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RADIANT HEATING TESTS OF SEVERAL 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 construction, were conceived as a means of alleviating thermal stress problems in the Langley Scramjet Engine. Test panels which utilized two different wickable honeycomb cores, facesheets with screen mesh sintered to the internal surfaces, and a liquid metal working fluid (either sodium or potassium) were tested by radiant heating at various heat-load levels. The heat-pipe panels reduced maximum temperature differences by 31 percent with sodium working fluid and 45 percent with potassium working fluid. Results indicate that a heat-pipe sandwich panel is a potential, simple solution to the engine thermal stress problem. Other interesting applications of the concept include: cold plates for electronic component and circuit card cooling, radiators for large space platforms, low-distortion large area structures (e.g., space antennas) and laser mirrors.

Introduction

NASA Langley Research Center is involved in a research program for the development of hydrogen-fueled airframe-integrated scramjet engine concepts.[1] The present engine design uses full-depth (1.8 in.) honeycomb sandwich walls whose heated surfaces are cooled regeneratively by circulation of hydrogen fuel through a cooling jacket as shown in figure 1. Typical honeycomb facesheet temperature histories, during engine startup and shutdown, are shown in figure 2 for two different materials (Hastelloy-X and Nickel 201). From these curves, a maximum value of net heat into the panel was calculated to be 7 Btu/ft^2-sec. The transient temperature differences across the sandwich walls cause excessive thermal stresses in the facesheets (over 200 ksi) and greatly reduce engine life. A suggested solution to this thermal stress problem offered in reference 1 is the incorporation of an additional heat exchanger on the unheated facesheet of the sandwich. This would not only complicate the original design, but it would add significant mass.

The heat-pipe sandwich panel was conceived as a simple cost- and mass-competitive method for alleviating thermal-stresses in the scramjet engine. The heat-pipe concept can drastically reduce transient temperature differences across the honeycomb walls with a modest (approximately 10 percent) increase in mass over the original, unacceptable non-heat-pipe design. This exceptional performance is possible because the integral heat-pipe sandwich panels synergistically combine the thermal efficiency of heat pipes with the structural efficiency of sandwich construction. In addition to reducing thermal stresses in engine structures, heat-pipe sandwich panels have potential applications to cold plates for electronic component and circuit card cooling, radiators for space platforms, low-distortion large area structures (e.g., space antennas) and laser mirrors.

To verify the feasibility of the heat-pipe sandwich panel concept in reducing thermal gradients and associated stresses in engine structures, a program was initiated (NASA Contract NAS1-16556) to fabricate and test several liquid metal heat-pipe sandwich panels. Preliminary radiant heating tests of hand-built prototypes[2] indicate that all-welded heat-pipe sandwich panels can be fabricated and successfully operated at elevated temperatures. The potassium filled prototype panel was capable of reducing startup temperature differences by approximately 30 percent. This paper summarizes the fabrication of these panels, discusses the subelement and radiant heat tests, compares startup performance of two working fluids (sodium and potassium), and discusses other potential applications.

Concept

The heat-pipe sandwich panel concept is shown schematically in figure 3. The panel consists of a wickable honeycomb core, internally wickable facesheets, and an appropriate working fluid. The term wickable is defined as porous and capable of wicking a working fluid by capillary pumping. For application to the scramjet engine, the working fluid could be either cesium, potassium or sodium. During operation, heat is absorbed at the heated face by the evaporation of the working fluid. The heated vapor flows (see inset, figure 3), 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. The core is perforated to allow intracellular vapor flow and is notched at both ends to allow intracellular liquid flow along the faces. The intracellular flow of both liquid and vapor is necessary to assure heat-pipe operation in the plane of the panel as well as through its depth. If intracellular flow is limited, a local

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panel hot spot could cause the depletion of working fluid in one region of the panel and an accumulation of fluid in another region, thus preventing normal heat-pipe operation. The faces are internally wickable to allow in-plane flow of liquid and to form a uniform film for evaporation, thus preventing local hot spots in the center of each honeycomb cell. The concept can accommodate many variations in the design of the internally wickable faces, choice of working fluid, and wickable core configuration depending on the application. The all-welded manufacturing technique eliminates concern for materials compatibility problems of the working fluid with a bonding agent.

Heat-Pipe Sandwich Panel Test Specimen

A sketch of the heat-pipe sandwich panels tested in this study is shown in figure 4. The panels are 6 inches square and 1 inch thick. The facesheets are made internally wickable by sintering one layer of 120 x 120 mesh 316 stainless-steel screen to 0.024 in. thick 316 stainless-steel sheet. Two different types of wickable stainless-steel honeycomb core designs are considered: (1) Dynapore - 165 x 1400 mesh stainless-steel woven wire screen having a thickness of 0.0055 in. and porous throughout (the material was oriented with the direction of the 1400 wires parallel to the plane of the panel) and (2) screen/foil composite - 325 x 325 mesh stainless-steel square weave screen (one layer 0.0025 in. thick) sintered to 0.003 in. thick 316L stainless-steel foil. Photomicrographs of the two types of core are shown in figure 5. The Dynapore core permits liquid flow between cells because it is porous through its thickness. The screen/foil core relies solely on notches cut in the top and bottom of the honeycomb cells (fig. 3) for liquid flow between cells. The core is perforated with two holes 0.125 in. in diameter; one at the top and one at the bottom of each cell wall to allow vapor flow between cells.

The entire sandwich panel is fabricated by simultaneously spot welding the core ribbons to each other and to the facesheets, forming a 0.375 in. cell configuration (fig. 4). The honeycomb panel sidewalls are formed by welding 321 stainless-steel sheet, 0.05 in. thick, to the facesheets. Panels were vacuum and leak checked, cleaned by vapor degreasing, furnace fired, outgassed in a vacuum chamber, and then processed with working fluid. Details of cleaning and processing procedures are given in reference 3. A total of 11 sandwich panels (2 evacuated and used as controls and 9 filled with working fluid) were fabricated and are listed in Table 1. The mass of both types of panels (unfilled) was very similar (0.0232 lbs/in.^2 for Dynapore core and 0.0239 lbs/in.^2 for screen/foil core). The mass of a filled heat-pipe panel is 10 percent heavier than an unfilled, non-heat-pipe panel.

Preliminary Tests

Several preliminary tests were needed to obtain data necessary to design and fabricate the heat-pipe sandwich panel test specimens. Samples of wick material used for the internally wickable faces and honeycomb core were tested to determine necessary wicking parameters. Three different types of stainless-steel honeycomb core sandwich panels were fabricated for preliminary testing: a resistance-welded core assembly for proof-pressure and weld integrity testing; a resistance-welded core assembly for structural compression testing; and a hand-built, spot-welded core assembly (ref. 2) for process and performance testing.

Determination of Wick Parameters

Wicking parameters (capillary radius (r_c) and permeability (k)) of the Dynapore and screen/foil composite core were determined by a series of tests. Details of these tests are presented in reference 3. Values of capillary radius of several wick samples were calculated by measuring the maximum static height a liquid will rise, against gravity, in a saturated environment when the bottom of the wick is immersed in the test fluid (methanol in this case). Results indicate an r_c of 9.1×10^{-4} in. for Dynapore and 1.36×10^{-3} in. for the screen/foil composite.

Determination of the permeability involves the measurement of maximum axial heat transport of heat-pipe test vehicles. Cylindrical stainless-steel heat pipes 0.5 in. in diameter and 12 in. long were fabricated with single layers of candidate wick material and methanol working fluid. These heat pipes were heated until a wicking limit was reached and this maximum value of axial heat transport was used to calculate the permeability as described in reference 3. Results of these tests indicate a k of 1.16×10^{-7} in.^2 for Dynapore and 4.47×10^{-7} in.^2 for the screen/foil composite.

The values of k and r_c were used in standard analytical expressions to calculate performance envelopes for each of the wickable core designs and sodium or potassium working fluids (figs. 6 and 7). The wicking and entrainment limits for the Dynapore material are slightly higher than for the screen/foil composite, hence, Dynapore would have slightly better performance. The circular symbol in the figure is the location of the operating design point for the engine application and it is well within the feasible region for both types of working fluids and cores.

Pressure Test Panel

A small stainless-steel test specimen (2 x 2 x 1 in.) with a facesheet thickness of 0.02 in., a sidewall thickness of 0.05 in., a 0.003 in. honeycomb foil thickness, and 0.375 in. cell size was pressure tested to check construction and weld integrity. The panel withstood internal pressures up to 560 psi and displayed no signs of structural damage or leakage. For the present application, the heat-pipe panels will operate at 1100°F; this results in an internal vapor pressure of 0.44 psi for sodium and 1.89 psi for potassium working fluids.

Compression Test Specimens

Several structural sandwich test specimens 1.5 in. square and 1.0 in. thick with 0.025 in. thick facesheets were tested to determine the ultimate compressive strengths of each type of core (Dynapore and screen/foil). The ultimate compressive strength of the screen/foil core was 484 psi compared to 147 psi for the Dynapore core. The low compressive strength of the Dynapore core is probably due to the 1400 mesh fiber direction being perpendicular to the direction of the load while the 165 mesh fiber direction is parallel to the loading direction. Some optimum orientation of this material would be desirable to produce a core with suitable tensile, compressive, and shear properties. The ultimate compressive strength of the honeycomb sandwich with 0.003 in. thick steel foil without screen sintered to it is 340 psi, hence, the screen/foil composite core increases the compressive strength of a foil core by 42 percent. Further structural testing (tension and shear) would be required to determine the structural integrity of the wickable cores as compared to the nonwickable, original foil design.

Prototype Panels

Two hand-built prototype panels, one empty and the other containing potassium, measuring 6 x 6 x 1.1 in. were radiantly heated simultaneously as described in reference 2 to evaluate processing procedures and panel performance. The core ribbon consisted of 150 mesh stainless-steel screen spot-welded to 0.003 in. thick stainless-steel foil and formed into a corrugated shape. The core was positioned to form rows 1.0 in. apart and then manually spot welded to the facesheets (i.e., the panel is actually a corrugated web panel). The facesheets were formed by spot-welding 150 mesh screen to 0.05 in. thick stainless-steel sheet. Results of radiant heat tests[2] of this panel indicate that the heat-pipe panel was operational and reduced maximum temperature gradients by approximately 30 percent.

Radiant Heat Tests of Heat-Pipe Sandwich Panels

A summary of the panels tested, test conditions, and panel performance is presented in Table 2. The sandwich panels were radiantly heated with quartz lamps having a lighted length of 25 in. and a rated power of 2.37 Btu/sec at 500 volts. Eight lamps are contained in a lamp bank (reflective container) and are spaced 0.5 in. apart. A total of six such lamp banks were energized for each test. The quartz lamps were cooled by pressurized air flowing through pinholes in tubes shown in figure 8. Two panels, one empty and the other filled with working fluid were tested simultaneously. Both panels were located the same vertical distance from the heaters (2 in.). Power was applied as a step voltage input to the heaters and was held for approximately 20 minutes. Voltage varied from 250 to 450 volts as shown in Table 2. At 450 volts, the net heat to the panel was approximately equal to the design point heat load of 7 Btu/ft^2-sec. The panels were instrumented with chromel/alumel thermocouples; one thermocouple was located in the center of each panel (top and bottom) and six thermocouples were located along one side (through the depth) to monitor heat-pipe startup performance. Both panels were insulated over the bottom and side surfaces to reduce free convective heat losses in an attempt to simulate an adiabatic boundary condition. Data were recorded at a rate of 20 frames per second by a digital recording system.

Radiant Heat Test Results

Prior to heating, the working fluid in the heat-pipe panel is frozen or solid and, hence, the heat pipe must startup from this frozen state. As mentioned in references 4 and 5, during heat-pipe startup from a frozen state a nearly constant temperature continuum region propagates from the evaporator to the condensor section of the heat pipe (heated or front facesheet to back facesheet in this application). The temperature above which continuum flow occurs was calculated using the following equation:

$$T^* = \frac{\pi}{2}\left(\frac{M}{g_0 R}\right)\left(\frac{\mu_v}{\rho_v \psi}\right)^2$$

where T^* is the temperature above which continuum flow occurs, M is the molecular weight of the working fluid, g_0 is a gravitational constant, R is the universal gas constant, μ_v is the viscosity of the vapor, ρ_v is the density of the vapor and the mean free path ψ is assumed to be .01 times the maximum vapor space dimension (honeycomb cell size). The equation indicates that continuum flow occurs above 605°F for potassium and above 800°F for sodium. The approximation of a continuum region temperature of 800°F is sufficient for analysis of a long, sodium heat pipe (ref. 5), however, the analysis of startup of the heat-pipe sandwich panel is complicated by the short length of the heat pipe (through the depth of the honeycomb). Since startup performance is the critical factor in panel design for this application, testing with several working fluids is necessary. Results of the radiant heat tests indicate that three of the nine heat-pipe sandwich panels operated successfully. Results of the successful tests are summarized in Table 2. Reasons for failure of the other six panels will be discussed in a later section. Performance of a sodium-filled heat-pipe sandwich panel with screen/foil core is shown in figure 9.

As shown in figure 9, the temperatures of the heated facesheets of both the heat-pipe and non-heat-pipe panels coincide up to a temperature of about 700°F. At 700°F, it can be assumed that the heat-pipe panel is beginning to operate, hence, more heat is transported to the back facesheet thus lowering the heated facesheet temperature. Once the continuum vapor flow region reaches the back facesheet of the heat-pipe panel, the temperature there rises very rapidly and approaches the front facesheet temperature. The back facesheet temperature of the non-heat-pipe panel begins to rise at a later time and at a lower rate than the heat-pipe panel and remains considerably lower (about 380°F) than the front facesheet. There is a steady-state front-to-back facesheet temperature difference (fig. 9) which indicates significant heat loss through the insulation on the unheated side of the test panel. The temperature difference of the heat-pipe panel at steady state should be lower than that shown in figure 9. This discrepancy is probably due to local temperature variations in the heated facesheet caused by air flow used to cool the heat lamps. Previous experience with the hand-built panels[2] which had five thermocouples over each surface indicate that front-to-back facesheet temperature differences were negligible at steady state.

A comparison of front-to-back facesheet temperature difference histories (fig. 10) indicates that the peak temperature difference for the heat-pipe panel occurs slightly before that of the non-heat-pipe panel and is 31 percent lower. Results for the potassium-filled panel with Dynapore core are shown in figure 11, which shows a decrease in maximum temperature difference of 46 percent. As shown in Table 2, the percentage decrease in maximum temperature difference remains fairly constant with respect to voltage input or heating rate for the range indicated. Although test data are not available at this writing, it is estimated based on the low value for T^* of 425°F that cesium will be capable of reducing the maximum temperature difference by 55 percent.

Figure 12 gives some indication of continuum region growth through the depth of the sodium filled honeycomb panel (panel no. 3, run 12). It takes 33 seconds for the thermocouple at $z = 1.0$ to reach 800°F after the thermocouple at $z = 0.0$ has reached 800°F (the calculated continuum region temperature). For a potassium panel (panel no. 1, run 3), it takes approximately 22 seconds assuming a continuum temperature of 605°F.

Failure of Test Specimens

The cesium panel with screen/foil core failed because of an obvious pinhole-sized leak in one of the welded 90 degree joints and the loss of vacuum as well as working fluid. The reason for failure of the other five test specimens (three potassium panels and one sodium panel with screen/foil core and one sodium panel with Dynapore core) was not immediately obvious. However, after heating the panels in a bell jar and inspection with a residual gas analyzer, it was apparent that each of the failed specimen had leaks in the welded joints. The welded joint problem can be avoided in the future by paying closer attention to the method of edge closeout of the panels. These failures indicate that fabrication methods must be improved and do not suggest a basic problem with the concept.

Potential Applications

Results of this study have indicated that the heat-pipe sandwich panel can significantly reduce temperature differences and, hence, could be a solution to thermal stress problems in engine structures. Other potential applications (using different working fluids) indicated in figure 13 include: cooling electronic components or circuit cards, limiting thermal distortions in large space structures (e.g., antennas, lasers, or other optical systems), serving as radiators for space stations or space transportation systems (Shuttle payload bay doors) and cooling leading edges for hypersonic cruise or earth entry vehicles. Because of the ability of the heat-pipe sandwich panel to contain high internal pressures, it is an attractive concept for cryogenic space radiators in which internal pressure is very high at ambient conditions. A radiator application which has the potential of reducing mass by 50 percent over other heat-pipe or fluid loop systems is currently being investigated by Hughes Aircraft Company under contract to NASA Johnson Space Center (NAS9-16581).

Conclusions

Results of this study indicate that stainless-steel heat-pipe sandwich panels can be fabricated and operated successfully using potassium or sodium as working fluids. Two sodium-filled heat-pipe panels with a screen/foil core and one potassium-filled panel with a woven wire mesh core operated successfully at maximum temperatures ranging from 1030°F to 1569°F. Failure of six of the heat-pipe panels was a result of fabrication procedures and is not indicative of a basic problem with the concept. The reduction in maximum ΔT attainable by using a heat-pipe panel is 31 percent for sodium working fluid and 46 percent for potassium working fluids. It is estimated that if cesium is used as the working fluid, the maximum temperature difference can be reduced by 55 percent. The limited structural tests of the screen/foil core indicate that the heat-pipe sandwich concept does not degrade the structural performance of the original (non-heat pipe) design. Hence, it appears the concept is a promising solution for alleviating excessive thermal stresses in the Langley Scramjet Engine. Other potential applications of the concept include: cold plates for electronic component and circuit card cooling, radiators for large space platforms, low-distortion large area structures (e.g., space antennas), and laser mirrors.

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Table 1 Matrix of fabricated panels

WORKING FLUID / CORE MATERIAL	NUMBER OF FABRICATED PANELS			
	SODIUM	POTASSIUM	CESIUM	NONE
SCREEN/FOIL	3	3	1	1
DYNAPORE	1	1	0	1

Table 2 Summary of radiant heat tests of heat-pipe sandwich panels

PANEL NO.	RUN NO.	WORKING FLUID	CORE	VOLTAGE, V	RATED POWER OF INDIVIDUAL LAMP Btu/sec	MAX ΔT, °F		PERCENT DECREASE IN MAX ΔT
						HEAT PIPE	NONHEAT PIPE	
1	1	POTASSIUM	DYNAPORE	300	1.23	531	930	43
	2			350	1.57	509	927	45
	3			400	1.94	545	1001	46
	4			450	2.28	578	1061	46
2	5	SODIUM	SCREEN/ FOIL	300	1.23	605	855	29
	6			350	1.57	599	960	38
	7			400	1.94	639	1019	37
	8			450	2.28	690	1068	38
3	9	SODIUM	SCREEN/ FOIL	250	.949	613	844	27
	10			300	1.23	726	879	17
	11			350	1.57	695	1013	31
	12			400	1.94	744	1067	30
	13			450	2.28	765	1066	28

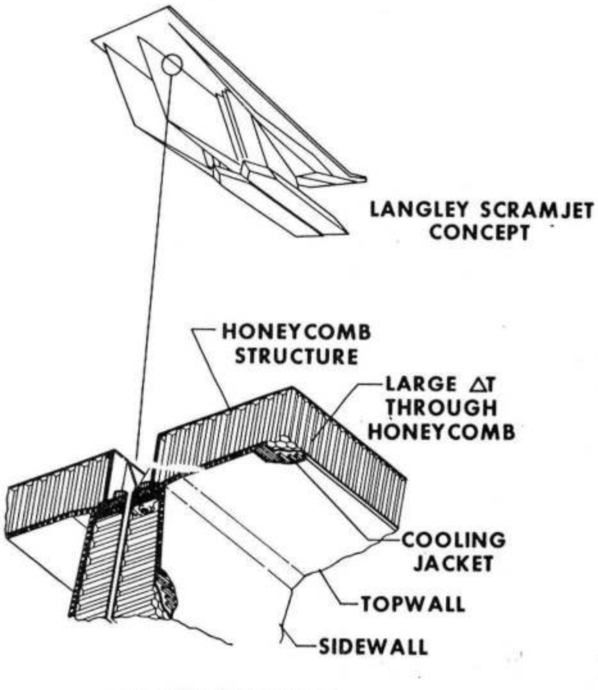

Fig. 1 Features of cooled scramjet structure.

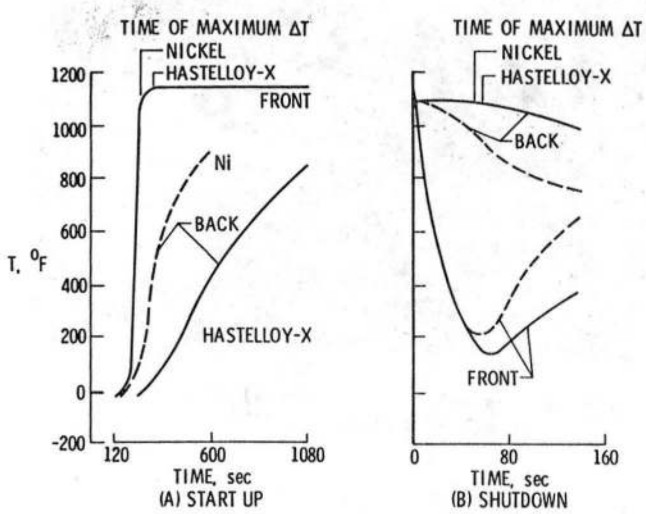

Fig. 2 Predicted honeycomb panel facesheet temperatures during engine transients.

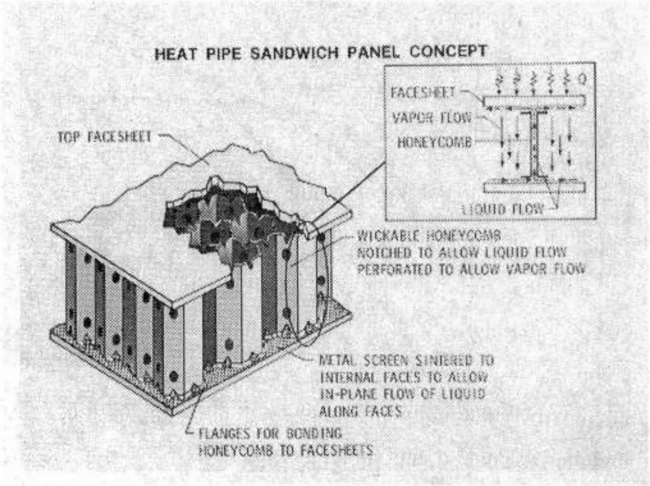

Fig. 3 Heat-pipe sandwich panel concept.

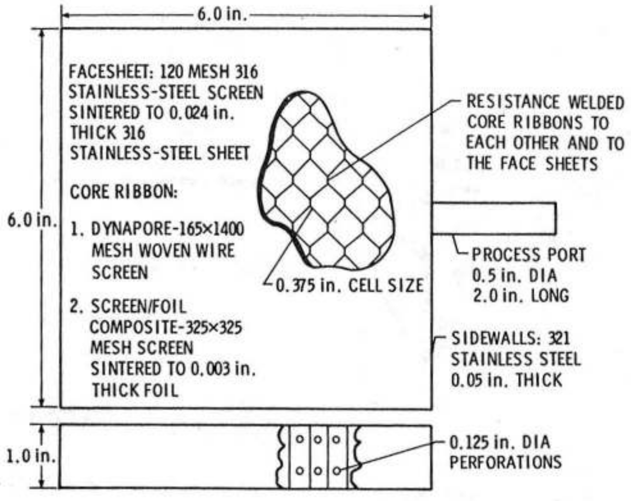

Fig. 4 Sketch of heat-pipe sandwich panel.

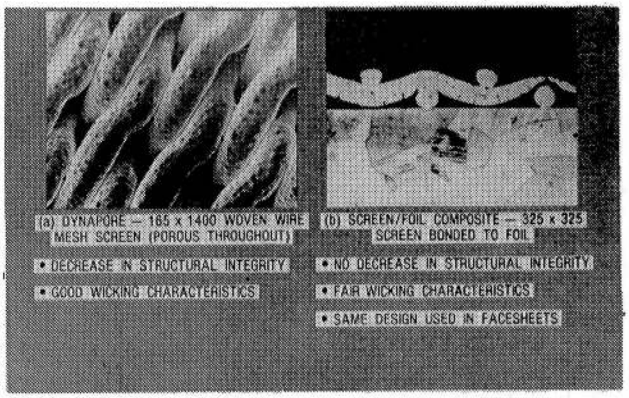

Fig. 5 Photomicrographs (300x) of stainless-steel wickable core materials.

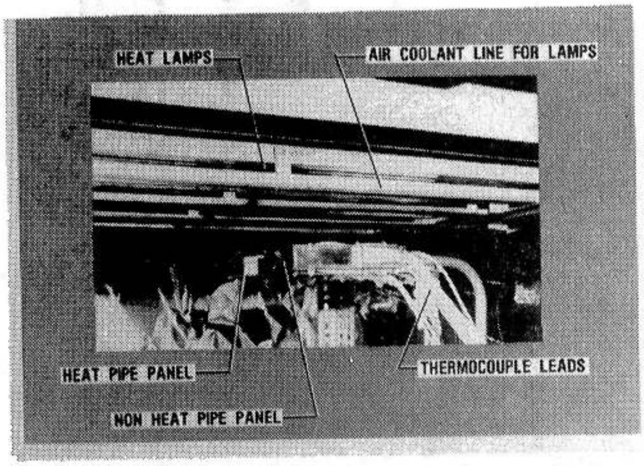

Fig. 8 Sandwich panels in position under radiant heat lamps.

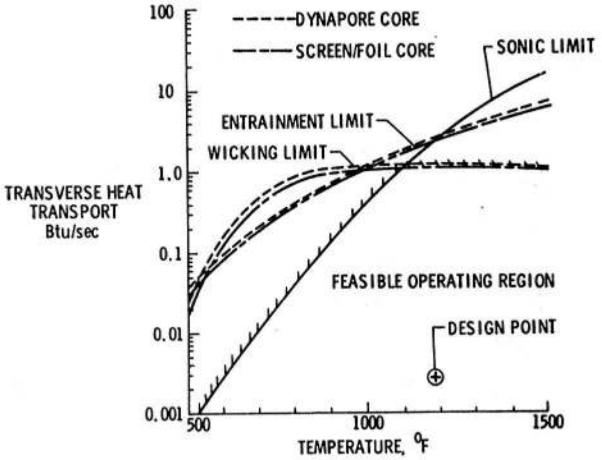

Fig. 6 Performance limits versus temperature for sodium working fluid.

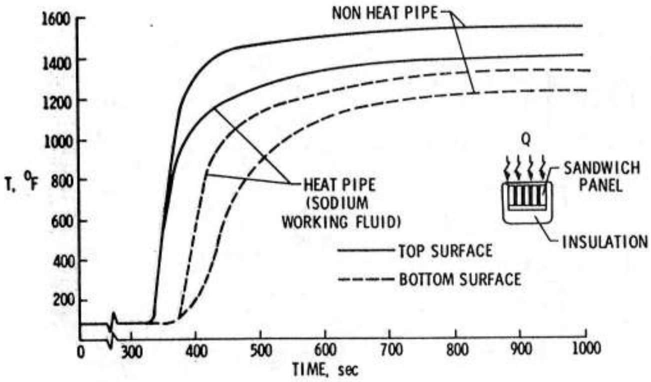

Fig. 9 Comparison of facesheet temperature histories of a sodium-filled heat-pipe panel and a non-heat-pipe panel (Run 11).

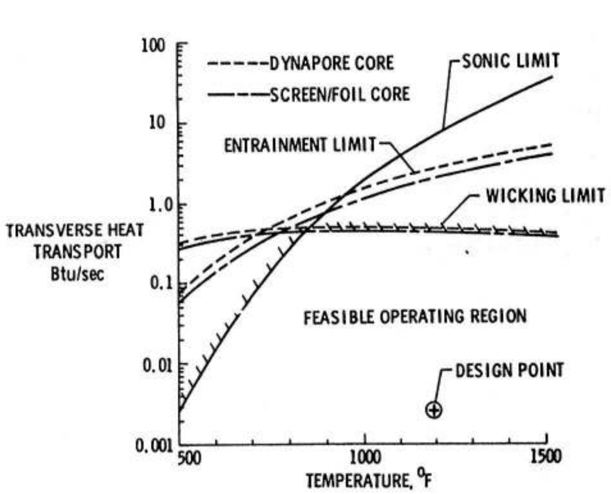

Fig. 7 Performance limits versus temperature for potassium working fluid.

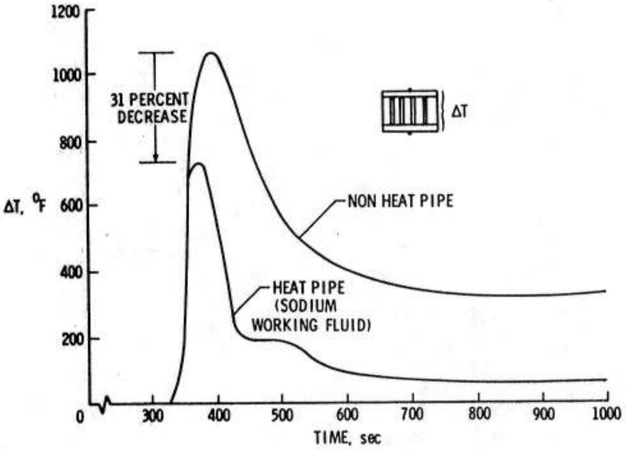

Fig. 10 Comparison of facesheet temperature difference histories of a sodium-filled heat-pipe panel and a non-heat-pipe panel (Run 11).

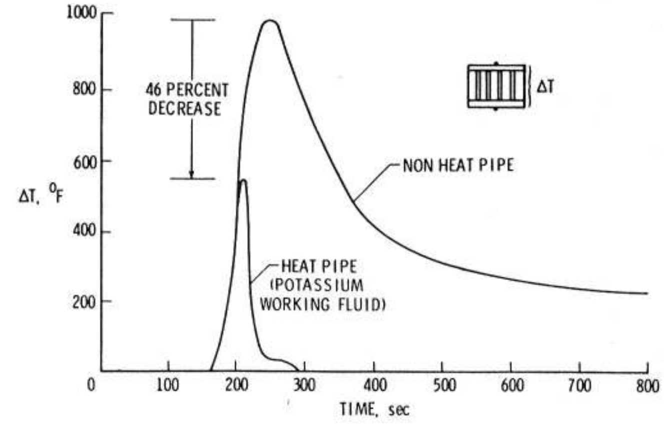

Fig. 11 Comparison of facesheet temperature difference histories of a potassium-filled heat-pipe panel and a non-heat-pipe panel (Run 3).

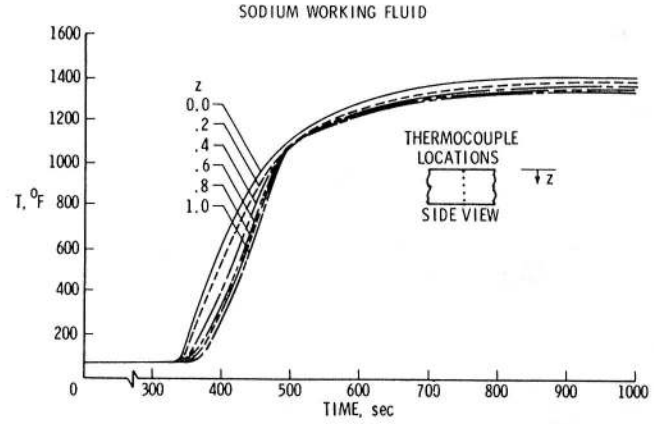

Fig. 12 Temperature histories along the side of a sodium-filled heat-pipe panel illustrating startup performance (Run 11).

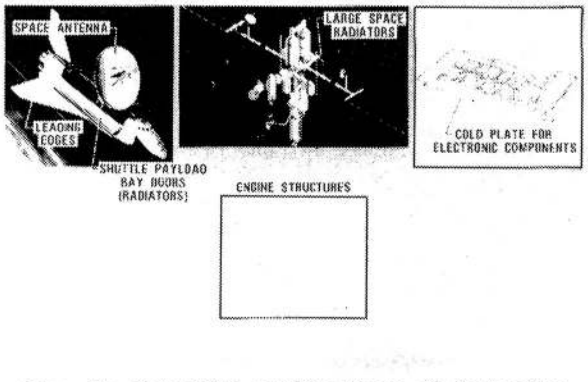

Fig. 13 Potential applications of heat-pipe sandwich panels.

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16. Abstract

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