as the panel heats up and the char front progresses. Char front progressions x_1 and x_2 at the conclusion of the test ($t=180$ s) are also indicated on Fig. 7 showing that charring occurred in regions upstream of a peak temperature of 600 K at the hot surface by the end of the test. This is seen by observing that the surface temperature curve crosses the forward char progression distance ($x_1=43$ cm) near $T=600$ K at 132 s. In general, the leading edge of the char front progressed to the 600 K surface temperature isotherm ± 40 K for all panels tested. Temperatures 21 cm off the centerline at the 30 cm streamwise location were usually lower by up to 60 K at the surface. This is presumably due to the proximity of the off-center location to the outer edge of the fuel pan and fire plume.

Figure 8 depicts temperature profiles within panel 2 as the test progressed in time. A dotted line for the 61 cm station is used because no temperature measurement was made in the honeycomb at that location. The temperature variations depend on many factors, and nonlinear profiles were common for all panels. Delamination of the facesheet from the honeycomb, porosity in the facesheet, possible detachment of the thermocouples, heats of gasification, and buckling of the honeycomb may cause the ΔT to deviate from a linear profile. Also, mass injection due to material decomposition is occurring. These results emphasize the complexities associated with making measurements under these conditions and indicate a need for modeling of this situation.

The net heat flux $\dot{q}_s$ into the panel is given by

$$\dot{q}_s = \alpha \dot{q}_r + \dot{q}_{\text{conv}} - \epsilon \sigma T_r^4 \tag{1}$$

The first term on the right-hand side is the absorbed incident radiation. The second term is convective heat transferred to the surface, and the third term is back radiation from the surface. For panel test conditions, we take $\alpha=\epsilon=0.9$, $\dot{q}_r=26$ kW/m^2, $T_r=575$ K, and $\dot{q}_{\text{conv}}=10$ kW/m^2. $\dot{q}_{\text{conv}}$ is determined using a convective heat-transfer coefficient of 50 W/m^2-K the authors have reported elsewhere.[16] These values give a net heat flux of $\dot{q}_s=28$ kW/m^2 (2.8 W/cm^2). We estimate that 5 kW/m^2 of the incident flux was dissipated in the decomposition of the Nomex using a heat of decomposition of 1255 J/g.

Other phenomena further complicate analysis of these data. For example, once the facesheet delaminates, an insulating air gap is formed that would create higher facesheet temperatures while reducing the net flux into the panel core. In fact, delamination may result in temporarily increased protection due to the air layer. However, it will eventually lead to direct fire impingement on the core in an actual fire situation. Finally, radiation from the front to the back facesheet may be significant when the ΔTs are high. We

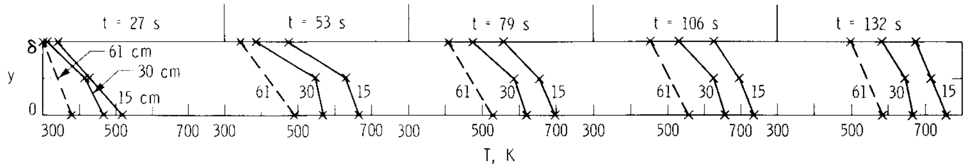


Fig. 8 Temperature profiles across panel honeycomb core thickness at 15, 30, and 61 cm from forward edge at five elapse times; panel 2, phenolic-graphite facesheet.

estimate that radiation may account for up to 5 kW/m^2 of heat transfer through the honeycomb core.

In conclusion, these results show that two phenolic-based facesheets performed best under the conditions and parameters studied in these tests. The combination of the charring characteristic of the phenolic substrate with a relatively inert reinforcing fiber material (fiberglass or graphite) resulted in the least mass loss and damage to the honeycomb core structure. The thermochemical characteristics of Kevlar apparently result in reduced protection, since the reinforcing fibers are decomposed irregardless of the polymer substrate used. In fact, the Kevlar-reinforced facesheets were observed to be porous in the charred areas following some tests. The result is that they performed no better than the baseline epoxy-fiberglass composition. It should be noted that these results are consistent with smaller-scale tests conducted in JPL's National Bureau of Standards Smoke Chamber modified to provide sample mass loss data at heat fluxes of 2.5, 5, and 8 W/cm^2. Also, the results are consistent with reduced scale flashover[17] and full-scale[18] tests conducted at FAATC.

Summary

Reduced-scale tests of aircraft ceiling panel materials have been conducted at Jet Propulsion Laboratory under conditions simulating aspects of the postcrash fire scenario. The results show that the panels with phenolic-fiberglass and phenolic-graphite facesheet compositions perform significantly better than a reference panel with an epoxy-fiberglass facesheet. Two other panels with epoxy-Kevlar and phenolic-Kevlar facesheets showed no improvement over the reference panel. It should be emphasized that these results were obtained under specific experimental conditions and should be interpreted as such. However, the experiment possesses key characteristics of the postcrash fire scenario (heat fluxes, fuel, and flow conditions) and the results should provide an accurate indication of the relative performance of panels in full-scale tests. Also, the results have been found to be consistent with other tests being used to evaluate these materials. Finally, rapid ignition, burning, and melting of the Tedlar film resulted in flaming debris dropping to the test section floor early in all panel tests. New formulations for the decorative films are needed and progress in this area has been reported by investigators at NASA Ames Research Center.[19]

Acknowledgments

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