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High Temperature Lightweight Heat Pipe Panel Technology Development

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Abstract – *Lightweight, high temperature capable heat pipe panels are needed for the radiator element of a space nuclear power system. An approach was developed to provide technology for space heat pipe radiators that are lightweight and can reject heat at temperatures in the range from 300 - 550K. The approach resulted from a trade-off of alternative heat pipe and radiator panel materials and configurations. A high conductivity, high temperature capable, organic matrix graphite fiber reinforced composite material was developed to provide the fin for radiating heat from titanium / water heat pipes. A face sheet having a thickness of less than 0.2mm was demonstrated. Graphite foam saddles were used to bridge the round heat pipe configuration to a flat panel design having optimal structural properties. A panel coupon was fabricated from representative materials, assembled and tested at design temperatures in a vacuum to evaluate the durability of organic resins as both the matrix and adhesive material for the sandwich panel. The test showed the ability of GFRC to provide a suitable, lightweight radiator panel at these temperatures.*
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I. INTRODUCTION

NASA is interested in nuclear power converters for space to provide energy missions including. While the nuclear power source and converters can be quite compact, a large radiator is required to dissipate the waste heat generated during the thermal-to-electric conversion process. For a typical mission, such as the proposed Jupiter Icy Moon Orbital (JIMO) mission (Mason, 2003, Siamidis et al., 2004) the radiator needs to reject hundreds of kilowatts of thermal energy. This makes the radiator a dominant component of the total spacecraft, in terms of both size and mass.

Nearly all space radiator systems have used aluminum heat pipes, aluminum face sheets and aluminum honeycomb core, but these components cannot function at the required temperatures. System optimizations lead to radiators with radiator temperatures in the 300 to 550 K range and minimum mass. Mason (2003) discusses the overall system concept. Siamidis et al. (2004) describe a typical radiator design for a Brayton system. The work discussed here addressed the approach to providing a panel technology which supports, structurally and thermally, the launch, deployment and operation of a large radiator comprising a network of titanium heat pipes. The design that was developed and demonstrated focused on the materials and processes for constructing the basic sandwich panel that is the common configuration of larger space radiator, comprising lightweight conductive facesheets and a honeycomb core

II. RADIATOR PANEL DESIGN

Alternative materials and configurations were investigated that are suitable to the temperature ranges, anticipated structural loads, thermal conductivities and CTE compatibility with titanium heat pipes. We started with some basic assumptions that enveloped our trade space. The general radiator configuration comprises tubular heat-pipes embedded in a flat panel with conductive face sheets for heat spreading and thermal radiation. The heat pipes have circular cross-section with no integral flanges, based on complementary work performed on this program. (Anderson, 2004) Their construction is titanium or Monel. We confined the heat pipe panel to a sandwich panel – for minimum mass we assumed composite face skins and lightweight core.

II.A. Requirements

Requirements for the radiator include temperature capability from 300 K to 550 K for all components for long-term operation (years in the vacuum of space). The materials and manufacturing processes needed to be able to scale up to meter size panels to meet multi-kW-thermal capability. For large lightweight space structures, launch environments are often a driving requirement. Since the performance of structural analysis was outside the scope of this research, we adopted a heritage design philosophy to be compatible with typical launch environments. We confined ourselves to configurations that are similar to large lightweight panel configurations that are currently launched on space missions, specifically solar panels which have similar sandwich construction and non-structural mass support needs.

II.B. Configurations

Initially, several configurations were considered. The basic configurations are shown in Figures 1, 2 and 3. Table 1 provides a list of major advantages and challenges for each of the configurations. The main driving design consideration for each configuration was the ability to maintain thermal connection between the heat pipe outer wall and the radiator fin (sandwich face-sheet), while maintaining good structural properties.

Figure 1. Configuration with heat pipes embedded in a sandwich panel with conformal face sheets.

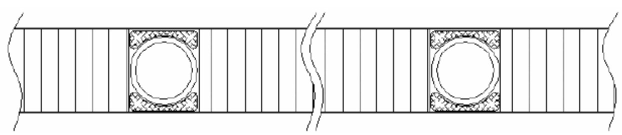

Figure 2. Configuration with heat pipes embedded in a sandwich panel with graphite foam saddles.

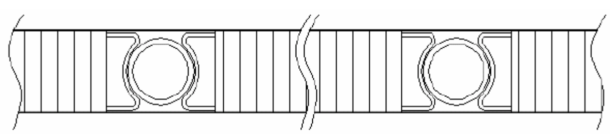

Figure 3. Configuration with heat pipes embedded in a sandwich panel together with metallic support clips

Based on the advantages and challenges we chose the option of Figure2. We did not want to needlessly extend the complexity of the composite technology for new materials, and so felt that flat laminates would be the easiest to control and assemble.

Table 1. Advantages and disadvantages of several alternative heat pipe configurations.

Configuration	Advantages	Challenges
1	• Direct thermal interface from heat pipes to face-sheets minimizes thermal gradient. • No graphite foam interface could reduce cost	• Direct connection of heat pipe to face-sheet may require additional mass to handle CTE stress • Formed high-K face-sheets have higher cost than flat face-sheets
2	• Graphite foam provides a low-mass flange interface to flat face-sheets • Flat face-sheets have lower cost • CTE of graphite foam similar to Monel	• The solid foam has high moment of inertia - would contribute to CTE stress • Graphite foam is not inexpensive • Two adhesive interfaces from heat pipe to face-sheet increases delta T
3	• Interconnects could be sheet metal brazed to Monel heat pipe – only one adhesive bonded thermal interface. • Interconnects build in stress relief to handle CTE mismatch to face-sheets	• Somewhat longer thermal path from heat pipe to face-sheet. Can't easily braze to titanium heat pipe. • Need structural analysis to confirm that we are supporting the pipe well enough

II.C. Materials

The choice of materials and processes was primarily driven by the temperature capability requirement. For the composite face skin we needed to develop a high conductivity composite laminate that would be compatible with temperature extremes, have sufficient stiffness and strength for panel structural stability, and have CTE compatibility with heat pipe. Graphite fiber reinforced composite laminates used for lightweight panel applications in spacecraft generally come in two forms – woven fabric and multiple plies of unidirectional tape. Because you can adjust the orientation of the plies in a unidirectional tape laminate and customize the thermal and mechanical properties, we chose that approach.

We evaluated alternative high conductivity fibers – K1100 from Cytec and the K13 series of fibers, including K13C2U and K13D2U from Mitsubishi provide sufficient conductivity for this application. We chose K13D2U for its combination of good thermal properties and reasonable cost. The main limiting factor for these composite laminates is long term survivability of the resin matrix. Conventional epoxies and cyanate polymers do not perform well long term at temperatures above 470K. Continued research in the past several years, driven by aircraft needs for high temperature capable composites, has led to more choices of specialized resins in the temperature ranges of interest. We evaluated a selection of resin matrices including cyanates, bismaleamides and polyimides, and decided upon a high temperature capable cyanate resin from Royal Ten Cate / Bryte Technologies.

Very little data is available for these kinds of composite materials describing the variation of thermal conductivity with temperature. Based on our analysis derived from data obtained from Mitsubishi, we expected to achieve a unidirectional thermal conductivity in excess of 400W/m-K. We used these data to design a laminate that would optimize the conductivity in the direction perpendicular to the heat pipes, while still providing good structural properties and manufacturability. The laminate we designed for each face-skin comprises 3-plies in a 30/0/-30 orientation. Analysis indicated that this would provide over 300W/m-K in the direction perpendicular to the heat pipe at room temperature, and more than 230W/m-K at 550K.

The RDU conceptual design was based on the calculated thermal conductivity of 300 W/m K. This is an engineering estimate, based on the orientation of the fibers (-30, 0 and +30 orientations. With this fiber layup, the room-temperature conductivity normal to the pipe was calculated to be 400 W/m-K in the direction perpendicular to the pipe. Although there is no vendor data on the conductivity of K13D2U fiber at 280°C, there is data at 100°C showing a reduction in conductivity of 0.097%/°C. This would put the conductivity at 100°C at 371 W/m-K, and, using a linear extrapolation, the conductivity at 280°C would be 301 W/m-K.

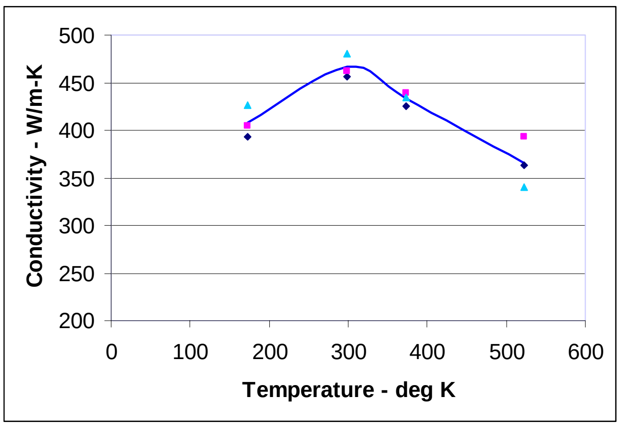

Figure 4. Extrapolated conductivity of K13D2U unidirectional composite as a function of temperature

To provide a structural and thermal interface between the round heat pipes and flat fins, we needed a very lightweight material with good conductivity. We chose a graphite foam - HTC material from POCO Graphite. It has a density of 0.9g/cc, so we could have the relatively thick cross sections needed for the saddles between the heat pipe and the composite fin without a large mass penalty. Typical properties for this material are shown in Table 2. The material also shows a change in thermal conductivity with temperature, which is characterized by the curve of figure 5.

Table 2. Typical Properties for POCO HTC graphite Foam

	Average
Density	0.9 g/cc
Compressive Strength	855 psi
Thermal Conductivity	
Out of Plane	245 W/mK
In Plane	70 W/mK
Total Porosity	61%
Open Porosity (% of total)	95%
Avg. Pore Diameter	350 microns

CTE		
Avg Temperature Range	**In-Plane**	**Out-of-Plane**
323 to 423°K/50 to 150°C	1.02	-1.07
423 to 573°K/150 to 300°C	1.91	-0.02
573 to 873°K/300 to 600°C	2.64	0.73
873 to 1073°K/600 to 800°C	3.26	1.31
Values in ppm/°K or ppm/°C		

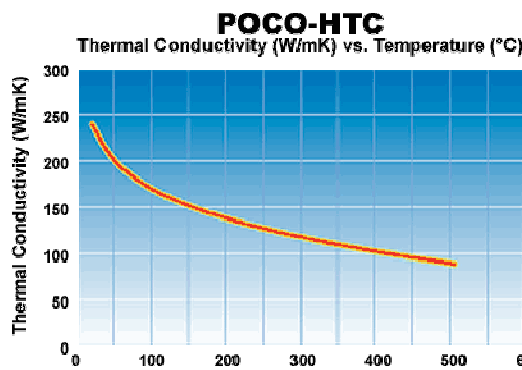

Figure 5. Conductivity of graphite foam with temperature

III. TEST PANEL

A test radiator panel was assembled using the chosen composite fin material and graphite foam saddles. A titanium tube was mounted between the saddles, and aluminum honeycomb core was used in the areas outside the tube/saddle region. The entire assembly was bonded using the same resin system as was used for the matrix in the composite fin, except in paste adhesive form. The test panel is shown in Figure 6.

Figure 6. Test panel with embedded titanium tube

The composite radiator panel was life tested in a bell jar vacuum system. The panel was electrically heated and radiatively cooled. The test consisted of operating the panel at a fixed heat input power and periodically observing an array of key panel temperatures. Any degradation of the panel such as delamination of the components or a slow decline in component conductivity would be evident by a change in the temperature distribution.

Thermal input to the panel was provided by a cartridge heater mounted in the bore of the titanium tube. The heater was 12" long and covered the full length of the panel. The heater was powered by a variac external to the vacuum system. The panel radiated to the room, which was nominally at 300 K.

Testing consisted of conditioning (or bakeout) then actual operation. The panel was conditioned by first running below 100°C until the system pressure fell. This drove any absorbed moisture from the composite portion of the panel. After this initial bakeout, the panel was ramped to its target temperature at a rate not exceeding 5°C per minute. The panel was tested at a peak temperature of 260°C for a total of 342 hours.

An examination of the panel after testing showed that it panel retained its structural integrity after test. No visual changes in the graphite laminate were apparent, and the bonds to the saddle and the titanium tube, as well as the honeycomb core were intact. A few disbond areas were noted and hypothesized to be caused by thermal expansion in the cartridge heater.

Flatwise tensile testing of the sandwich coupon in several areas showed a mean strength of 1.44MPa (209 PSI), with nominal mode of interlaminar failure. This indicated that good adhesion was retained by the cyanate ester resin system to the aluminum honeycomb core, and that the core itself did not degrade. After completion of mechanical testing, the panel was cross-sectioned and post-test visual inspection was performed. We observed some pyrolysis of the cyanate, but the material was contiguous and did not display embrittlement or charring at these temperatures. Figure 7 shows the panel after cross-sectioning at the edge of the heat pipe. The test results were encouraging for future use of these materials in this configuration.

Figure 7. Cross-sectioned view of titanium pipe, foam and face sheets

IV. CONCLUSIONS

A composite sandwich panel was developed that shows compatibility with operation of a high temperature heat pipe system needed for nuclear power systems in space. Careful material selection and composite laminate design allow such a sandwich panel to survive long term high temperature exposure while maintaining structural integrity.

ACKNOWLEDGMENTS

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REFERENCES

1. Anderson, W. G., and Bienert, W., "Loop Heat Pipe Radiator Trade Study for the 300-550 K Temperature Range," in these proceedings of *Space Technology and Applications International Forum (STAIF-05)*, edited by M. S. El-Genk, American Institute of Physics, Melville, New York, 2005.

2. Anderson, W. G. and Stern, T., "Water Heat Pipe Radiator Trade Study for the 300-550 K Temperature Range," *Spacecraft Thermal Control Workshop, El Segundo, CA, March 9-11, 2005*

3. Mason, L.S., "A Power Conversion Concept for the Jupiter Icy Moons Orbiter," NASA/TM-2003-212596, 2003.

4. Siamidis, J., Mason, L., Beach, D., and Yuko, J., "Heat Rejection Concepts for Brayton Power Conversion Systems," *2nd International Energy Conversion Engineering Conference*, American Institute of Aeronautics and Astronautics, ISBN 1563477157, 2004, pp. 556-564.