

# NASA Contractor Report 165962

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## Fabrication and Development of Several Heat Pipe Honeycomb Sandwich Panel Concepts

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## NOMENCLATURE

$A_v$	Vapor area
$A_w$	Wick cross-sectional flow area
$g$	Acceleration due to gravity
$h$	Capillary height
$K$	Permeability of wick
$L$	Length
$L_{eff}$	Effective length of heat pipe
$M$	Molecular weight
$\Delta P_c$	Capillary head pressure difference
$\Delta P_l$	Pressure drop in the liquid
$\Delta P_v$	Pressure drop in the vapor
$\Delta P_g$	Pressure drop due to gravity
$Q_{max}$	Quantity of heat, maximum
$Q_e$	Entrainment limit
$Q_s$	Sonic limit
$Q_w$	Wicking limit
$r_v$	Radius of vapor space
$r_p$	Effective pore radius
$R_o$	Universal gas constant
$T$	Temperature
$T^*$	Continuum transition temperature

$\gamma$	Ratio of specific heats
$\theta$	Contact angle
$\phi$	Inclination angle of heat pipe
$\lambda$	Latent heat of vaporization
$\mu_l$	Dynamic viscosity of liquid
$\mu_v$	Dynamic viscosity of vapor
$\rho_l$	Density of liquid
$\rho_v$	Density of vapor
$\sigma$	Surface tension
$\psi$	Molecular mean free path

## FOREWORD

This report was prepared by the Hughes Aircraft Company, Electron Dynamics Division, for the NASA Langley Research Center.

The purpose of this program was to determine the feasibility of fabricating honeycomb panel chambers which can be used with alkali metal fluids. The effort is defined as exploratory development. The scope of the program includes the fabrication, testing, and delivery of eleven (11) prototype panels. The program was conducted in accordance with the requirements and instructions of NASA Contract NAS1-16556, with revisions mutually agreed on by NASA and HAC-Torrance.

Mr. A. Basiulus was the HAC-Torrance Program Manager. Mr. T.R. Lamp was responsible for manufacturing concept evaluation, honeycomb structure design, and preliminary performance predictions. Mr. H.J. Tanzer was responsible for heat pipe fabrication, processing and testing, and final performance predictions. Technical direction was provided by Mr. C. J. Camarda, Technical Representative, NASA Langley Research Center.

## 1.0 SUMMARY

The feasibility of fabricating and processing liquid metal heat pipes in a low mass honeycomb sandwich panel configuration for application on the NASA Langley Airframe-Integrated Scramjet Engine was investigated. A variety of honeycomb on panel facesheet and core-ribbon wick concepts were evaluated within constraints dictated by existing manufacturing technology and equipment. Concepts evaluated include: type of material, material and panel thicknesses, wick type and manufacturability, liquid and vapor communication between honeycomb cells, and liquid flow return from condenser to evaporator facesheets. In addition, performance of honeycomb panel constituents was evaluated analytically.

The design selected for fabrication consists of an all-stainless steel structure, sintered screen facesheets, and two types of core-ribbon; a diffusion-bonded wire mesh and a foil-screen composite. Cleaning, fluid charging, processing, and process port sealing techniques were established. The liquid metals potassium, sodium and cesium were used as working fluids. Eleven honeycomb panels 15.24 cm (6.0 in) x 15.24 cm (6.0 in) x 2.94 cm (1.16 in) were delivered to NASA Langley for extensive performance testing and evaluation; nine panels were processed as heat pipes, and two panels were left unprocessed.

## 2.0 INTRODUCTION

Design studies of the NASA Langley Airframe-Integrated Scramjet Engine<sup>1</sup> have indicated potential thermal stress problems. The thermal stresses result from large transient temperature gradients across the honeycomb sandwich walls of the engine structure during engine startup and shutdown. The isothermalizing characteristics of conventional heat pipe panel designs could reduce structural temperatures at local hot spots. 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 substantial increases in panel mass. An alternate solution to these problems is the development of an integral heat pipe sandwich panel<sup>2</sup> that synergistically combines the thermal efficiency of heat pipes with the structural efficiency of honeycomb sandwich construction, with only a negligible increase in mass. A preliminary evaluation of such a concept has been reported<sup>3</sup>.

The purpose of the program was to determine the feasibility of fabricating several alkali metal heat pipe honeycomb test panels which can operate at 922°K and reduce thermal gradients sufficiently to satisfy the Scramjet Engine requirements. The program consisted primarily of three tasks:

- Task I - Performance Evaluation of Honeycomb Panel Constituents.
- Task II - Survey and Screening of Candidate Assembly Concepts.
- Task III - Fabrication of Selected Concepts.

The results of these tasks are presented in Sections 3, 4 and 5, respectively.

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### 3.0 PERFORMANCE EVALUATION

The purpose of this task was to evaluate the performance of the honeycomb panels. The honeycomb panel constituents investigated were wicking material, working fluid, and structure.

#### 3.1 Determination of Wick Parameters

The wicking parameters, permeability (K), and effective pore radius ( $r_p$ ) were determined for candidate wick materials. Pore size measurements were made using the static height method (Figure 1), an experimental technique for measuring the maximum height (h) to which a liquid will rise in a wick material when the bottom of the material is immersed in the liquid<sup>4</sup>. The effective pore radius was then determined using the pressure balance

$$P_{\rho}gh = \frac{2\sigma \cos\theta}{r_p}$$

and solving for  $r_p$ . The conservative approach of obtaining the effective pore radius corresponding to the rising liquid level was used. During these measurements, the wick material was enclosed in a saturated atmosphere to avoid attaining too low a maximum height which can result from evaporation. Methanol was used as the test fluid.

Determination of permeability (K) involves the measurement of maximum axial heat transport of heat pipe test vehicles. Stainless steel cylindrical heat pipe samples with methanol working fluid, 1.27 cm (0.5 inch) in diameter and 30.48 cm (12 inches) in length were fabricated with single layers of candidate wick materials, and tested for maximum heat transport. The test set-up, test samples, and methods for the determination of heat pipe performance are described in Figure 2. Heat pipe operational failures are generally caused by exceeding one of several performance limits, resulting in a deficiency of liquid working fluid available for evaporation at the heated surfaces of the evaporator. For the specific geometry and test conditions of the fabricated heat pipe test vehicles, the maximum performance is wick limited.

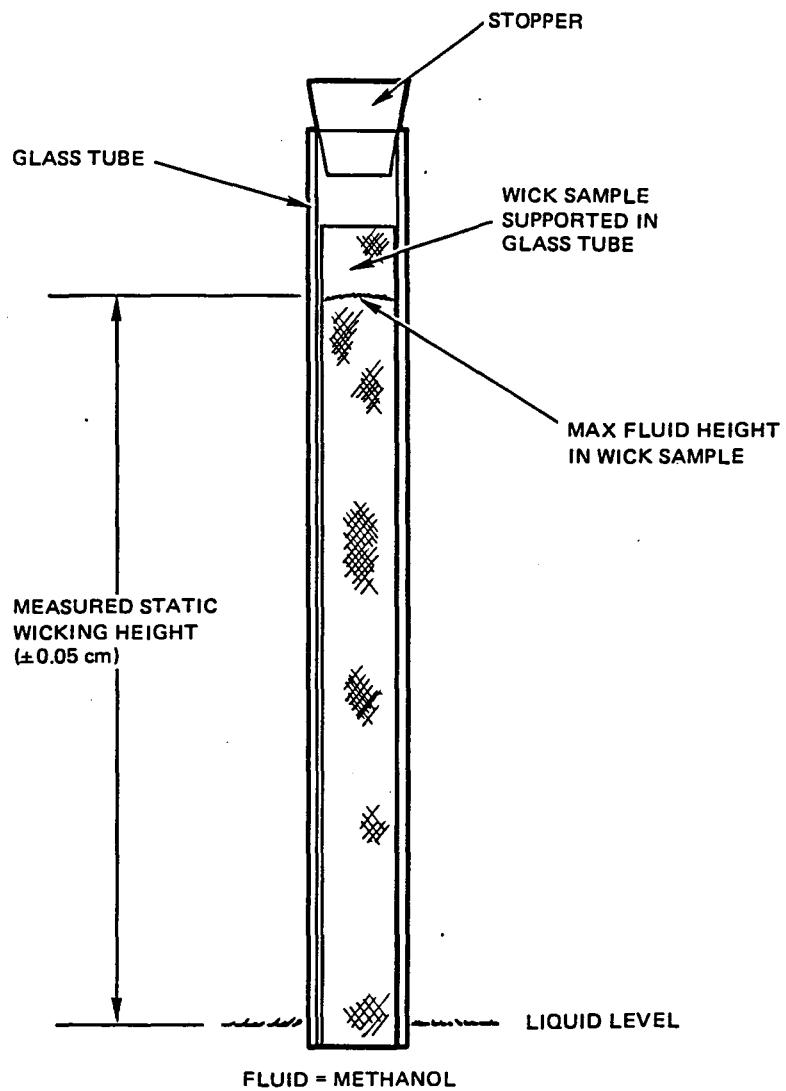
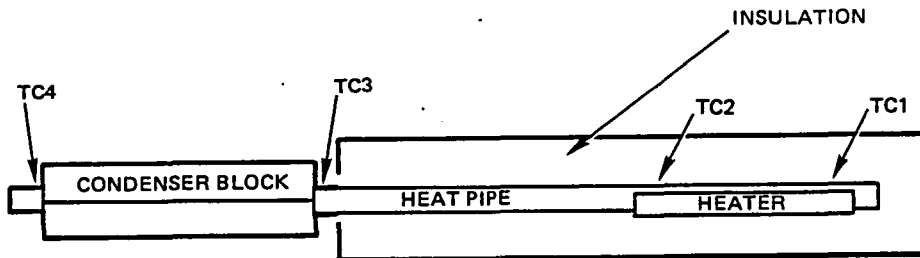


Figure 1 Measurement method for static wicking height.



- **HEAT PIPE:** 1.27 cm DIA. x 0.051 cm WALL x 30.48 cm LONG  
 ENVELOPE - 316 STAINLESS STEEL  
 WICK - HOMOGENEOUS, CONCENTRIC ANNULUS TYPE.  
 EACH TEST HEAT PIPE HAD ONE LAYER OF  
 CANDIDATE WICK ON I.D.  
 WORKING FLUID-METHANOL, 100% FILL EXPERIMENTALLY  
 DETERMINED.
- **HEATER:** THERMOFOIL, MINCO-TYPE M, 180  $\Omega$ , 5.84 cm LONGx3.25 cm WIDE  
 TAPED TO HEAT PIPE WITH KAPTON TAPE
- **THERMOCOUPLES:** TYPE T, RDF CORP THERMOFOIL
- **CONDENSER:** WATER COOLED CU CLAMSHELL BLOCK, 8.9 cm LONG
- **INSULATION:** 3 LAYERS LOOSE WRAPPED ALUMINIZED MILAR COVERED  
 BY 1.27 cm THICK WALL CLOSED-CELL FOAM RUBBER TUBE
- **TILT MEASUREMENT:** VERNIER HEIGHT GAGE
- **TEST METHOD:** FOR EACH TILT CONDITION - HEATER POWER INCREASED  
 IN SMALL INCREMENTS UNTIL A RUN-AWAY CONDITION  
 IS EXHIBITED BY TC 1. HEAT PIPE TEMPERATURES ARE  
 ALLOWED TO FULLY STABILIZE BETWEEN POWER INCREMENTS

NOTE: TC = THERMOCOUPLE

Figure 2 Description of test method and set-up.

The wick limit is based on a pressure drop balance of the working fluid within the heat pipe. Heat pipe failure will occur when the capillary pumping ability ( $\Delta P_c$ ) is exceeded by the sum of the vapor pressure drop ( $\Delta P_v$ ), the pressure drop of the liquid in the wick structure ( $\Delta P_l$ ), and the adverse hydrostatic liquid head ( $P_g$ ):

$$\Delta P_v + \Delta P_l + \Delta P_g > \Delta P_c$$

Substituting into this equation the appropriate pressure drop terms, neglecting  $\Delta P_v$ , and considering the horizontal tilt case ( $\Delta P_g \sim 0$ ), the following expression solving for the permeability (K) results:

$$K = Q_{\max} \left[ \frac{1}{\frac{P_l \sigma \lambda}{\mu_l} \frac{Aw}{L_{\text{eff}}} \left( \frac{2}{r_p} \right)} \right]$$

Plotted in Figure 3 are measured heat pipe dryout points at various angles of inclination for several candidate wick materials. The data point chosen for inclusion into the above equation for determining permeability was obtained for maximum power held at horizontal heat pipe inclination. The  $Q_{\max}$  values for power held at horizontal inclination are 8.3 watts for Dynapore wick and 6.55 watts for screen/foil composite wick.

Table 1 is a listing of results obtained from the wick porosity and wick permeability measurements and calculations.

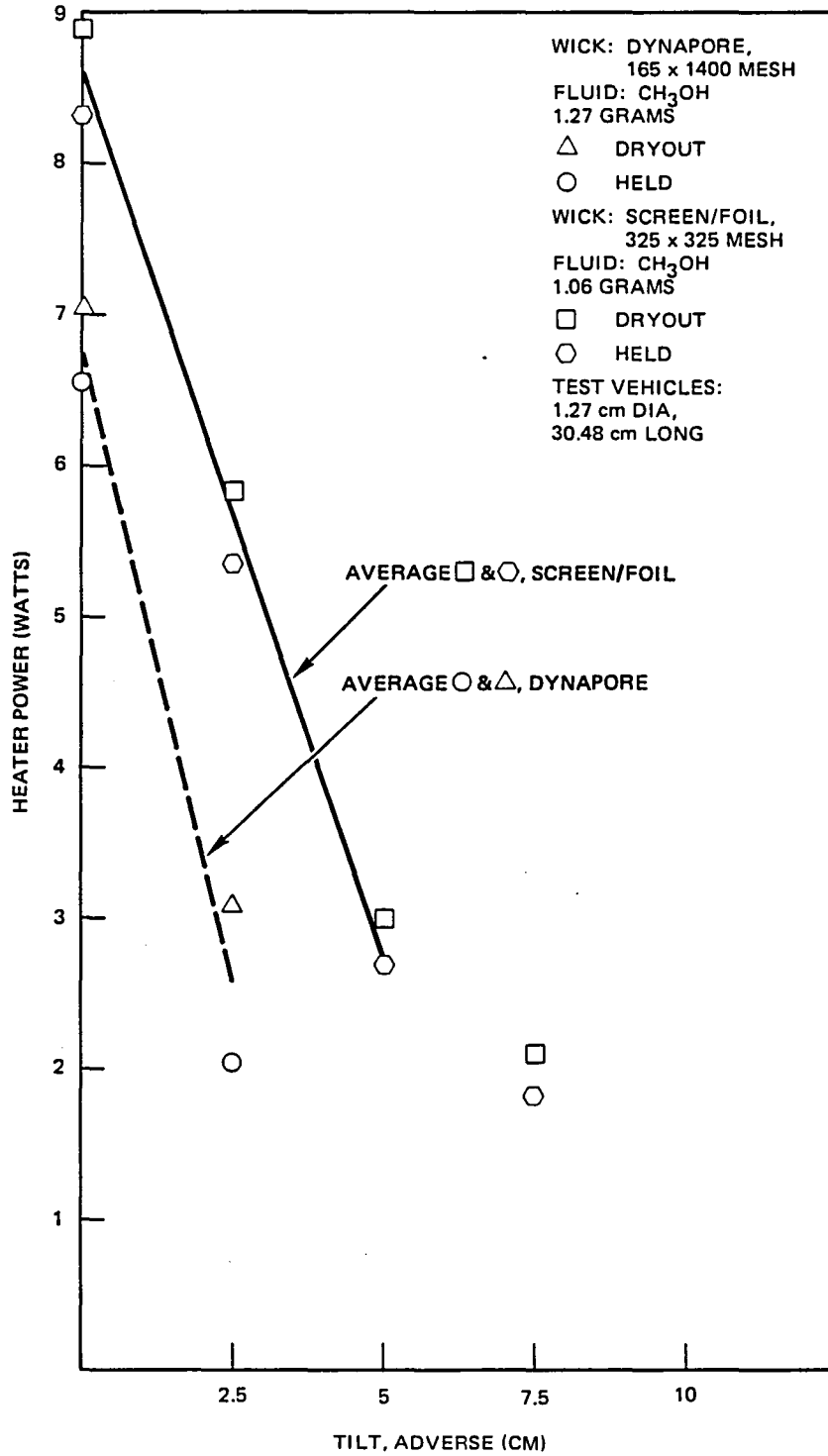


Figure 3 Measured thermal performance vs. tilt for wick parameter experiments.

TABLE 1  
SUMMARY OF WICK TEST RESULTS

Item	Material	Permeability (K),m <sup>2</sup>	Pore size (r <sub>p</sub> ),m
1	Rigimesh H sintered wire mesh, 304L SST, 325x2300 - 0.036mm (0.0014 in)x0.025mm (0.0010 in) wire dia.	4.267 x 10 <sup>-12</sup>	9.96 x 10 <sup>-6</sup>
2	Rigimesh K sintered wire mesh, 304L SST, 200x1400 - 0.071mm (0.0028 in)x0.041mm (0.0016 in) wire dia.	2.047 x 10 <sup>-11</sup>	8.77 x 10 <sup>-6</sup>
3	Dynalloy X-4 felt metal	1.08 x 10 <sup>-10</sup>	10.28 x 10 <sup>-6</sup>
4	Dynalloy X-7 felt metal	6.75 x 10 <sup>-11</sup>	30 x 10 <sup>-6</sup>
5	SST 304 screen 120x120 mesh	3 x 10 <sup>-10</sup>	105 x 10 <sup>-6</sup>
6	Facesheet material 120x120 - 0.094mm (0.0037 in) wire dia., 316 SST screen diffusion bonded to 0.61mm (0.024 in) thick 316 SST sheet	8.16 x 10 <sup>-11</sup>	84.9 x 10 <sup>-6</sup>
7	Dynapore sintered wire mesh, 304 SST, 165x1400 - 0.071mm (0.0028 in) x 0.041mm (0.0016 in) wire dia.	7.51 x 10 <sup>-11</sup>	23 x 10 <sup>-6</sup>
8	Screen/foil composite 325 x 325 - 0.036mm (0.0014 in) wire dia., 304L SST diffusion bonded to 0.076mm (0.003 in) thick 316L SST foil	2.85 x 10 <sup>-10</sup>	34 x 10 <sup>-6</sup>

Values for items 3, 4, and 5 are determined from Ref. 5.

### 3.2 Heat Pipe Performance Prediction

Wick parameter test results and analytical calculations were used to determine performance envelopes for each of the working fluids and wick concepts contained in the delivered honeycomb sandwich panels. These performance envelopes include wicking limit, sonic limit, and entrainment limit calculations. The working fluids evaluated are the liquid metals potassium, sodium, and cesium. Thermo-physical properties of these working fluids at various temperatures were obtained from Reference 6. Two types of honeycomb core wicks were evaluated; sintered wire mesh (Dynapore) and screen/foil composite. The facesheet consists of screen diffusion bonded to sheet. Wick characteristics for these materials are listed in Table 1. Each honeycomb cell was modeled as a separate heat pipe, therefore for the Dynapore case, adjacent cell walls were halved when determining wick cross-sectional area.

#### 3.2.1 Calculation of heat pipe limits

The design and performance of heat pipes are governed by phenomena which limit the vapor and liquid flow and consequently the maximum heat transfer rates that can be sustained. The basic analytical relationships used for defining heat pipe performance limits are described as follows:

- Wicking Limit - Described in Section 3.1.

$$\Delta P_{\ell} + \Delta P_{\nu} + \Delta P_{g} > \Delta P_{c}$$

The following pressure term expressions are from Reference 7:

$$\Delta P_{c} = \frac{2\sigma \cos \theta}{r_p}$$

$$\Delta P_{g} = \rho_{\ell} g L \sin \phi$$

$$\Delta P_v = \frac{8}{\pi (r_v)^4} \frac{\mu_v}{\rho_v \lambda} L_{\text{eff}} Q_w$$

$$\Delta P_\ell = \frac{\mu_\ell}{\rho_\ell \lambda} \frac{Q_w L_{\text{eff}}}{A_w K}$$

- Sonic Limit - Choked mass flow at the evaporator exit may limit the maximum power handling capability of the heat pipe. The following expression for calculating the sonic limit ( $Q_s$ ) is from Reference 4:

$$Q_s = A_v \rho_v \lambda \sqrt{\frac{\gamma R_o T}{2(\gamma+1)M}}$$

- Entrainment Limit - Stripping of liquid from the wick and entrainment of liquid droplets in the vapor at the evaporator are the result of the inertial forces of the vapor exceeding the surface tension forces of the capillary wick structure. The onset of entrainment ( $Q_e$ ) is defined by Reference 8:

$$Q_e = A_v \left[ \frac{\rho_v \sigma \lambda^2}{2r_p} \right]^{1/2}$$

- Free Molecular Transition to Continuum Flow - Liquid metal heat pipes typically encounter an additional limit during start-up. If the working fluid is initially solid, the pressure in the heat pipe is a hard vacuum. Thus, the first limit encountered results from the existence of free molecular flow conditions at low temperatures. The heat pipe will be ineffective until the temperature and corresponding vapor pressure is increased to a level where continuum flow conditions are present. Continuum flow is assumed to occur when the mean free path ( $\psi$ ) of the vapor molecules is less than or equal to one percent of the minimum vapor passage dimension.

The temperature required for transition from free molecular to continuum flow as a function of vapor passage diameter for several alkali metals is presented in Reference 3. The transition temperatures ( $T^*$ ) were calculated from the following relationship per Reference 9:

$$T^* = \frac{\pi}{2} \frac{M}{gR_o} \left[ \frac{\mu_v}{\rho_v \psi} \right]^2$$

Based on a 0.95 cm (0.375 inch) equivalent vapor passage diameter in the face-to-face direction of the honeycomb sandwich panel, Reference 3 predicts transition temperatures of 585°K for potassium and 700°K for sodium. Neither of these present limits to the required honeycomb panel operating temperature of 922°K.

- Boiling Limit - Nucleate boiling of the working fluid in the wick adjacent to the heated surfaces at the evaporator region will result in the formation of vapor bubbles, which will prevent flow of liquid to that area and cause local wick dryout. The boiling limit of liquid metals is encountered only at very high heat fluxes, since their very high thermal conductivities create relatively small temperature gradients in the wick. Boiling limits should not be encountered for the Scramjet Engine application.

### 3.2.2 Heat pipe performance envelopes

Specific geometries of the honeycomb sandwich panel, wick characteristics, and fluid properties were determined and substituted into the appropriate performance equations. Resulting heat pipe performance limitation curves are shown in Figures 4, 5 and 6 for potassium, sodium and cesium working fluids respectively.

### 3.3 Compression Tests of Honeycomb Core

Compression testing was done on honeycomb panel samples having core construction identical with the deliverable units. The compression test samples measured

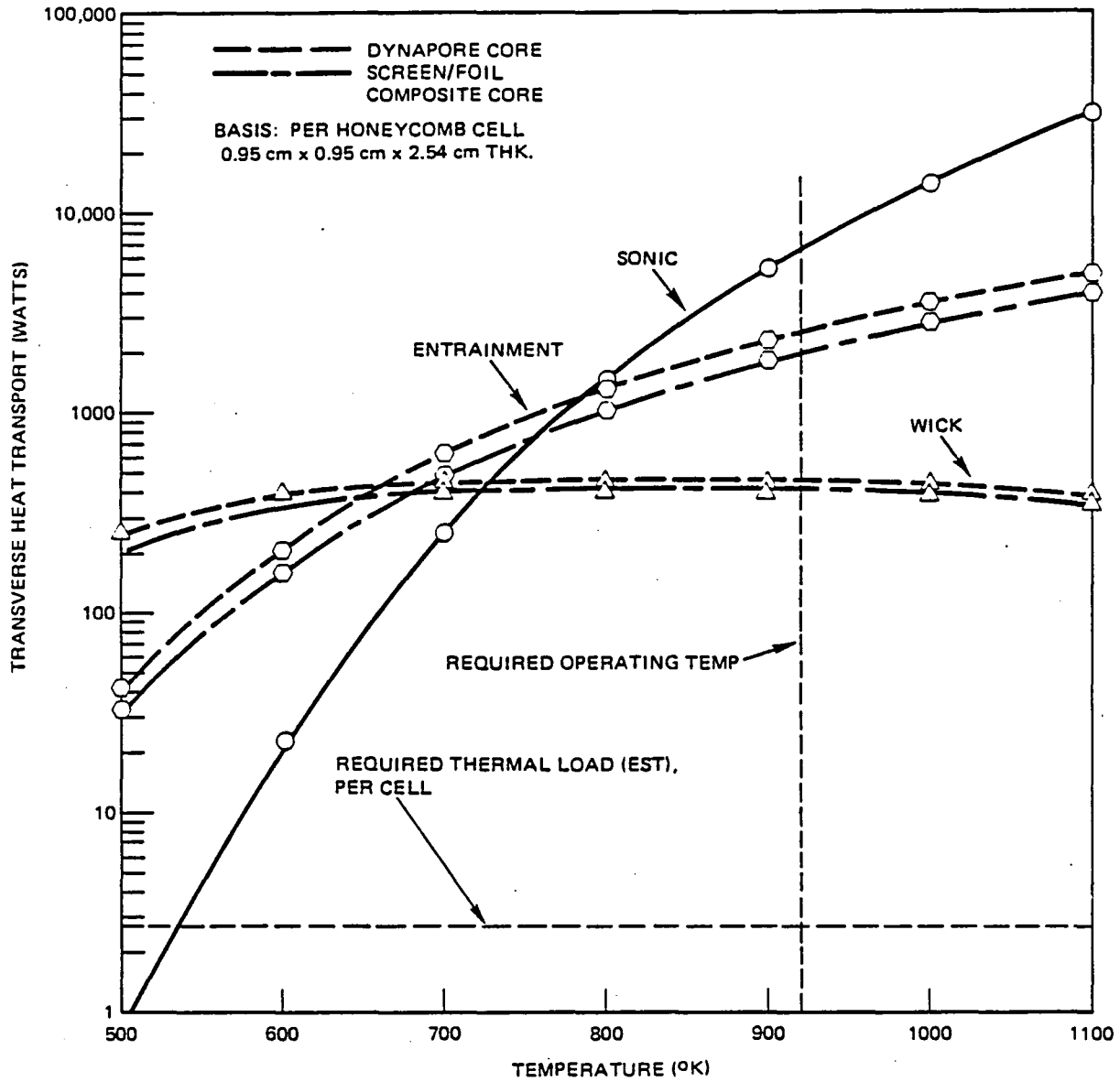


Figure 4 Performance limits vs. temperature for potassium working fluid.

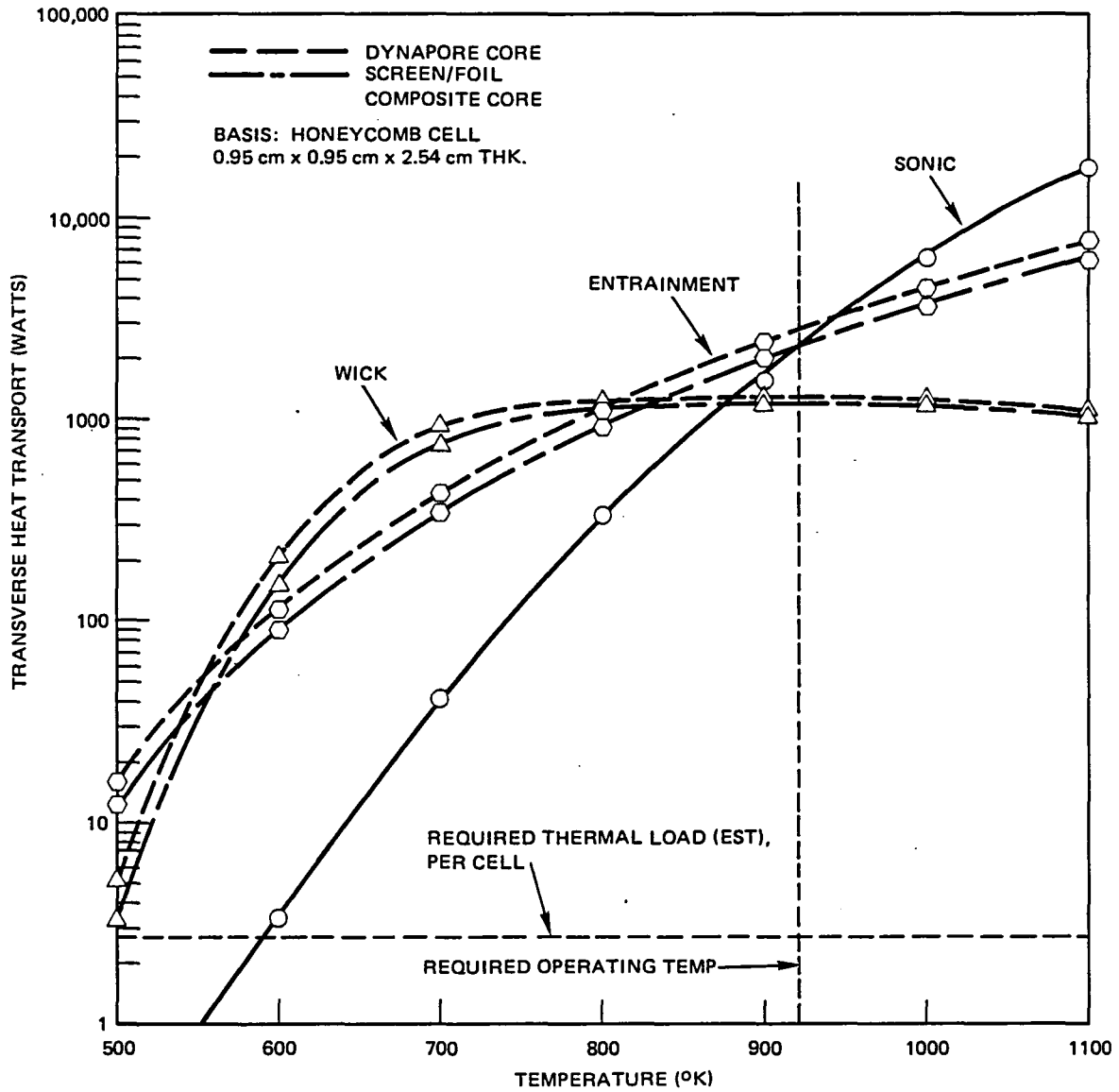


Figure 5 Performance limits vs. temperature for sodium working fluid.

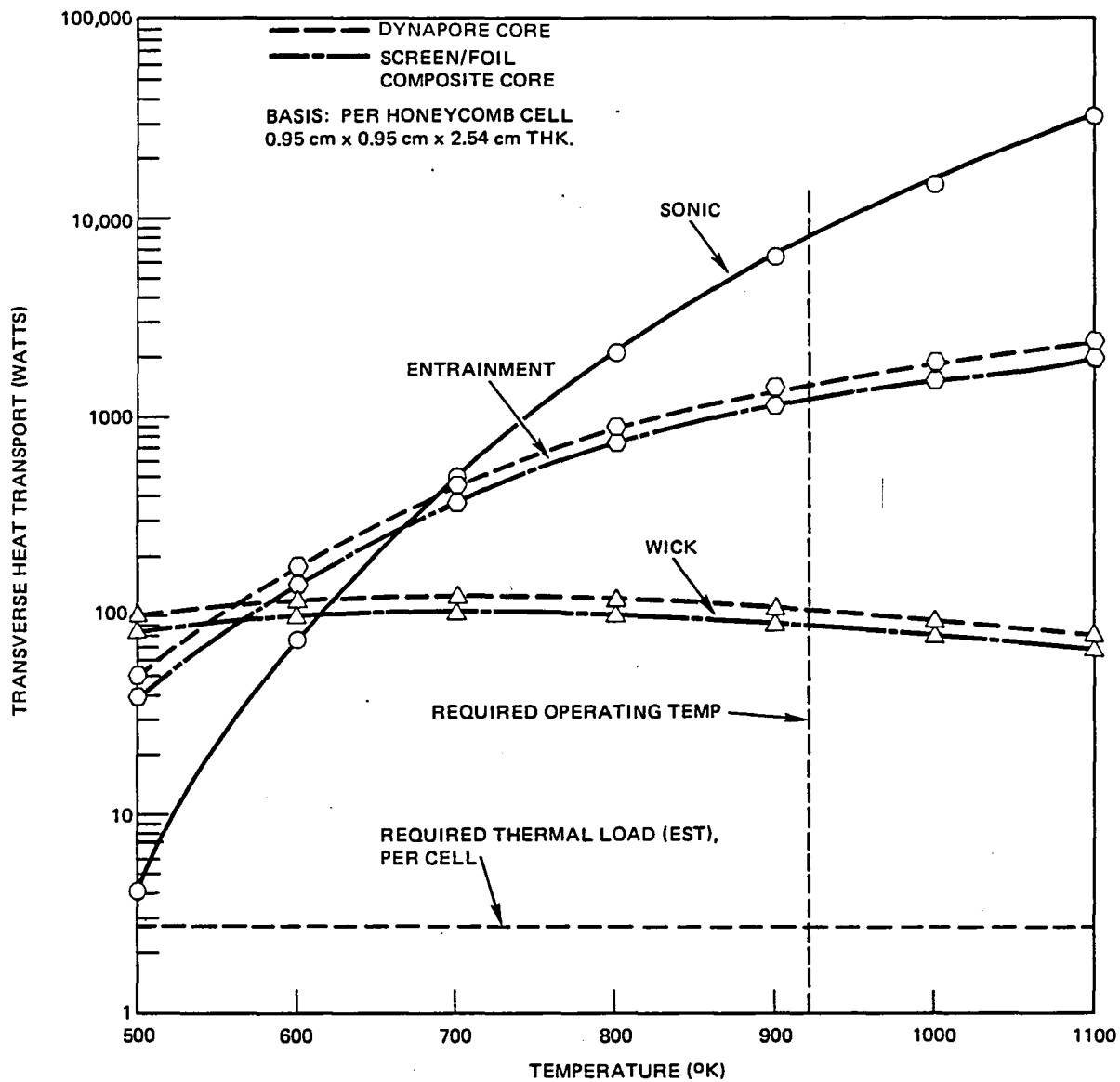


Figure 6 Performance limits vs. temperature for cesium working fluid.

3.81 cm (1.5 inches) square by 2.94 cm (1.16 inches) thick. The wire mesh laminate (Dynapore) and screen/foil composite core samples were measured to peak compression loadings of  $1.0135 \times 10^6$  Pa (147 psi) and  $3.337064 \times 10^6$  Pa (484 psi), respectively, before initiation of structure failure. Results obtained from an independent testing laboratory are included in the Appendix.

## 4.0 PANEL DESIGN EVALUATION

### 4.1 Design Concepts

The primary objective of the program was to design and fabricate a cost- and mass-effective sandwich panel using existing manufacturing techniques and equipment. The honeycomb sandwich panel would be a leak-proof design, using a wickable honeycomb core, appropriate working fluid, and wickable internal faces. This concept would enhance the transverse heat transfer capability of the honeycomb and alleviate excessive thermal gradients. Evaporation of the working fluid would occur at the facesheet exposed to heating. The heated vapor flows to the opposite or unheated facesheet, due to a pressure differential, where it condenses and gives up its stored heat. The cycle is completed with the return of liquid condensate, via capillary action of the wickable core, to the hotter facesheet for re-evaporation. The net effect of this design is to reduce the temperature gradient across the depth of the panel by approximately 50 percent during engine startup and this alleviates a thermal stress problem.

A schematic of the heat pipe sandwich panel is shown in Figure 7. A wickable internal facesheet of the sandwich is provided to allow intracellular liquid flow by capillary action. This design also allows the entire surface of the facing to be wetted by liquid thus aiding in evaporation and reducing thermal gradients in the faces. The wickable honeycomb core could be a foil-gage woven mesh screen or a screen sintered to foil ribbons, which allows face-to-face liquid flow. Notches at the end of each honeycomb cell allow intracellular liquid flow, and perforating enables intracellular vapor flow. The primary mode of heat transfer for the present application is in the transverse direction (face-to-face).

### 4.2 Candidate Subelement Concepts and Assembly Techniques

To accommodate the heat-pipe sandwich panel design requirements, the structure must consist of two facings having internally wickable faces bonded to a perforated, wickable honeycomb core material. Various concepts were screened and results are described in the following section.

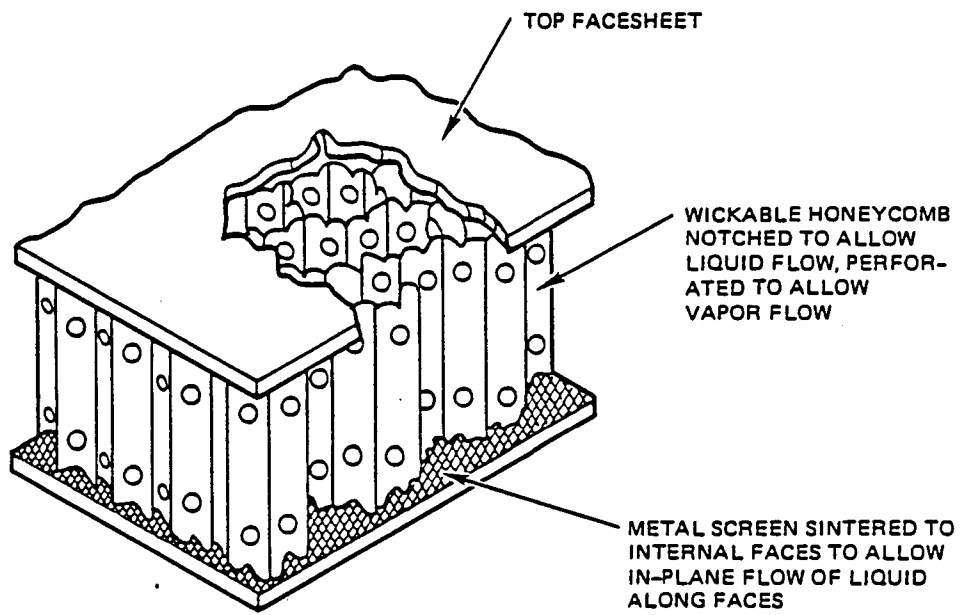


Figure 7 Heat pipe sandwich panel concept.

#### 4.2.1 Honeycomb panel fabrication

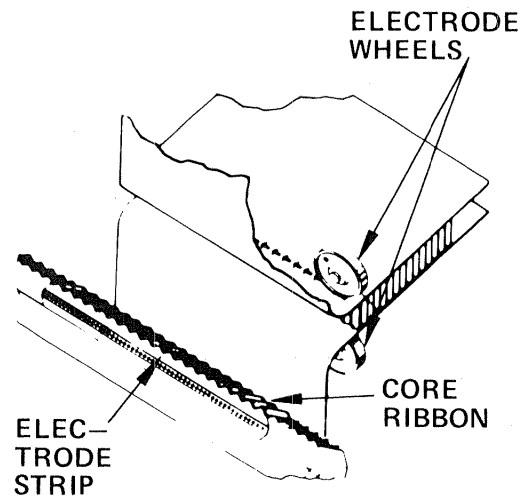
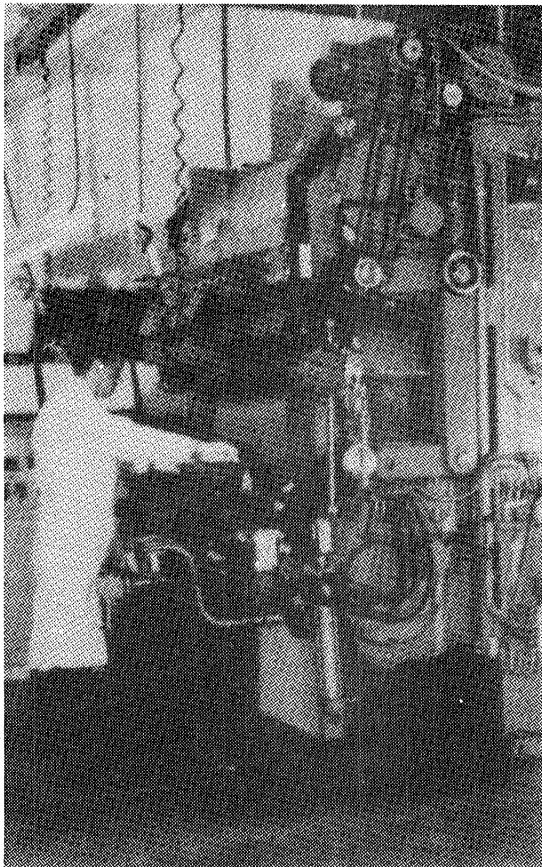
Honeycomb panels were obtained from Astech (TRE Corp., Santa Ana, Ca.) using existing manufacturing techniques and equipment. Panels have a honeycomb structure consisting of core ribbons which are sandwiched between facesheets, and are manufactured entirely by resistance welding of its components. Minute flanges are formed on the upper and lower ends of the core ribbons which are micro-spot-welded to the faces, and ribbons are nested and welded at the nodes. The manufacturing technique is illustrated in Figure 8. The all-welded construction eliminates the need for foreign bonding agents and possible materials compatibility problems. The honeycomb structure can be manufactured from any weldable material, up to 1.22 m (48 inches) width, in any reasonable length, a variety of cell sizes, face sheet and foil thicknesses, and a minimum overall thickness of 0.635 cm (0.25 inch). Only an all stainless-steel construction was considered for fabrication to limit program costs. The basic panel is readily producible into components by cutting, stretch-wrapping, forming, crushing, welding, and riveting.

#### 4.2.2 Internal facesheet wicking

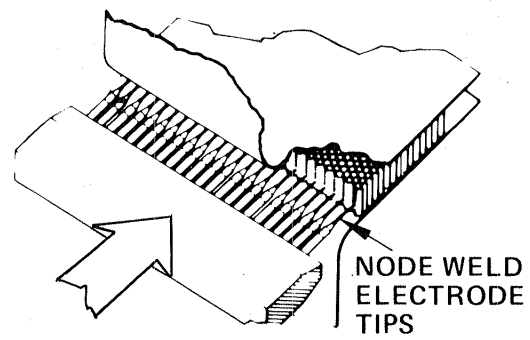
Several techniques were considered for internal facesheet wicking: sintering a screen to the facing, spot welding a screen to the facesheet, and grooving or roughening the facesheet.

The panel manufacturer, Astech, prefers that facesheet thickness be in the range of 0.254 mm (0.010 inch) to 0.762 mm (0.030 inch) due to the bending which occurs during welding of the core-ribbons to the facesheets. Sample constructions of alternative forms of wickable facesheets were evaluated. A grooved facesheet was constructed using a single-point cutter technique, and a sample which was roughened by grit-blasting was prepared. Figure 9 shows a 1.27 mm (0.050 inch) thick facesheet section which has 0.381 mm (0.015 inch) wide rounded-edge grooves, spaced on 0.762 mm (0.030 inch) centers. Figure 10 shows a 1.27 mm (0.050 inch) thick 15.24 cm (6 inch)x15.24 cm (6 inch) sample which has been grit-blasted with approximately 100 mesh beads, causing severe

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1. FLANGE WELD



2. NODE WELD

Figure 8 Honeycomb panel welding machine and manufacturing technique (courtesy of Astech).

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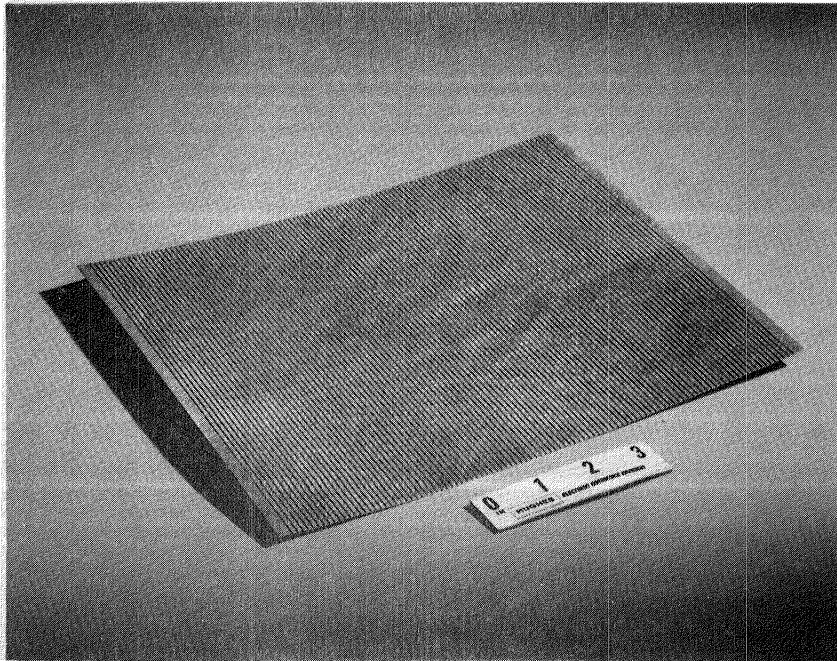


Figure 9 Grooved Facesheet. Warpage is visible.

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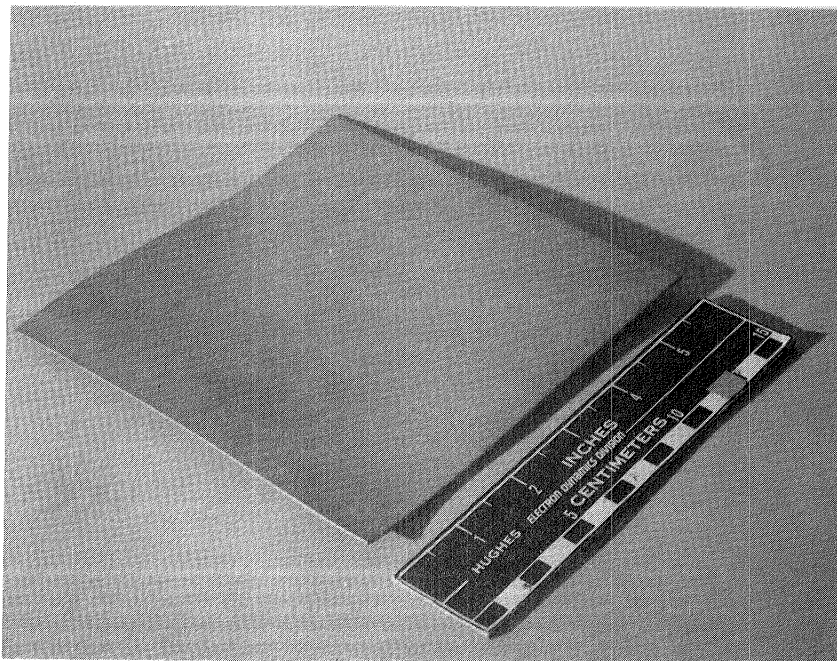


Figure 10 Grit-blasted facesheet. Note warpage caused by grit-blasting. Facesheet thickness is 0.127 cm (0.050 in).

warpage. Maximum out-of-flatness was 1.27 cm (0.5 inch). Both grooving and roughening were rejected because of facesheet warping and consequent poor surface for core-ribbon to facesheet spot welds. A sample of wire mesh which has been spot welded to a facesheet is shown in Figure 11. Astech personnel felt that the spot welded approach will not be viable since the spot-welded screen may buckle as a result of facesheet bending during the honeycomb panel fabrication process. Sintering the screen to the facing was chosen as the best alternative because it has higher structural integrity than the spot-welding. Figure 12 shows a photomicrograph of a sintered screen facesheet. Facesheet material used for construction of the honeycomb panels consisted of 316 SST 120x120 mesh screen which was diffusion bonded to 316 SST 0.61 mm (0.024 inch) thick sheet.

#### 4.2.3 Sidewall construction and joining

Each panel sidewall was fabricated from a single piece of metal sheet material and was welded in place, as depicted in Figure 13. Sidewall material selected for incorporation into the deliverable panels was 321 SST and 1.27 mm (0.050 inch) thick. A small test model was constructed and sidewall welds were evaluated for integrity by a single pressure cycle. (Ref. Section 5.1).

#### 4.2.4 Core-ribbon materials

4.2.4.1 manufacturing techniques - Material selection and methods of fabricating the core ribbon were discussed with the honeycomb panel manufacturer (Astech). Materials initially evaluated include: Rigimesh\* H and K sintered screens, and Dynalloy\*\* X-4, X-5, X-7, and X-7G feltmetals. Samples of each of these materials were available during the discussions. Astech manufacturing personnel indicated some concern that the Rigimesh materials (shown in Figure 14) would not hold their shape after forming into the honeycomb core ribbon. They also indicated that the X-7G material showed a great deal of promise as core-ribbon material if it could be fabricated to a thickness of 0.127 mm (0.005 inch) to 0.254 mm (0.010 inch). Feltmetal grades X-4 and X-5 also looked promising as core-ribbon materials. The requirement that the core-ribbon material be on the order of 0.076 mm (0.003 inch) thick is apparently not absolute. This greatly

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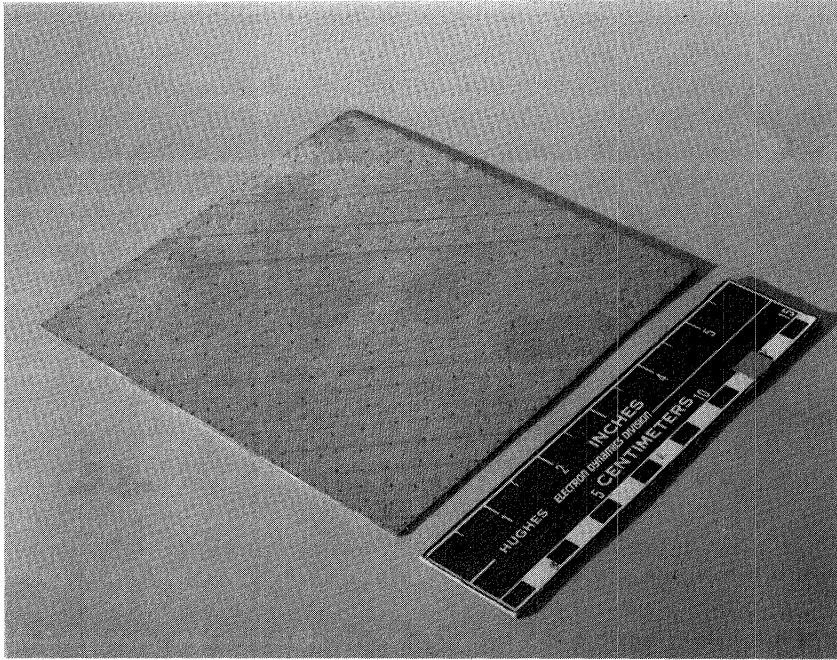


Figure 11 Example of SST wire mesh spot-welded to SST facesheet.

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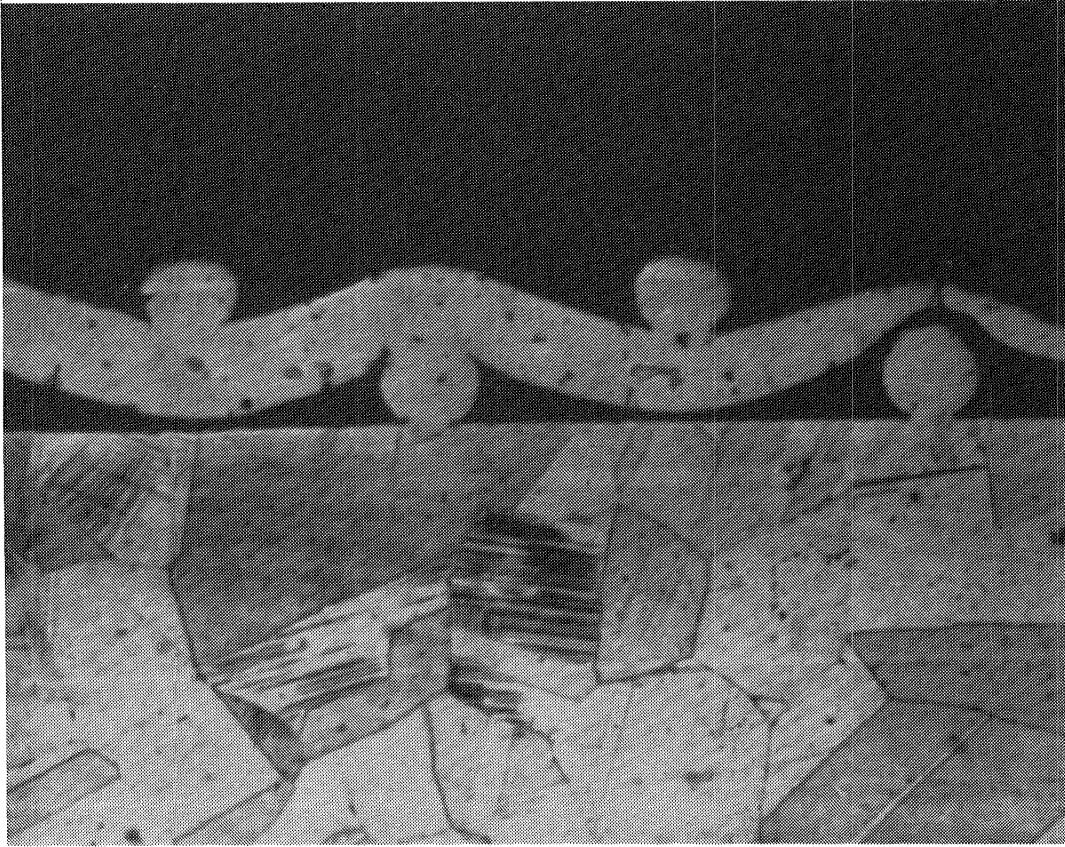
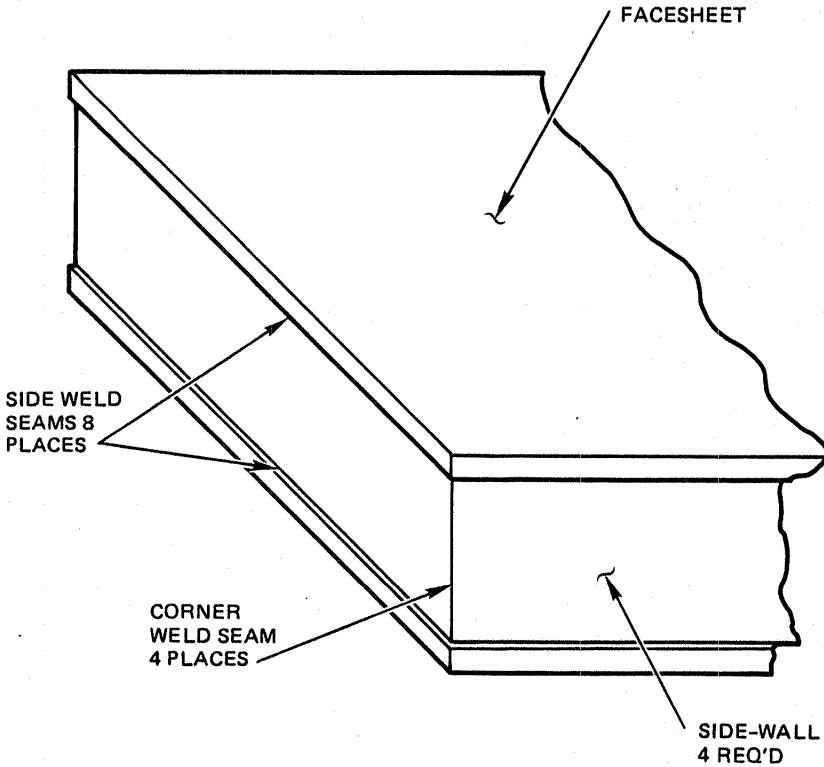


Figure 12 Photomicrograph showing diffusion bonding of screen sintered to facesheet (stainless steel).

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NOTE: ALL-STAINLESS STEEL CONSTRUCTION

Figure 13 Sketch of side wall configuration and required weld seams.

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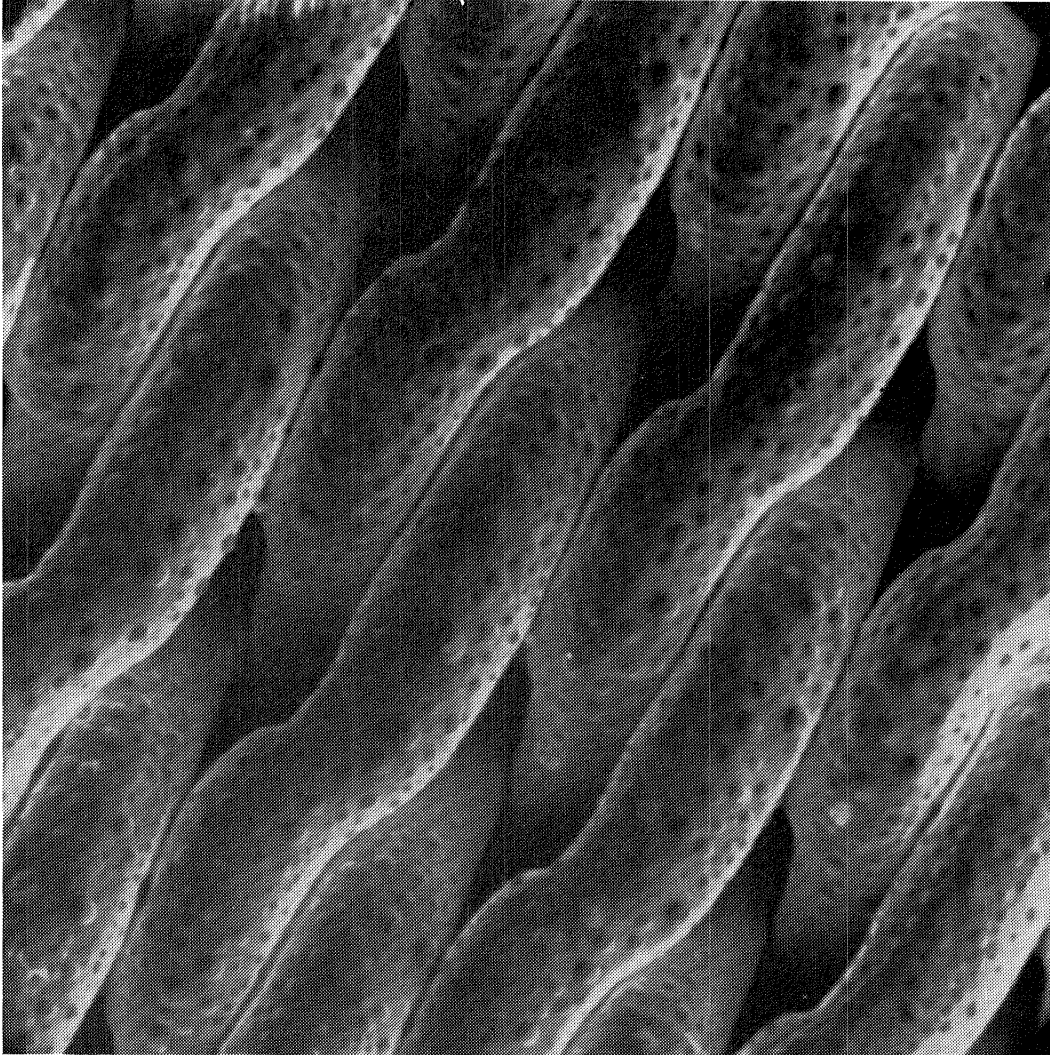


Figure 14 Photomicrograph of Rigimesh K sintered screen.  
(300X).

expands the range of material and techniques available to fabricate the core ribbon.

4.2.4.2 sample constructions - Pieces of the following wicking materials were supplied to Astech for use in fabricating core-ribbon samples:

- 1) Rigimesh K - 200x1400 screen-screen diffusion bonded composite, 0.14 mm (0.0055 inch) total thickness.
- 2) Dynalloy X-4 - 0.28 mm (0.011 inch) thick feltmetal.
- 3) Dynalloy X-5 - 0.36 mm (0.014 inch) thick feltmetal.
- 4) Dynalloy X-7G - 0.254 mm (0.010 inch) stock feltmetal rolled down to 0.152 mm (0.006 inch) thick.

Rigimesh H was eliminated from further consideration due to its very low permeability (approximately 20 percent that of Rigimesh K; see Table 1) exhibited during the wick parameter experiments done in Task I.

The X-4 and X-5 materials were too thick for use with existing Astech tooling. Use of materials which have thicknesses greater than 0.152 mm (0.006 inch) would require fabrication of new dies and spot weld fixtures. For the current program, funds and schedule dictated the use of existing tooling. Core-ribbon samples were fabricated from the Rigimesh K and Dynalloy X-7 materials. Both materials showed signs of cracking as a result of the forming process. The K-mesh sample cracked in the weld flange area and the X-7 sample cracked both in the weld flange area and the face of the material. Although cracking of the core-ribbon samples presents a problem for assembly, construction of the honeycomb panels from these materials may still be feasible, especially in regard to the K-mesh material. The greatest problems presented by the cracking are the amount of scrap which will result, and possible reduction of shear and tensile strengths of the honeycomb.

Fabrication of core-ribbons from other possible materials would include spot-welding or diffusion bonding of screen material to thin foil. The screen-foil composite could then be formed into the core-ribbon. Figure 15 is an example of screen which was hand spot-welded to foil core-ribbon.

4.3.4.3 final core-ribbon construction - Based on investigative findings, a diffusion bonded wire mesh and a screen-foil composite were selected for core-ribbon evaluation. Rigimesh and Dynapore\*\*\* are tradenames for the generic term: diffusion-bonded wire mesh. Due to better availability, Regimesh-K (200x1400 meshes) was replaced by a very similar Dynapore (165x1400 meshes) material. Wick parameter experiments show Dynapore to have 260 percent the pore size, and 370 percent the permeability of Regimesh K (see Table 1), the combined effect being slightly favorable in light of heat pipe performance being wicking-limited at the operating temperature of 922<sup>o</sup>K (see Figures 4, 5 and 6). The Dynapore manufacturer also produces an acceptable screen-foil composite, and this was chosen for core-ribbon construction as well. The selected materials are described as follows:

- 1) Dynapore - 165x1400 304 SST twilled dutch weave wire mesh, diffusion bonded, 0.14 mm (0.0055 inch) overall thickness.
- 2) Screen/foil composite - 325x325 square weave screen 304L SST (1 layer), diffusion bonded to 0.076 mm (0.003 inch) thick 316L SST foil; 0.14 mm (0.0055 inch) overall thickness.

Both materials were formed into sample honeycomb ribbons by Astech using standard equipment. Cell walls were corrugated for added strength, perforated with 0.318 cm (0.125 inch) diameter holes for vapor communication between cells, and formed into a 0.95 cm (0.375 inch) hexagonal arrangement of honeycomb cells. The honeycomb core height is 2.54 cm (1.0 inch). Both the sintered screen and screen on foil designs met structural and wicking requirements, with the former offering better wicking and the latter providing a stronger structural design. Figure 16 shows the completed honeycomb structure, of which two types were delivered to Hughes for further processing. Measured unit weights of both types of complete honeycomb panel are 1.63 gr/cm<sup>2</sup> for the dutch twilled weave and 1.68 gr/cm<sup>2</sup> for the screen-foil honeycomb.

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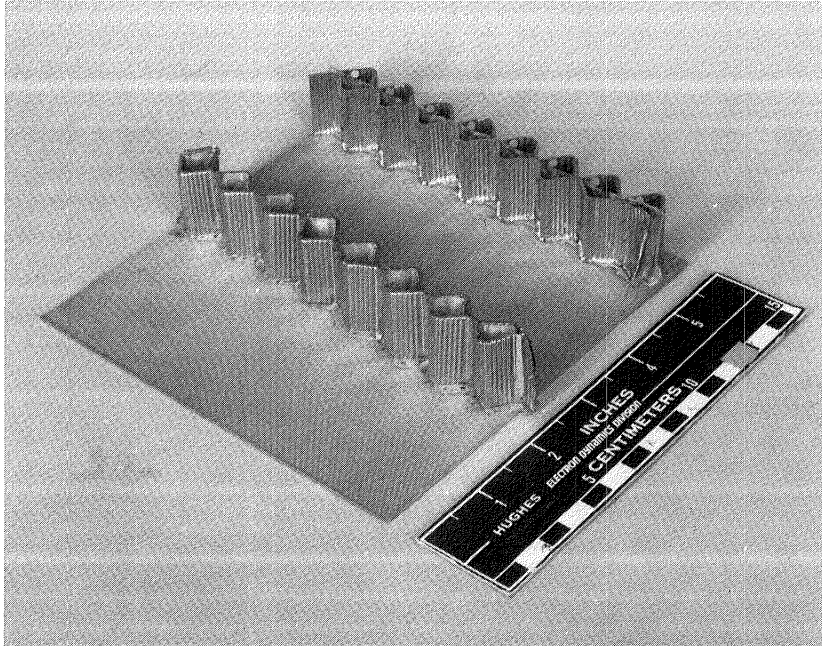


Figure 15 Core-ribbons fabricated by spot welding 120x120 mesh screen to one surface of core-ribbon material supplied by Astech.

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DETAIL

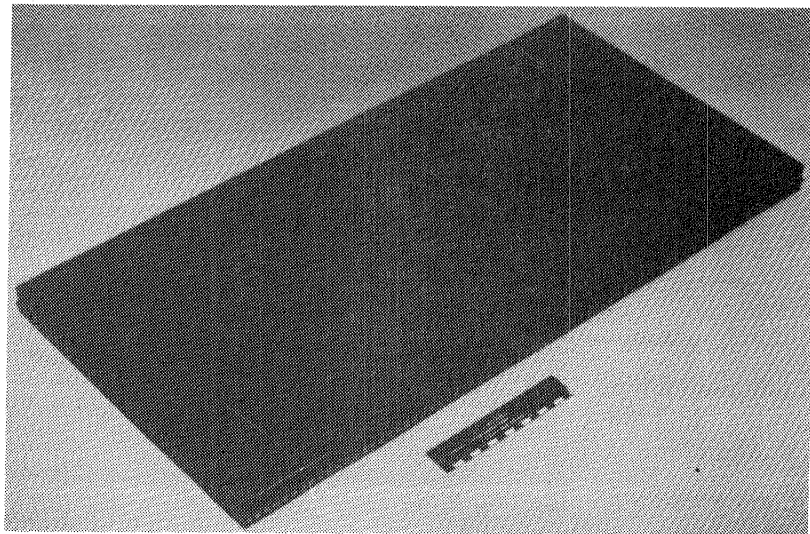
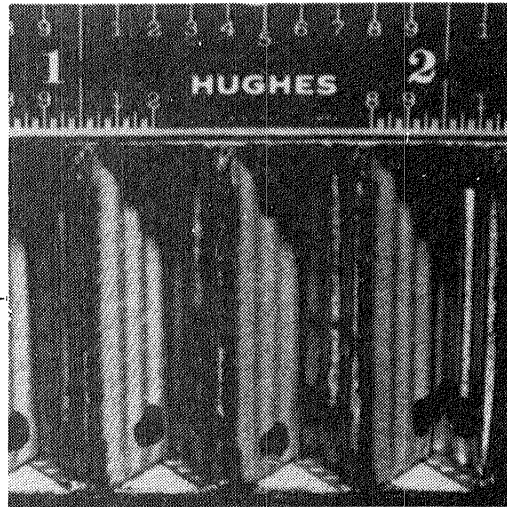


Figure 16 Completed honeycomb panel prior to processing and final assembly.

Honeycomb panel mass per unit area:

Dynapore -  $1.63 \text{ gr/cm}^2$   
Screen/Foil -  $1.68 \text{ gr/cm}^2$

### 4.3 Cleaning Procedures

Fabrication of the honeycomb panels requires the use of both water and lubricating oils. During forming of the core ribbons, lubricating oil is used on the punch-press. During welding of the core ribbons to the facesheets, untreated tap water is continually sprayed over the parts to reduce weld shrinkage and oxidation. Since both the use of lubricants and water appear critical to fabrication, stringent cleaning procedures were necessary at Hughes after receipt of the honeycomb panels. To eliminate potential contamination, the following sequential cleaning was done:

- Trichloroethane vapor degrease with ultrasonic agitation - all parts including panel section, sidewalls, processing port and tube.
- Furnace fire in dry hydrogen at 1173<sup>o</sup>K
- Repeat furnace firing after welding up heat pipe assembly
- Final outgassing in vacuum chamber at 1273<sup>o</sup>K after leak check.

### 4.4 Heat Pipe Processing Procedures

A glove box enclosure is purged with an inert gas and is used for opening of glass ampoules which contain the alkali metals, and for cutting and melting of the metals. All tools, vials, syringes and other articles used in the glove box for the charging process shall first be thoroughly cleaned by degreasing and heated. Heat pipe charging with sodium, potassium, and cesium working fluids follow identical procedures. The glove box hot plate is set for 393<sup>o</sup>K temperature, allowing the alkali metal to melt in a stainless steel dish. A heated syringe is used to inject the required volume of working fluid into the heat pipe. A process pin is then placed into the heat pipe process port, and the pipe is transferred to the vacuum process chamber. Resistance heating clamps are attached to the heat pipe, the vacuum chamber is activated, and the high current power supply is adjusted to maintain the heat pipe temperature at

approximately 1073<sup>o</sup>K. The heat pipe is considered completely processed once all gases are expelled from the pipe, and the process port is sealed by fusion welding. Figure 17 is a schematic of the alkali metal process set-up.

Note: The charging, processing, and sealing of high-temperature heat pipes utilizing alkali metal working fluids requires that utmost care and caution be observed due to the hazardous nature of alkali metals.

\* Tradename for Mectron Industries, Inc., City of Industry, CA.

\*\* Tradename for Fluid Dynamics, Div. Brunswick Corp., Cedar Knolls, N.J.

\*\*\* Tradename for Michigan Dynamics, Subsidiary of United Technologies Corp., Garden City, MI.

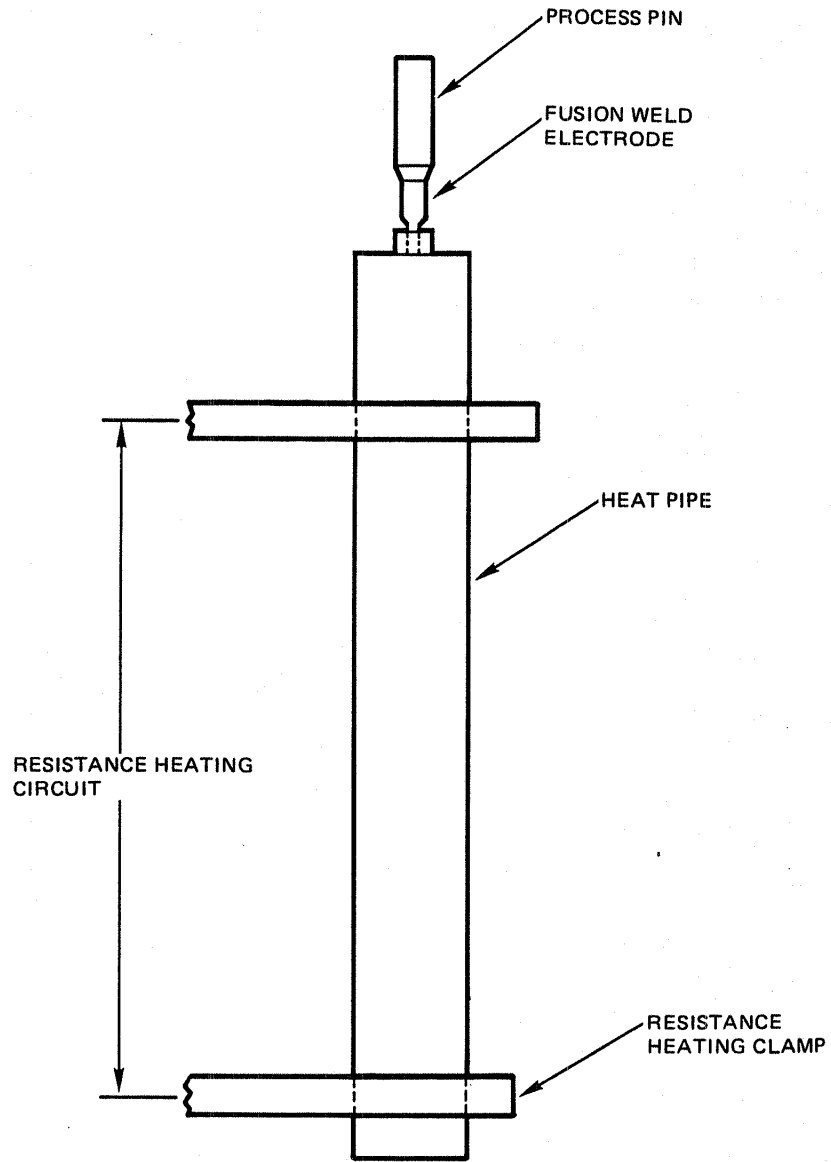


Figure 17 Liquid metal heat pipe process set-up (inside vacuum chamber).

## 5.0 FABRICATION OF TEST PANELS

### 5.1 Test Models

Three different designs of all-stainless steel construction honeycomb sandwich panels were fabricated: a resistance-welded core assembly for proof-pressure and weld integrity testing; a hand-built, spot-welded core assembly for process testing and preliminary performance testing; and machine-assembled resistance-welded test panels for delivery and final testing.

#### 5.1.1 Proof-pressure/weld-integrity specimens

The proof-pressure test specimen and construction details are shown in Figure 18. Astech constructed the core from 0.076 mm (0.003 inch) thick foil-gage ribbon, formed it into 6.35 mm (0.25 inch) x 6.35 mm (0.25 inch) cells, and then resistance welded the honeycomb sandwich together. The sidewalls were hand-welded onto the sandwich structure to complete the panel. The specimen was pressure tested to 3.86 MPa (560 psia) without signs of structural damage. Helium leak testing at  $9 \times 10^{-9}$  atm cc/sec before and after pressure testing gave no indication of leakage.

#### 5.1.2 Hand-built prototype panels

Two hand-built prototype honeycomb sandwich panels measuring 15.24 cm (6 inches) x 10.16 cm (4 inches) x 2.79 cm (1.1 inches) thick were constructed. The core ribbon consists of 150x150 square mesh screen, spot-welded to 0.076 mm (0.003 inch) thick foil which had been formed into the corrugated shape by Astech. The core was positioned to form rows and were then manually spot-welded to sintered screen facesheets. Construction details are shown in Figure 19. One unit was processed with potassium working fluid and the other unit was left unprocessed. The potassium unit was tested for operation at 1075<sup>o</sup>K (1475<sup>o</sup>F). Temperature measurements taken over the panel surfaces with an optical pyrometer indicated small temperature reductions of 5<sup>o</sup>C to 10<sup>o</sup>C at the corners of the panel, indicating small amounts of non-condensable gas.

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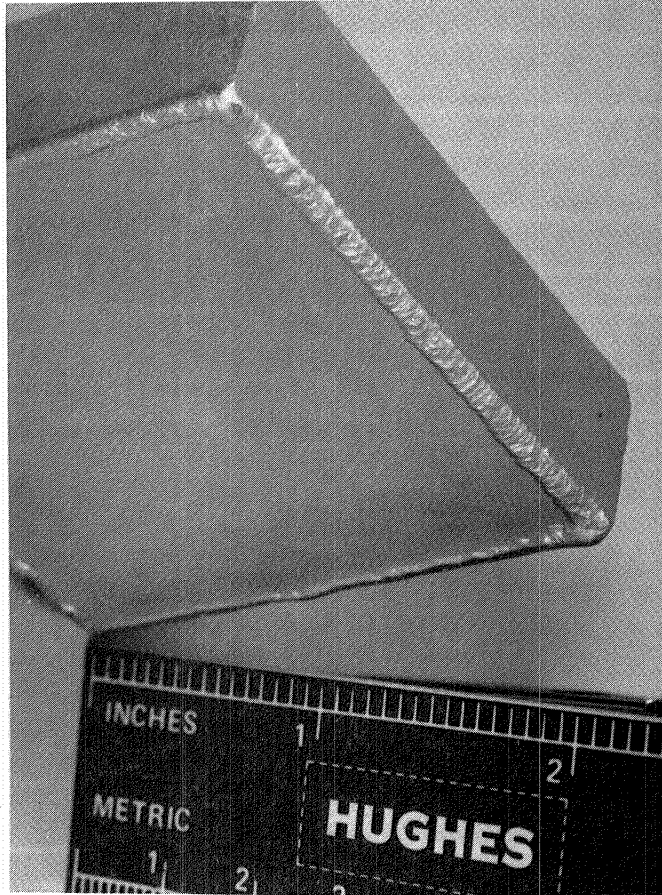


Figure 18 Photograph of the honeycomb panel used to establish weld integrity for sidewalls. The sample measures 5.08x5.6x1.27 cm thick, face sheet thickness = 0.0508 cm, sidewall thickness = 0.127 cm.

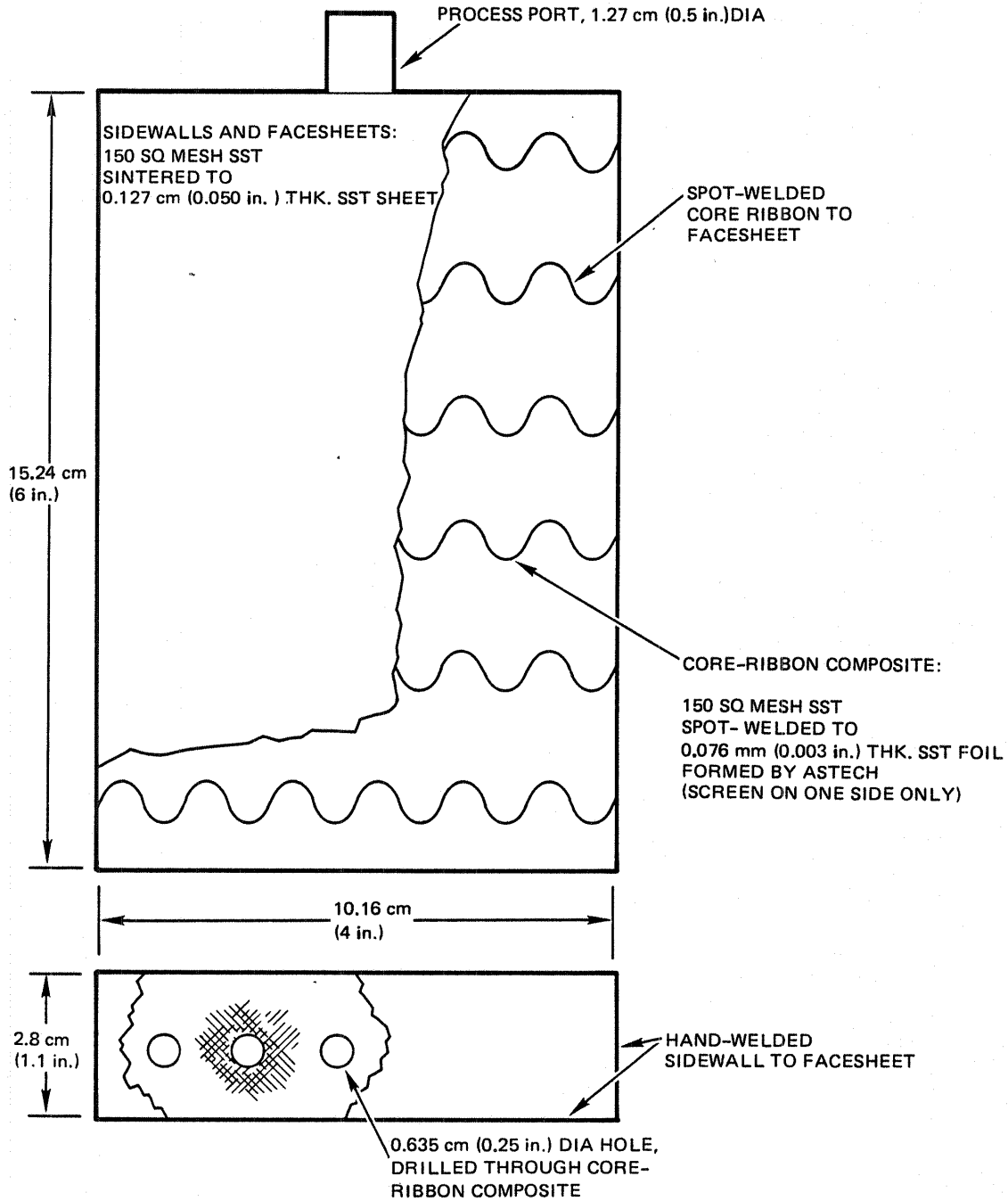


Figure 19 Hand-built panel configuration.

During vacuum chamber processing, the panel developed a bowed-out shape due to the internal working fluid pressure. The maximum processing temperature was approximately 1000<sup>o</sup>K, which corresponds to a potassium working fluid vapor pressure of 7300 N/m<sup>2</sup> (1.06 psi). The manual spot-welding of core ribbon to facesheet did not provide the quality joining and structural rigidity as the Astech honeycomb panel. Both units were delivered to NASA-Langley Research Center for further testing.

### 5.1.3 Deliverable test specimens

Details of construction and processing of the deliverable test panels are described in Section 4.0. Panel configuration details are described in Figure 20. To reduce non-condensable gas which appears as temperature variations along the prototype panel surfaces, an improved processing set-up was used. More consistent heat flux input was accomplished by positioning radiant-type resistance heaters approximately 2 cm from both sides of the test panels. The completed heat pipe assembly is shown in Figure 21. A total of eleven (11) units were delivered to NASA Langley Research Center. The units consist of various combinations of core material and working fluid which are listed in Table 2. The test panels containing foil-screen composite core as delivered to Hughes from Astech required additional reworking prior to completing the heat pipe assembly. It was observed that wick communication between adjacent cells of the foil-screen composite core panel is inadequate, potentially severely limiting both distribution of the initial fluid charge and longitudinal heat transport. Wicking between cells by action of the sintered screen facesheets is not possible due to the impervious nature of the continuous seam welds around each honeycomb cell. To overcome this problem, selective cuts (notches) were made through the cell walls at the facesheet interface for the eight composite core units. This was done with the aid of X-acto blades and small round files used as electric drill bits.

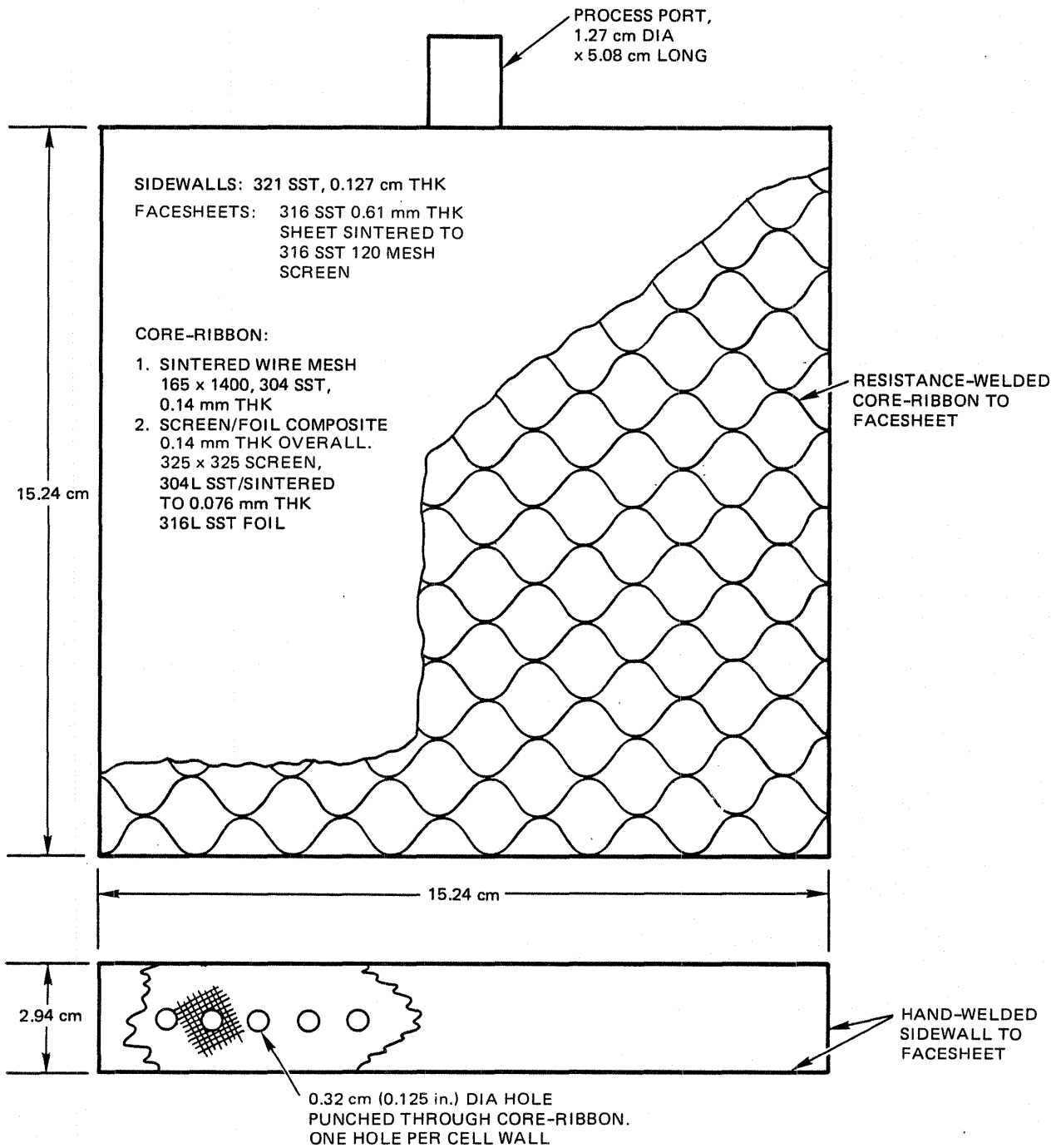


Figure 20 Deliverable panel configuration.

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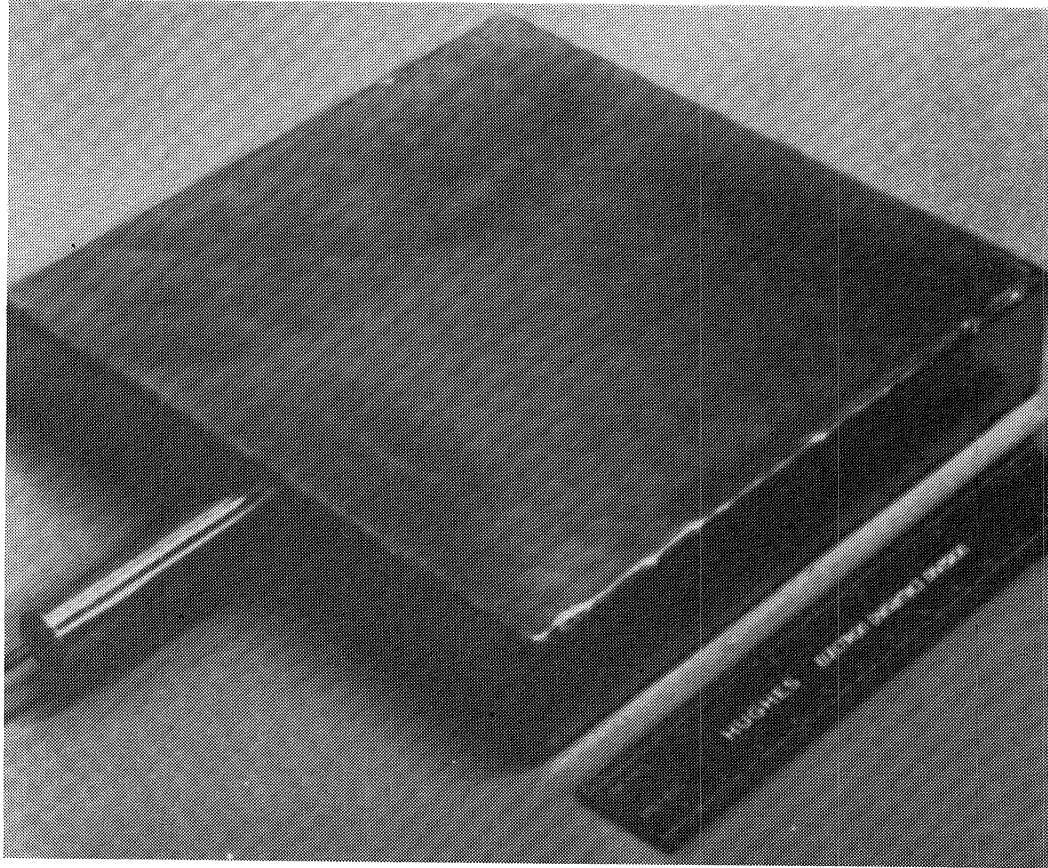


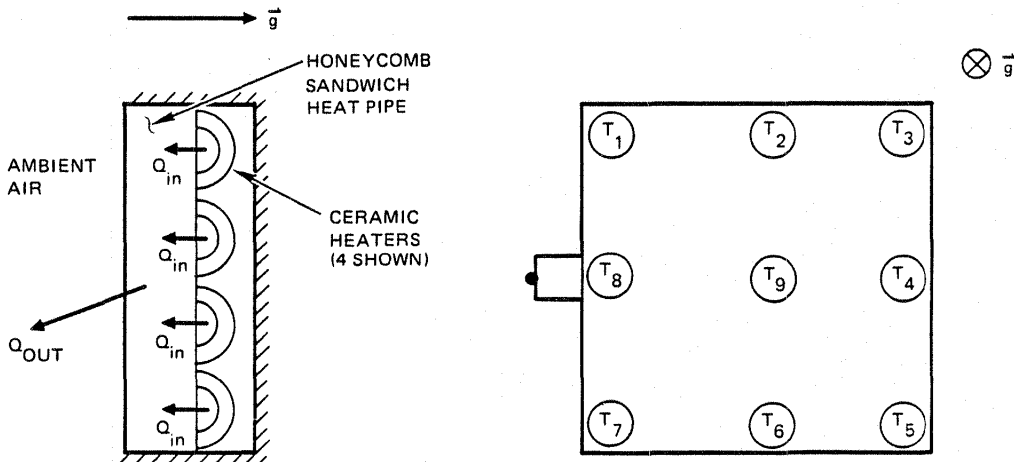
Figure 21 Complete heat pipe assembly prior to processing.

## 5.2 Heat Pipe Testing

Testing of panels consisted of an operational check on isothermality only. Performance limitations and extensive test simulations were not carried out. Test panels were heated with ceramic heaters placed on the underside and ceramic wool insulation on sides, leaving the top surface exposed to ambient. The temperature of the top surface was measured with an optical pyrometer having a sensitivity of  $\pm 5^{\circ}\text{C}$ . The test panels were subject to heat inputs ranging from 1350 watts to 1700 watts, producing measured surface temperatures of  $700^{\circ}\text{C}$  to  $900^{\circ}\text{C}$ . Temperature profiles of the delivered test panels are shown in Table 2. Figure 22 shows the heat-pipe panel during preliminary test. Some results of preliminary radiant heat testing of the prototype panels sent to NASA (Sec. 5.1.2) comparing temperature gradients for a heat-pipe and non-heat-pipe sandwich panel have been reported.<sup>10</sup>

TABLE 2  
SUMMARY OF OPERATIONAL TEST RESULTS

Contract Item No.	Description	Fill (gr /Fluid)	Heater Output (watts)	Temperature ( $^{\circ}\text{C}$ )								
				T1	T2	T3	T4	T5	T6	T7	T8	T9
1.1	Screen/foil (SF-1)	4.1 Na	1720	810	870	870	870	860	850	810	810	870
1.1	Screen/foil (SF-2)	4.9 Na	1660	790	790	790	790	790	790	790	790	790
1.1	Screen/foil (SF-3)	4.1 Na	1700	850	850	850	850	850	850	830	840	850
1.2	Screen/foil (SF-4)	4.33 K	1350	750	---	775	775	775	---	770	775	775
1.2	Screen/foil (SF-5)	3.41 K	1400	700	770	710	770	710	770	700	700	780
1.2	Screen/foil (SF-6)	3.6 K	1400	750	---	750	750	750	---	730	---	750
1.3	Screen/foil (SF-8)	---	(unprocessed)									
1.3	Dynapore (Rigimesh-4)	---	(unprocessed)									
1.3	Screen/foil (SF-7)	10 Cs	1460	740	---	740	735	730	---	750	---	740
1.5	Dynapore (Rigimesh-2)	14.0 Na	1560	840	880	860	830	790	790	760	780	880
1.6	Dynapore (Rigimesh-1)	11.3 K	1400	750	---	750	750	750	---	750	---	750



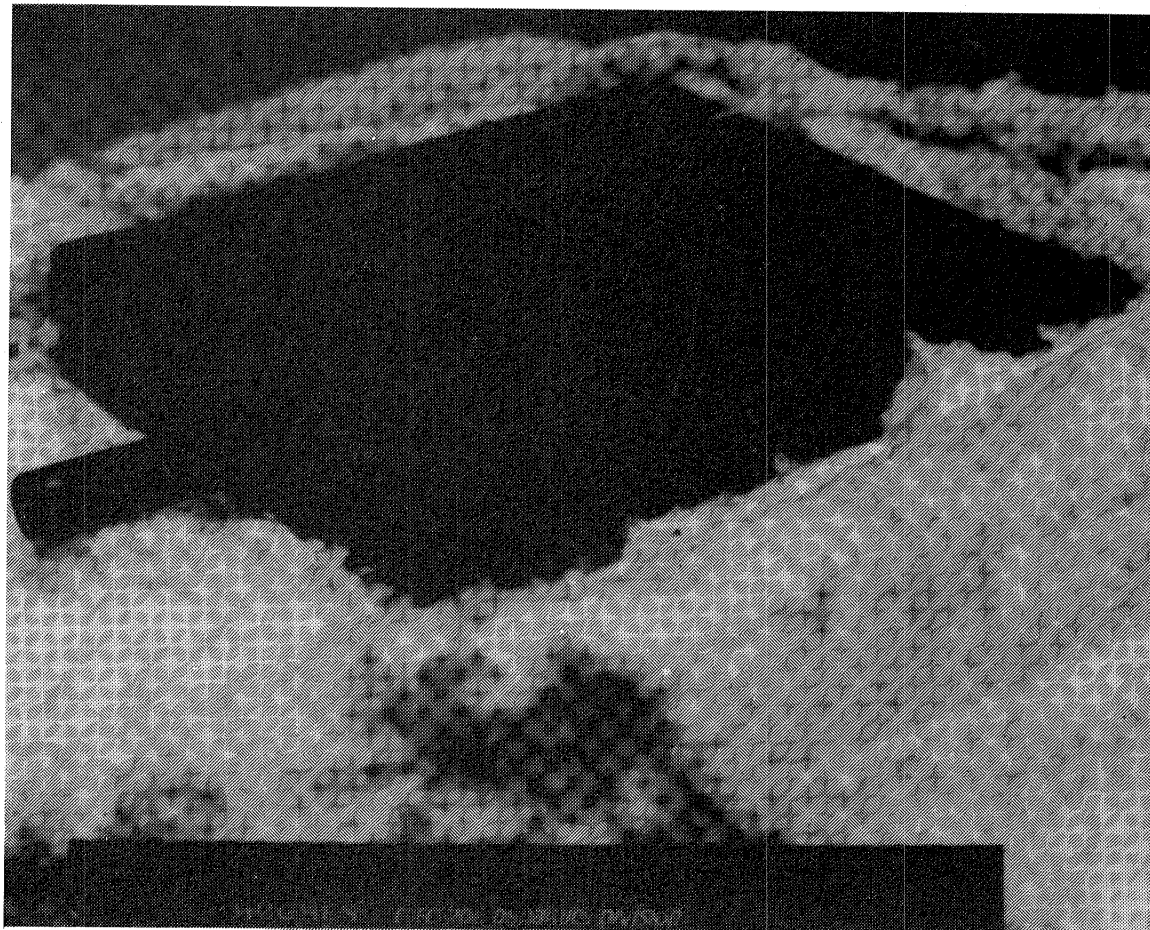


Figure 22 Heat-pipe panel during preliminary testing.

## 6.0 CONCLUSIONS

The following general conclusions are drawn from this program.

The technology and commercial equipment are available to construct all-welded machine-assembled honeycomb panels. Honeycomb panels are currently being constructed using the following materials:

- Steel; 300 and 400 series, precipitating hardening, carbon and high strength alloy.
- High nickel super alloys; Inconel 625 and 718.
- Nickel cobalt alloys; Haynes 188, Waspaloy.
- Titanium and titanium alloy.

Not included is aluminum.

The feasibility of fabricating and processing liquid metal heat pipes in a stainless steel honeycomb configuration has been successfully established.

Additional potential applications of heat pipe sandwich panels include: cooling electronic components and circuit cards, limiting thermal distortions in large structures such as space antennas, and as radiators for space platforms.

## 7.0 RECOMMENDATIONS

For the present application, the primary mode of heat transfer is in the transverse direction (face to face). Selection of other design alternatives and parameters will permit varying degrees of in-plane (long axis) heat transfer. It is recommended that thermal performance of honeycomb heat pipes in the in-plane direction be investigated. Performance demonstration of test vehicles and correlation with analytical prediction should be pursued. A test vehicle can be provided with a high transport capacity side flow channel system to increase in-plane heat transfer, and with gas reservoirs to provide variable conductance temperature control characteristics.

Liquid communication between cells by action of the wicked facesheets is not possible due to the quality weld integrity at the core ribbon to facesheet interface. Therefore, when using a foil composite core, provision must be made for incorporating notches at the interface to permit liquid flow.

APPENDIX  
COMPRESSION LOADING TEST REPORT

TEST REPORT SUMMARY

Material: Stainless steel honeycomb panel

4 samples, each 3.81 cm x 3.81 cm x 2.94 cm

Investigation: Compression loading of honeycomb

<u>Sample</u>	<u>Area</u>	<u>Peak Loading</u>	<u>Peak Stress</u>
A - Dynapore core	14.5 cm <sup>2</sup>	149.7 kg (330 lbs)	1.013x10 <sup>6</sup> Pa (147 psi)
B - Screen/foil core	14.5 cm <sup>2</sup>	494.4 kg (1090 lbs)	3.337064x10 <sup>6</sup> Pa (484 psi)
C - Screen/foil core	14.5 cm <sup>2</sup>	494.4 kg (1090 lbs)	3.337064x10 <sup>6</sup> Pa (484 psi)
D - Dynapore core	14.5 cm <sup>2</sup>	No data	---

Date Tested: June 4, 1982

By: Truesdail Laboratories, Inc.

Los Angeles, Ca.

P. O. No. 3-800353-UIS

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16. Abstract  The feasibility of fabricating and processing liquid metal heat pipes in a low mass honeycomb sandwich panel configuration for application on the NASA Langley Airframe-Integrated Scramjet Engine was investigated. A variety of honeycomb panel facesheet and core-ribbon wick concepts were evaluated within constraints dictated by existing manufacturing technology and equipment. The chosen design consists of an all-stainless steel structure, sintered screen facesheets, and two types of core-ribbon; a diffusion bonded wire mesh and a foil-screen composite. Cleaning, fluid charging, processing, and process port sealing techniques were established. The liquid metals potassium, sodium and cesium were used as working fluids. Eleven honeycomb panels 15.24 cm X 15.24 cm X 2.94 cm were delivered to NASA Langley for extensive performance testing and evaluation; nine panels were processed as heat pipes, and two panels were left unprocessed.					
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