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DESIGN, FABRICATION AND TEST OF LIQUID METAL HEAT-PIPE SANDWICH PANELS

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DESIGN, FABRICATION AND TEST OF LIQUID METAL HEAT-PIPE SANDWICH PANELS

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Abstract

Integral heat-pipe sandwich panels, which synergistically combine the thermal efficiency of heat pipes and the structural efficiency of honeycomb sandwich panel construction, were fabricated and tested. The designs utilize two different wickable honeycomb cores, facesheets with screen mesh sintered to the internal surfaces, and potassium or sodium as the working fluid. Panels were tested by radiant heating, and the results indicate successful heat pipe operation at temperatures of approximately 922K (1200°F). These panels, in addition to solving potential thermal stress problems in an Airframe-Integrated Scramjet Engine, have potential applications as cold plates for electronic component cooling, as radiators for space platforms, and as low distortion, large area structures.

Introduction

Design studies of the NASA Langley Airframe-Integrated Scramjet Engine[1] have indicated potential thermal stress problems. Excessive thermal stresses result from large transient temperature gradients across the honeycomb sandwich walls of the engine structure during engine startup and shutdown. Conventional heat-pipe panel designs can reduce the thermal gradients. However, inherent in these designs are problems associated with bonding the heat pipes to the honeycomb panels, the resultant thermal gradients due to contact resistances, and the probability of a substantial increase in panel mass. An alternate solution to these problems is the development of an integral heat-pipe sandwich panel[2] that synergistically combines the thermal efficiency of heat pipes with the structural efficiency of sandwich construction, with only a negligible increase in mass. A preliminary evaluation of such a concept was reported by Peeples.[3]

In addition to the above application, heat-pipe sandwich panels have potential as cold plates for electronic and circuit card cooling, as radiators for space platforms, and as low distortion, large area structures (e.g., space antennas). To verify the feasibility of a heat-pipe sandwich panel, a program was initiated (NASA Contract NAS1-16556) to fabricate several low mass liquid metal heat-pipe honeycomb panels.

This paper describes the thermal environment that led to the investigation of a heat-pipe sandwich panel, illustrates the preliminary design considerations and testing, describes manufacturing and fabrication details, discusses preliminary performance testing, and comments on potential future applications.

Design of Heat-Pipe Sandwich Panels

NASA Langley Research Center has been involved in a research program for the development of Airframe-Integrated Scramjet Engine concepts.[1] Results of that study indicate that an all-honeycomb primary structure, illustrated in Fig. 1, has less deflection and complexity than beam and honeycomb combinations of equal mass. Hence, an all-honeycomb configuration was chosen as the best structural concept. All internal and external engine surfaces exposed to aerodynamic flow are cooled regeneratively by the circulation of hydrogen fuel (prior to injection) through a cooling jacket. Inconel 718 was chosen for the honeycomb primary structure, with Hastelloy-X or Nickel-200 chosen for the cooling jacket. The honeycomb front facesheet is 0.15 cm (0.06 in.) thick, the back facesheet is 0.13 cm (0.05 in.) thick, and the honeycomb cell is a 0.64-cm (0.25 in.) hexagonal arrangement constructed of 0.008-cm (0.003 in.) foil-gage ribbon.

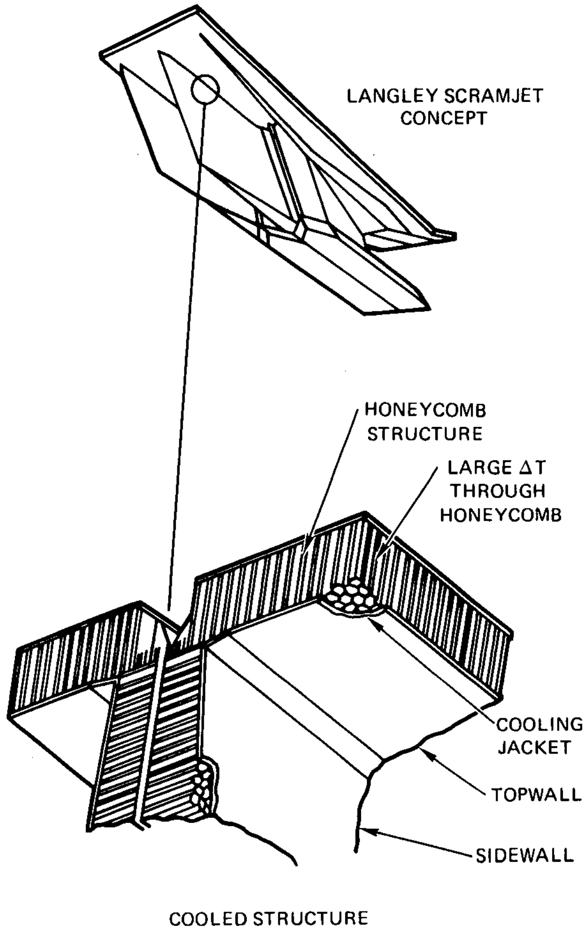

Fig. 1 Features of cooled scramjet structure.

Environment

Temperature gradients through the honeycomb walls during transient operation (i.e., engine startup or shutdown) may very well control the structural design. A mission profile of a research-type vehicle was used by Buchmann[1] to predict the thermal/structural response quantities. A finite-difference analysis model of a section of the sidewall-topwall (Fig. 2) was used to calculate the transient temperatures shown in Fig. 3. Note from Fig. 3(a) that at startup, the front facesheet quickly rises to 890K

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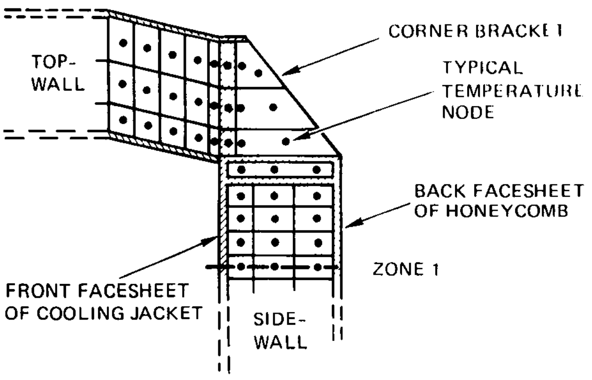


Fig. 2 Mathematical model for transient thermal analysis of honeycomb topwall-sidewall corner section.[1]

(1140°F), resulting in a front-to-back ΔT of 667K (1200°F) for a Hastelloy-X core. At engine shutdown, whether caused by normal occurrences or an abnormality such as a flameout, the temperature relationships of the front of the cooling jacket and the back of the honeycomb are reversed, as shown in Fig. 3(b). The front-to-back ΔT developed is somewhat less than at startup--on the order of 556K (1000°F) for the Hastelloy-X core. These thermal gradients result in excessive thermal stresses and premature fatigue failure.[1] Solutions to this problem noted in Ref. 1 result in concepts that are either more complex or heavier, or both.

Concept

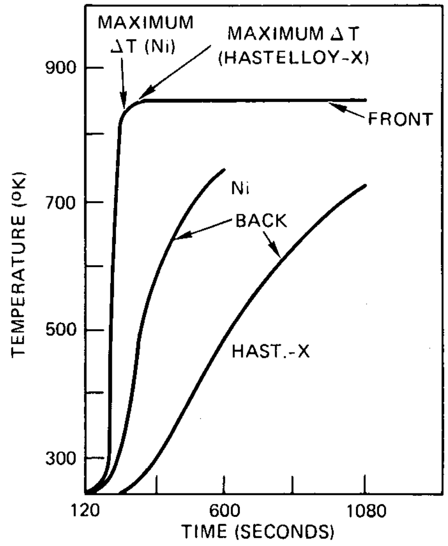
The basic idea for the heat-pipe sandwich panel emerged as a solution to the above problem. The heat-pipe sandwich panels fabricated in the past met unique requirements of uniform temperature over a large surface area. These panels have demonstrated operation in a zero-g field,[4] uniform temperature over a large area[5] (0.5x6 meters (1.64x19.7 ft.)) and an isothermal surface[6] (within 0.01K (0.02°F)). However, all these panels were built by welding or furnace brazing by highly skilled technicians and, although they met all the technical requirements, they were very costly to manufacture.

The objective during this program was to design and fabricate a cost- and mass-effective sandwich panel using existing manufacturing techniques and equipment. The upper and lower ends of the core have flanges that enable spot welding to the faces. The entire sandwich panel can be constructed by simultaneously spot welding the core ribbons to each other and to the faces using the manufacturing technique illustrated in Fig. 4. The spot welds are so close together that they form an almost continuous bond. Since the entire panel is spot welded, this eliminates the need for bonding and possible materials compatibility problems.

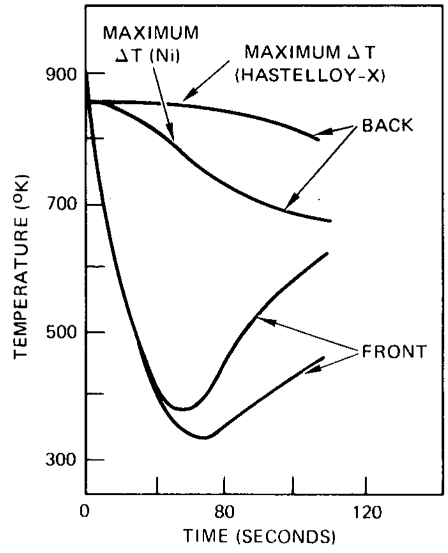
The primary objective was to fabricate a heat-pipe honeycomb sandwich using a wickable honeycomb core, appropriate working fluid, and wickable internal faces that would enhance the transverse heat transfer capability of the honeycomb. During operation, heat would be absorbed at the heated face by the evaporation of working fluid. The heated vapor flows, due to a pressure differential, to the cooler face, where it condenses and gives up its stored heat. The cycle is completed with the return flow of liquid condensate back to the heated face by the capillary pumping action of the wickable core. A schematic of the heat-pipe sandwich panel concept is shown in Fig. 5. A screen is sintered to the internal faces of the sandwich to allow intracellular liquid flow by capillary action. This design also allows the entire surface of the facing to be wetted by liquid and thus aid in evaporation and also help to reduce thermal gradients in the faces. The wickable honeycomb core could be a foil-gage woven mesh screen or a screen sintered to foil ribbons; this allows face-to-face liquid flow. The honeycomb is notched at each end to allow intracellular liquid flow and perforated to enable intracellular vapor flow. Although the primary mode of heat transfer is in the transverse direction (face to face) for the present application, the choice of other design alternatives can enable varying degrees of in-plane heat transfer.

Critical Element Evaluation

To accommodate the heat-pipe sandwich panel requirements, the structure must consist of two facings with internally wickable faces bonded to a perforated, wickable honeycomb core material (as shown in Fig. 5). Several



(a) STARTUP



(b) SHUTDOWN

Fig. 3 Honeycomb temperature histories at zone 1.[1]

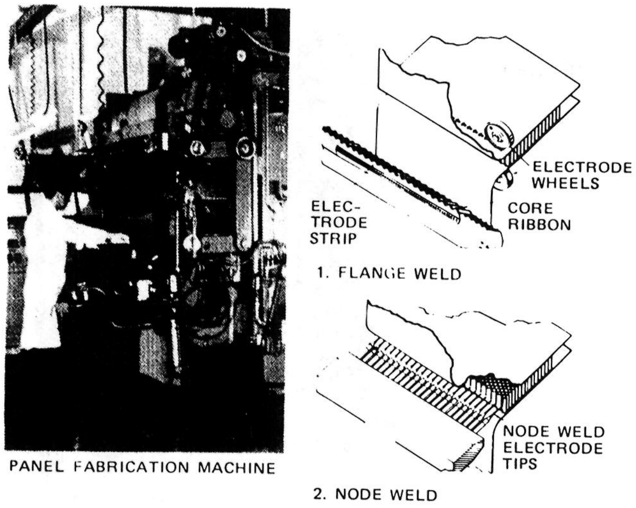


Fig. 4 Honeycomb panel welding machine and manufacturing technique (courtesy of Astech).

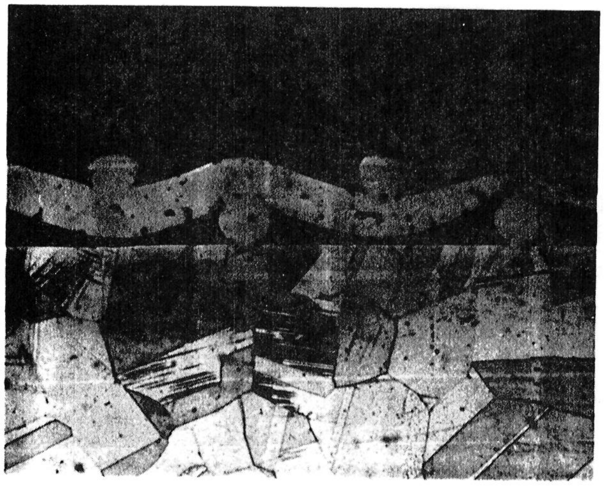


Fig. 6 Photomicrograph showing diffusion bonding of screen sintered to facesheet.

techniques were considered for internal facesheet wicking: sintering a screen to the facing, spot welding a screen to the facesheet, and grooving or roughening the facesheet by grid blasting. Grooving and roughening were rejected because of facesheet warping and the poor surface left for subsequent welding. Sintering the metal screen to the facing was chosen as having more structural integrity than spot welding. Figure 6 shows a photomicrograph of the sintered screen facesheet.

Two designs for the honeycomb core were considered: a foil-gage sintered screen material (shown in Fig. 7) and a metal screen sintered to foil-gage stainless steel material. Both designs met structural and wicking requirements, with the former offering better wicking and the latter providing a stronger structural design. Figures 8 and 9 show performance limits for a heat-pipe honeycomb sandwich panel constructed with Regimesh K material for sodium and potassium working fluids.

Sample honeycomb ribbons were formed by Astech* using standard equipment, and test samples were fabricated for evaluation. Both samples, sintered screen and screen on foil, met strength and wicking requirements.

Three different designs of honeycomb sandwich panels were fabricated: a resistance-welded core assembly for proof-pressure testing; a handmade, spot-welded core assembly for process testing and preliminary performance testing; and a machine-assembled resistance-welded prototype for delivery and final testing.

The proof-pressure test specimen was assembled, vacuum leak checked, pressure tested up to 3.45 MPa (500 psi), and vacuum leak checked again. During and after testing, the honeycomb panel assembly retained structural and vacuum integrity. A hand-built, spot-welded core assembly was fabricated, processed with potassium working fluid and, after preliminary test at 1075K (1475°F), was delivered to NASA Langley Research Center for further testing.

Fabrication of Test Models

Sandwich panels were fabricated by Astech using an automated procedure for simultaneously resistance welding honeycomb ribbons to the facesheets. Completed sandwich

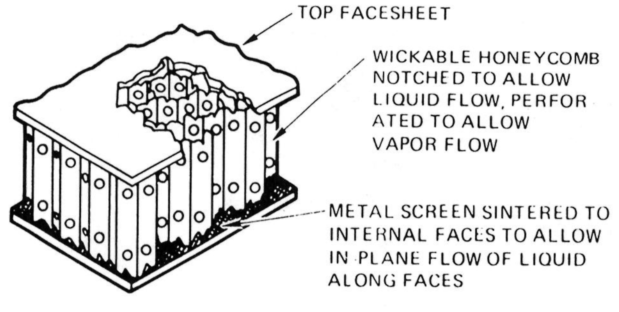


Fig. 5 Heat pipe sandwich panel concept.

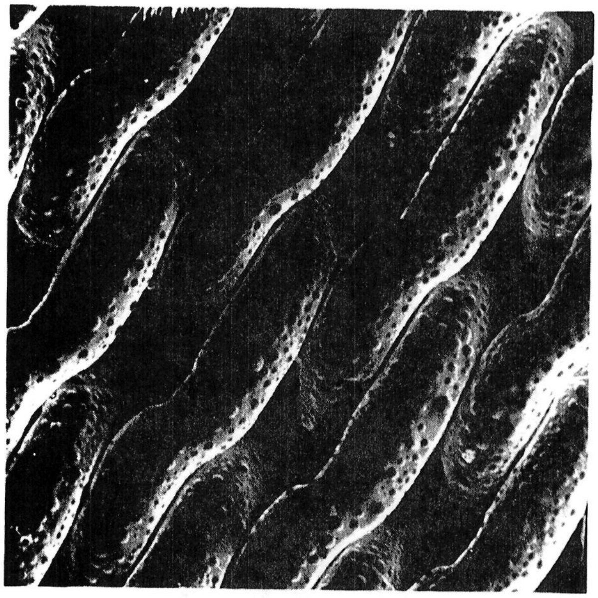


Fig 7 Photomicrograph of Regimesh K sintered screen.

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* A division of TRE Corporation, Santa Ana, CA.

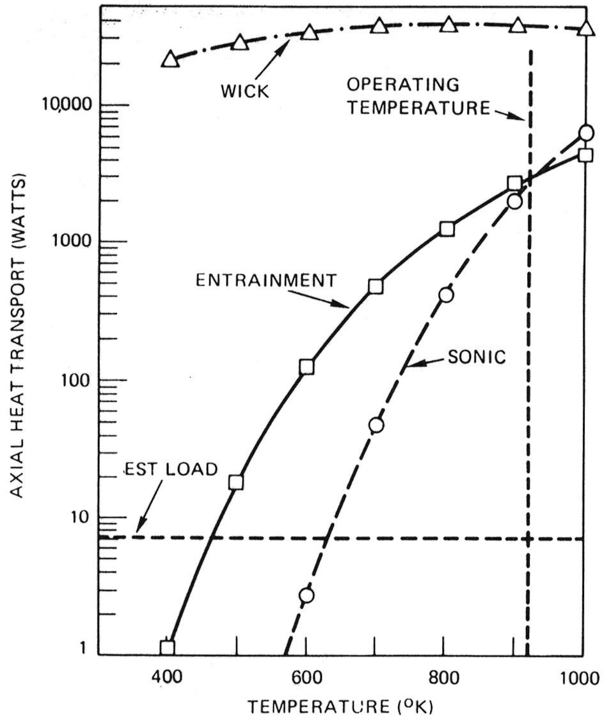


Fig. 8 Performance limits vs. temeprature for Regimesh K and soduim fluid.

panels were delivered to Hughes for further processing. Figure 10 shows the completed honeycomb panel. To eliminate potential contamination, panels were degreased, then fired in dry hydrogen at 1173K (1652°F). At this point the sidewalls and processing tube were welded in place, completing the heat pipe assembly. Figure 11 shows the complete heat pipe assembly. The panel was then fired in dry hydrogen at 1173K (1652°F) to remove oxides which were formed during final assembly. After leak check, the panel was placed in a vacuum chamber and heated to 1273K (1832°F) for final cleaning and outgassing. After final leak check, the panel was charged with working fluid and processed. During preliminary tests, the heat-pipe panel was isothermal over the active surface but did show some excess fluid in the processing tube. Figure 12 shows the heat-pipe panel during preliminary test.

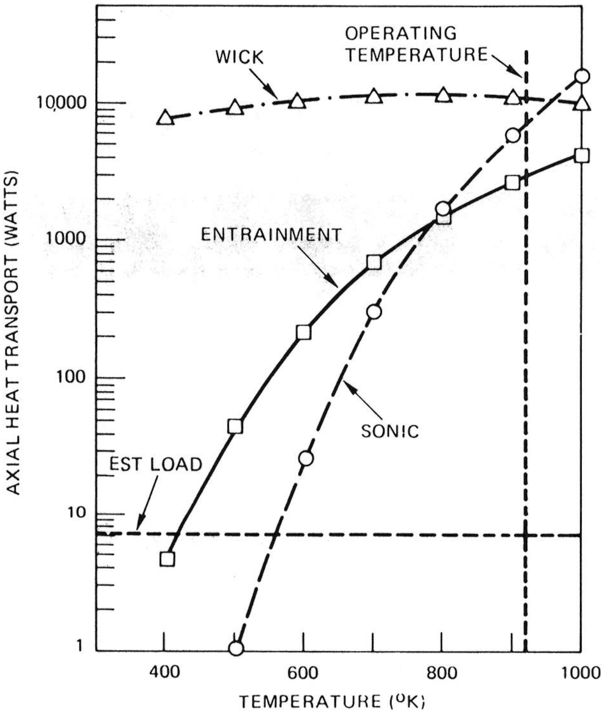


Fig. 9 Performance limits vs. temeprature for Regimesh K and potassium fluid.

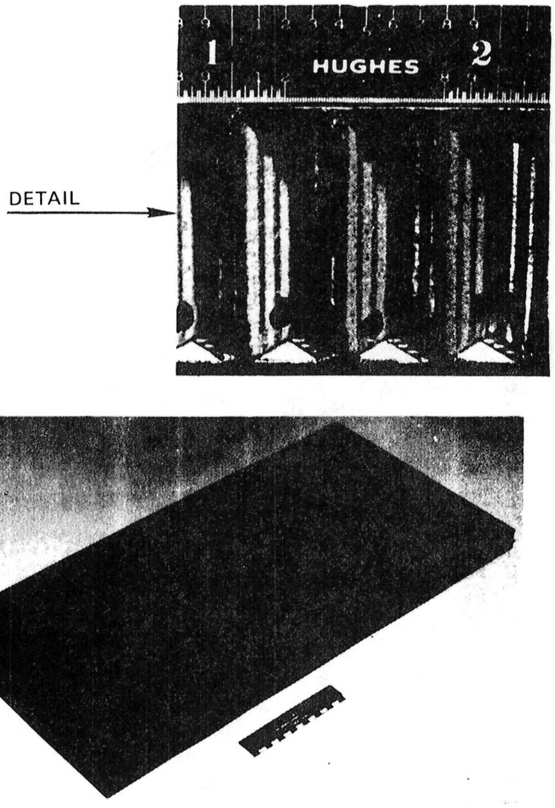


Fig. 10 Completed honeycomb panel prior to processing and final assembly.

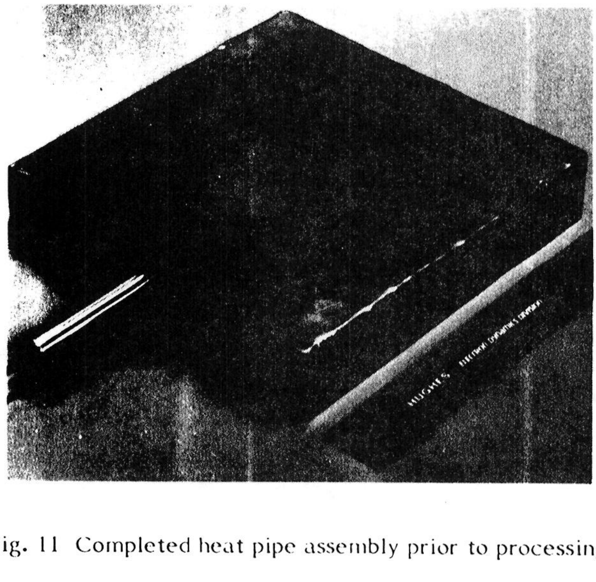


Fig. 11 Completed heat pipe assembly prior to processing.

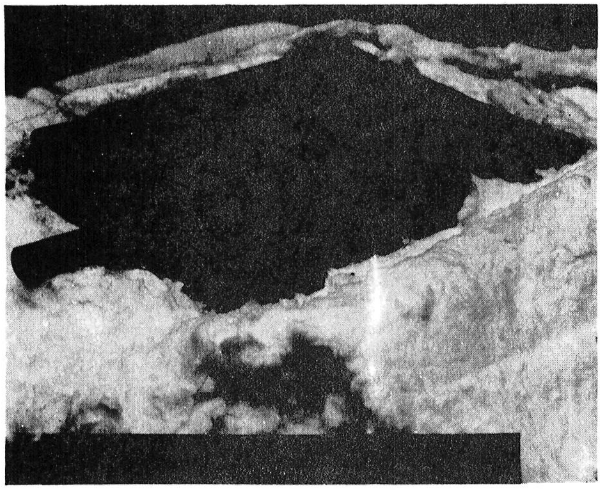


Fig. 12 Heat-pipe panel during preliminary testing.

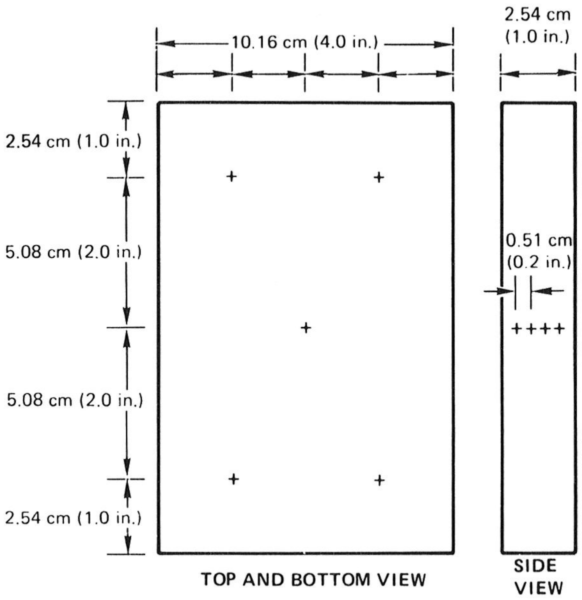


Fig. 14 Thermocouple locations.

Preliminary Radiant Heat Tests

Two prototype panels, one empty and the other containing potassium as the working fluid, were heated simultaneously by radiant heat lamps, as shown in Fig. 13. The heaters are quartz lamps with a heated length of 6.35 cm (25 in.) and having a rated power of 2500 watts (2.37 Btu/s) at 500 volts. Each lamp bank contains eight lamps. Six lamp banks were energized for each test. One of the panels was located directly under one lamp bank and the other panel was located the same vertical distance from the heaters but under another lamp bank. The distance of the panels from the lamp banks and the voltage to the lamps were varied. Power was applied as a step voltage input to the lamps. Power was applied for approximately 5 to 10 minutes and then abruptly shut off. Five thermocouples were located on the top and five on the bottom surfaces of the panels to measure temperature gradients, and four thermocouples were located along one side to study heat pipe startup performance. Thermocouple locations are shown in Fig. 14. The panels were tested with and without insulation covering the bottom and sides of the panels. The insulation prevents heat loss by free convection and simulates the adiabatic boundary conditions described in Ref. 1.

The panels were tested nine times, and results of those tests are summarized in Table 1. Comparisons of temperature histories of a heat-pipe and non-heat-pipe sandwich panel with insulated and uninsulated surfaces are shown in Fig. 15. For the insulated panel tests shown in Fig. 15(a), the temperatures of the back face of the non-heat-pipe panel and the heat-pipe panel temperatures continue to rise and slowly approach the temperature of the front facesheet of the non-heat-pipe panel as expected. Results of the uninsulated panel tests (Fig. 15(b)) indicate that all temperatures level off and appear to reach a steady-state condition. As mentioned in Refs. 8 and 9, during heat-pipe startup from the frozen state, a nearly constant temperature continuum region propagates from the evaporator to the condensor section of the heat pipe. As shown in

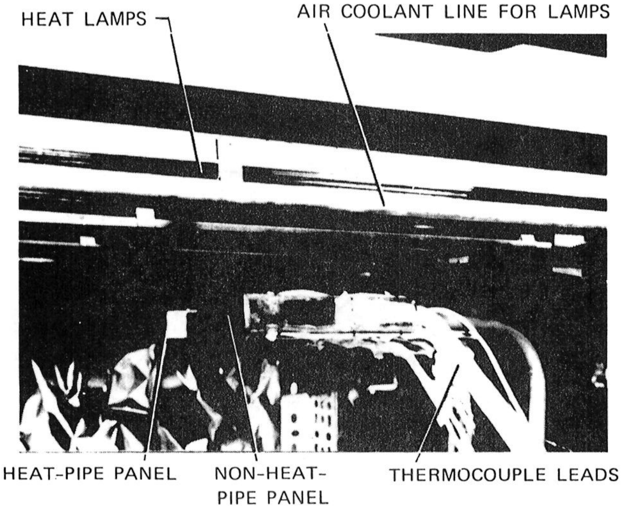
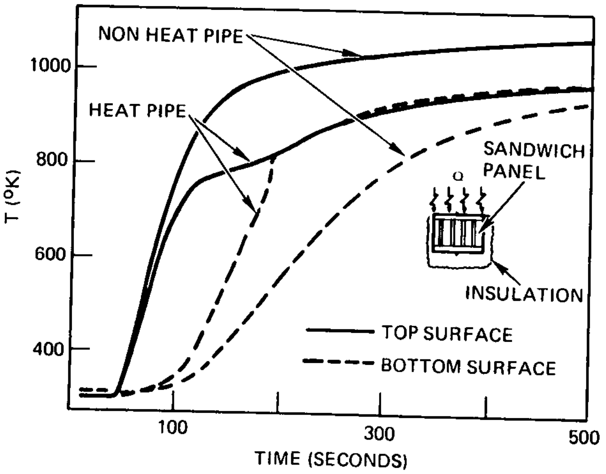


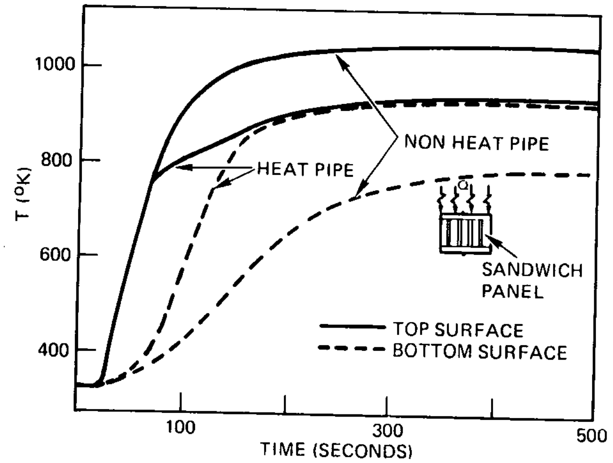
Fig. 13 Sandwich panels in position under radiant heat lamps.

Table 1 Summary of radiant heat tests of heat-pipe sandwich panel

RUN NO.	INSULATED	DIST. FROM HEATERS CM (IN.)	VOLTAGE V	MAX ΔT K (°F)		MAX T K (°F)	
				HEAT PIPE	NON HEAT PIPE	HEAT PIPE	NON HEAT PIPE
1	NO	10.5 (4.125)	380	338 (609)	403 (725)	891 (1145)	926 (1208)
2	↓		460	352 (634)	474 (854)	916 (1189)	970 (1287)
3	↓	5.1 (2.0)	250	313 (564)	407 (733)	803 (986)	863 (1093)
4	↓		300	343 (617)	467 (841)	856 (1081)	920 (1197)
5	↓		358	353 (635)	487 877)	904 (1167)	984 (1312)
6	YES		250	319 (575)	467 (840)	842 (1056)	894 (1150)
7	↓		307	354 (638)	490 (882)	923 (1202)	974 (1293)
8	↓		356	378 (680)	535 (963)	968 (1283)	1020 (1376)
9	↓		463	422 (760)	587 (1056)	1073 (1472)	1078 (1480)



(a) WITH INSULATION



(b) WITHOUT INSULATION

Fig. 15 Comparison of temperature histories of a heat-pipe and non-heat-pipe sandwich panel with and without insulation.

Fig. 15, once this continuum front reaches the back facesheet, the temperature there rises very rapidly as compared to the back facesheet of the non-heat-pipe panel. The temperature at which continuum flow begins and the rate at which the continuum front propagates depend on the working fluid, the temperature, the heat input and the sonic flow limit of the vapor.

The average reduction in maximum ΔT during startup using a potassium heat-pipe sandwich panel instead of a non-heat-pipe panel is 27 percent. It is possible that this reduction can be increased by using cesium as the working fluid; this is currently being investigated. Figure 16 gives some idea of the rate of continuum region growth. The results are characteristic of startup of liquid metal heat pipes as presented in Ref. 9. A typical comparison of temperature gradients through the depth of the honeycomb is shown in Fig. 17. As shown, the non-heat-pipe panel temperature gradient peaks slightly after that of the heat-pipe panel and is 29 percent higher for this particular run.

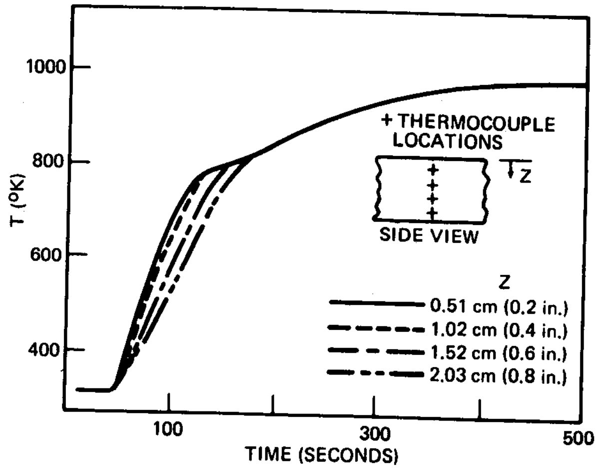


Fig. 16 Temperature histories along the side of the heat-pipe panel, illustrating startup performance.

Conclusions and Recommendations

Initial studies indicate the heat-pipe honeycomb sandwich panels can be fabricated. The technology and commercial equipment are available to construct all-welded machine-assembled honeycomb panels. At present, such honeycomb panels are constructed and formed into various shapes for use in airframe structures. Calculations and experiments with subscale test specimens indicate the feasibility of full-scale heat-pipe sandwich structures. Potential applications for heat-pipe sandwich panels include: alleviating excessive thermal stresses in jet engines, cooling electronic components and circuit cards, limiting thermal distortions in large structures such as space antennas, and as radiators for space platforms.

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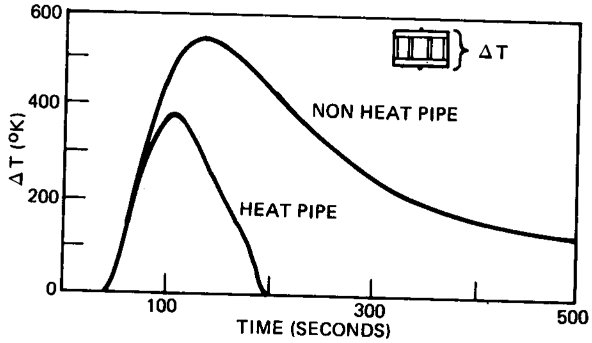

Fig. 17 Comparison of temperature gradients for a heat-pipe and non-heat-pipe sandwich panel.

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