High Temperature Water-Titanium Heat Pipe Radiator

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Space nuclear systems require large area radiators to reject the unconverted heat to space. System optimizations with Brayton cycles lead to radiators with radiator temperatures in the 400 to 550 K range. To date, nearly all space radiator systems have used aluminum/ammonia heat pipes but these components cannot function at the required temperatures. A Graphite Fiber Reinforced Composites (GFRC) radiator with high temperature titanium-water heat pipes is currently under development. Three candidate fin materials have been evaluated: K13D2U fibers with 5250-4, EX1551, and HPFE resin. Titanium was selected over Monel as the baseline envelope material, due to its lower mass and previous experience with bonding titanium into honeycomb panels. Graphite foam saddles are used to bond the heat pipes to the radiator fins. In addition to providing a heat transfer path between the round heat pipes and flat fins, the graphite saddle also provides micrometeroid protection, and reduces the effects of the coefficient of thermal expansion difference between the heat pipe and the fin. This paper also discusses mechanical and thermal tests of the laminate material, as well as a series of test panels.

Nomenclature

T_g = Glass Transition Temperature

I. Introduction

Space nuclear power systems require a large radiator to dissipate the waste heat generated during the thermal-to-electric conversion process. System optimizations lead to radiators with radiator temperatures in the 400 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. To date, 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.

This paper discusses the current status of the development of a high temperature Radiator Demonstration Unit (RDU), designed to operate at temperature from 350 to 500 K, with excursions to 530 K. The program concentrates on the upper end of the temperature range, since there are no current radiators suitable for operation in this range. The final radiator design would probably use a series of heat pipe radiator panels, with optimized working fluids, heat pipe envelopes, and radiator materials for each temperature range.

II. Radiator Concept

The objective of the program is to develop a panel and heat pipe technology which supports, structurally and thermally, the launch, deployment and operation of a large radiator comprising a network of titanium heat pipes. The basic radiator design is shown in Figure 1. Stern and Anderson (2005, Anderson and Stern, 2005) discuss the

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different concepts and trades that were examined to arrive at this design. The design is based on the standard aluminum radiator, which has lightweight conductive facesheets and a honeycomb core.

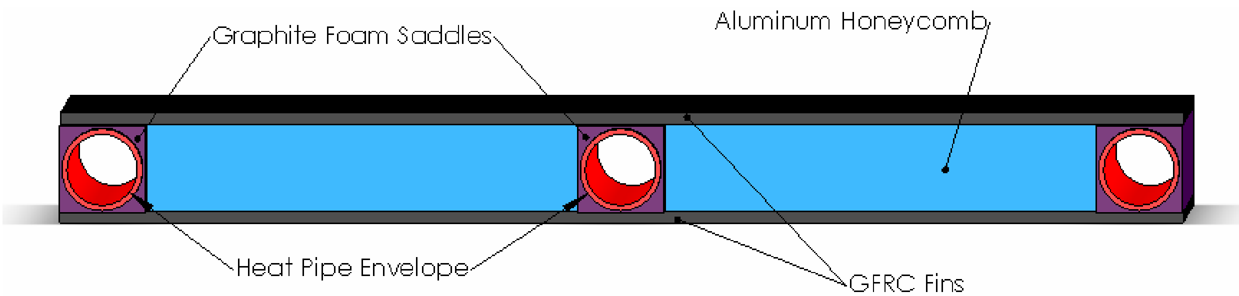

Figure 1. Cut-away section through the radiator panel.

The radiator panel has the following:

1. A series of titanium/water heat pipes to transfer heat from the secondary fluid to the radiator panel
2. High conductivity foam saddles to form an interface between the circular heat pipe and the flat fin
3. High conductivity fins
4. Aluminum honeycomb to provide stiffness to the structure

The heat pipe configuration assumes that a series of round heat pipes are embedded in the radiator panel to distribute heat. Aluminum/ammonia heat pipes are typically fabricated with an integral saddle that is used to transfer heat from the heat pipe to the radiator panel. This is not suitable for a titanium heat pipe, for two reasons:

1. Titanium is difficult to extrude
2. Unlike aluminum, the thermal conductivity of titanium is very low. The titanium thickness is minimized to minimize the temperature drop from the heat pipes to the fin.

The radiator fins use high-temperature-capable Graphite Fiber Reinforced Composites (GFRC's). This is a polymer matrix material, which we feel represents a technologically better developed alternative to carbon-carbon panels. Carbon-carbon has not been commonly used as a self-supporting structure in lightweight spacecraft panels because in thin cross-sections it is rather brittle, but GFRC facesheets with aluminum core is very commonly used. The main difference from conventional panels is that a high-temperature resin matrix is required to allow the panel to operate at temperatures up to 550 K.

III. Bonding the Heat Pipe and Fins

The panel design has titanium heat pipes, an aluminum honeycomb for stiffness, and a high conductivity fin material. There are two basic methods of thermally connecting the heat pipes to the fin material: (1) directly bonding the heat pipe to the fins; and (2) using a high-conductivity graphite saddle between the heat pipe and the fins; see Figures 2 and 3. With direct bonding, the fins are wrapped around the heat pipes. The mass of the graphite saddle is eliminated, however, only half of the heat pipe condenser is active. Tooling is more complicated, since the optimum heat pipe to heat pipe spacing will vary with temperature.

With a graphite saddle, the entire condenser is active, but the design must demonstrate reliable titanium/graphite and graphite fin joints. The flat fins are easier to make, and the saddles provide additional micrometeoroid protection. A trade study was conducted to compare direct bonding versus saddle radiators, looking at a single heat pipe and associated radiator, carrying 360 W power at 500 K. The following variables were examined:

- 90° and 60° angles for direct bonded fins. (The 90°C case was considered to be the maximum reasonable achievable angle
- Poco High Thermal Conductivity (HTC) and regular Poco graphite for the saddle
- 3.2 mm versus 0.51 mm minimum saddle thickness

A minimum saddle thickness of 3.2 mm is believed to be easily achievable, while 0.51 mm is probably the minimum practical thickness. The two saddle materials examined were Poco graphite, and Poco HTC graphite. Poco graphite has a density of 550 kg/m^3 and a thermal conductivity of 90 W/m K (at 500 K) in the high conductivity direction. The density (900 kg/m^3) and thermal conductivity (135 W/m K) of Poco HTC foam are roughly double those of Poco graphite. An emissivity of 0.9 and sink temperature of 200 K was used for the radiation boundary condition. The heat pipe power is 360 W at a temperature of 500 K

Table 1. Single Heat Pipe Radiator Masses, Direct Bond vs. Poco vs. Poco HTC Saddles.

Pipe O.D.	1.91 cm 90º	1.91 cm 60º	1.91 cm 0.51 mm	1.91 cm 3.2 mm	1.91 cm 0.51 mm	1.91 cm. 3.2 mm
Bond	Direct	Direct	Poco	Poco	HTC	HTC
Fin Width (cm)	6.86	7.17	6.82	6.79	6.76	6.73
Saddle (g)	0	0	58.9	180.2	96.3	295
Fin (g)	83.1	86.2	75.1	74.7	74.3	73.9
Honeycomb (g)	31.4	45.9	43.5	58.2	42.9	57.4
Titanium Wall (g)	285.6	285.6	285.6	285.6	285.6	285.6
Titanium Wick (g)	101.4	101.4	101.4	101.4	101.4	101.4
Total (g)	501.4	519.1	564.4	700.1	600.5	813.2

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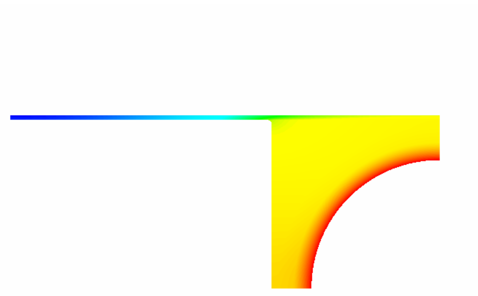


Figure 2. Temperature Profile in Kelvin for Graphite Saddle Design with HTC Graphite.

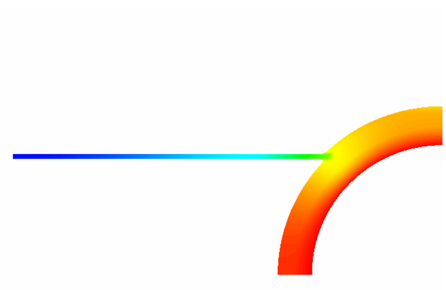


FIGURE 3. Temperature Profile in Kelvin for the Direct Fin Mount Design for a 2.54 cm O.D. Heat Pipe and 90° Fin Covering.

Figures 2 and 3 show graphical temperature results from the CFDesign finite analysis for the saddle and direct bonded fins, respectively. The temperatures are plotted in Kelvin, with a maximum of 500 K in the heat pipe interior. The minimum temperature (at the fin tip) is 489 K in Figure 2, and 488 K in Figure 3. In both Figure 2 and Figure 3, there is a large temperature drop by the circular arc. This represents the relatively large temperature drop through the low conductivity wick (3 W/m K) and heat pipe wall (22 W/m K). The saddle is relatively uniform in color, indicating good conduction. Essentially the entire heat pipe condenser is active with the saddle design. On the other hand, Figure 3 shows that not the entire condenser is fully utilized. The fin removes heat from a 90° arc at the top of the heat pipe (half of the arc is shown) efficiently. The portion of the heat pipe located in the center of the honeycomb is hotter, indicating less condensation and heat transfer. Roughly 2/3 of the heat pipe condenser is active.

The results of the trade study are shown in Table 1. While no test samples have been fabricated, 90° contact is believed to be achievable for the direct bonded case. A comparison between the 90° and 60° cases shows that the design is not very sensitive to the contact arc. The saddle designs are heavier than the direct bond designs. A comparison shows almost no effect on radiator size when switching from HTC to the regular foam. On the other hand, the mass of the radiator with regular foam is reduced by 5 to 15% when compared with the HTC foam, due to the reduced foam density. For the best case (0.51 mm minimum thickness), the saddle design has a 9 - 12% higher mass than the direct bond. Even though it is slightly heavier than the direct bond design, the Poco graphite saddle was chosen for two reasons: (1) the extra micrometeroid protection that the saddle provides for the heat pipe, and (2), the accommodation of the coefficient of thermal expansion (C.T.E) mismatch between the fin and the heat pipe.

IV. Stress Analysis, Saddle and Direct Bond Designs

A Finite Element Analysis (FEA) was conducted to compare the thermal stresses with the saddle and direct bond designs. The concern is that the different Coefficients of Thermal Expansion (C.T.E.'s) of the materials may cause high stresses as the radiator panels fluctuate in temperature. The titanium heat pipe has a C. T.E. of 8.8e-6 m/m °C (4.9E-6 in/in °F). The laminate structure of the fin has orthotropic C.T.E.'s depending on the orientation of the fibers in the reinforcing mesh. As discussed above, the weave orientation is tailored to match the titanium C.T.E. in the axial heat pipe direction, minimizing C.T.E. issues in that direction. However, that results in a negative C.T.E. in the perpendicular direction, which causes a potential issue with thermal stresses between the heat pipe and the laminate fin material. As the temperature is lowered, the heat pipe will contract, while the fin will try to expand, causing potentially damaging thermal stresses.

The thermal stresses in the direct bonded approach were roughly 380 MPa (55,000 psi), well above both the yield stress for titanium (128 MPa, 20,000 psi), and the allowable stress for the laminate fin in all three directions. Preliminary results with the foam saddle showed much lower stresses, due to the compliance of the graphite foam. The direct bond approach was then abandoned.

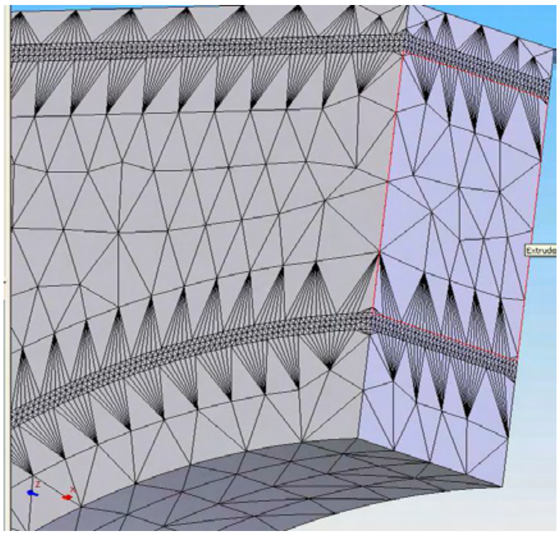


Figure 4. Refined Mesh Model.

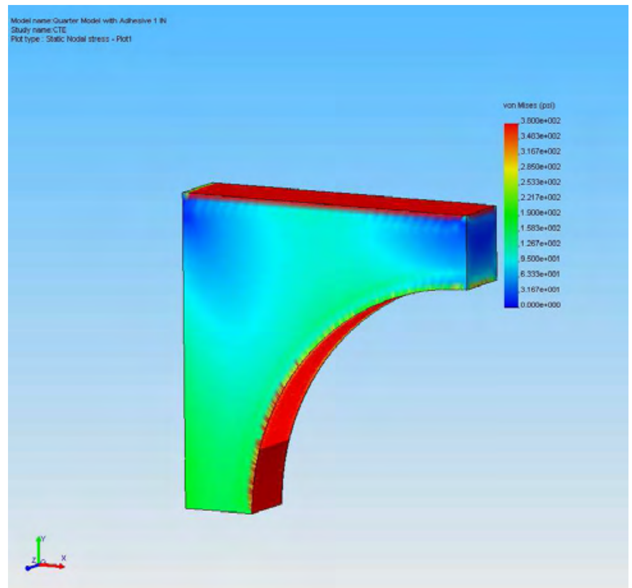


Figure 5. Stress plot for the Poco Foam Saddle, with better modeling of the adhesive layers. The limits are set equal to the compressive stress of the foam.

Initial FEA models of the saddle design showed that the stresses were low, except at the heat pipe/foam and foam/fin interfaces. The initial model neglected the adhesive layers at the interfaces, which are roughly 0.13 mm (0.005 in.) thick.

As shown in Figure 4, the adhesive layers were added into the model, and the mesh was refined at the interfaces. The results are shown in Figure 5. The stresses are low everywhere except at the interface, where they are roughly equal to the maximum allowable stress in the Poco foam, 2.1 MPa (300 psi). The FEA model gives a rough estimation of the stresses. At this point, a decision was made to go with the saddle design, and fabricate test panels.

V. Radiator Panel Development

A. Materials Selection

The choice of materials and processes was primarily driven by the temperature capability requirement: The panel should operate at 500 K, with excursions up to 530 K. . 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. Multiple plies of unidirectional tape were chosen, since the C.T.E. can be chosen to match titanium. High conductivity fibers were evaluated: 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. Three candidate resins were selected for use with the K13D2U fibers: (1) HFPE (composite supplied by NASA Glenn), (2) Cytec Cycom 5250-4 BMI, and (3) Bryte Tech EX1551 Cyanate. A significant criterion for the resin down selection is the glass transition Temperature, T_g. One relatively simple description for the glass transition temperature is that the resin is solid below this temperature and the molecules have very low mobility. As the material is heated above the T_g, there is enough thermal energy available to increase the mobility of the molecules and the material properties will begin to be affected. For the radiator development unit, a high T_g is desired to ensure that adequate properties of the resin will remain at the elevated temperatures.

All 3 of these materials have a T_g that is higher than the 530 K maximum operating temperature of the RDU. The Cytec 5250-4 materials is a bismaleimides (BMI), the Bryte EX 1551 is a cyanate ester (CE). The laminates were laid up in a 0/+30/-30/-30/+3/0 orientation to match the C.T.E. of titanium along the heat pipe axis. The panels are 0.41 mm (0.016 inch) thick. Test has been conducted on laminates, panels with an aluminum honeycomb, and panels with an aluminum honeycomb, heat pipe, and graphite saddle.

The materials have been designated as follows:

- Material A is the skin laminate material provided by NASA (K13D2U fiber with HFPE resin matrix)
- Material B is the skin laminate made using K13D2U fiber with 5250-4 BMI resin matrix,
- Material C is the skin laminate made using K13D2U fiber with EX-1551 Cyanate Ester resin matrix

For the panels that used Material A and Material B skin laminates, 5250-4 BMI resin film was used for all bonds (Core, foam, and heat pipe). For panels that used material C skin laminates, EX-1551 Cyanate Ester resin film was used for all bonds (Core, foam, and heat pipe). This was done to ensure compatibility between the resin matrix in the skin and the resin used to bond everything together.

B. Laminate and Panel Mechanical and Thermal Tests

Laminate and small panels were then fabricated for thermal and mechanical tests. The material A laminate was post-cured at 644 K for 2.3 hours. The material A panel, and the material B and C laminates and panels were postcured at 530 K for 2 hours. Prior to testing, all of the materials were thermal cycled for 20 cycles with a 2 minute dwell at the temperature extremes. The temperature was varied from 150 K to 530 K (-190 ºF to 495 ºF).

The laminate mechanical test results are shown in Table 2. It can be seen that there is generally good agreement between the measurements and predictions.

Table 2. Summary of Laminate Mechanical Test Results / Predicted Properties. All tests at room temperature.

Laminate Testing (Post Thermal Cycling)	Test Method	Material A HFPE	Material B 5250-4	Material C EX1551	Predicted
0-Degree Tension Strength	ASTM D3039	369 MPa	401 MPa	527 MPa	462 MPa
0-Degree Modulus	ASTM D3039	174. GPa	139. GPa	179. GPa	376. GPa
90-Degree Tension Strength	ASTM D3039	45.4 MPa	50.1 MPa	54.6 MPa	46.2 MPa
90-Degree Modulus	ASTM D3039	11.7 GPa	11.9 GPa	13.5 GPa	13.4 GPa
0-Degree Compression Strength	ASTM D695	215. MPa	212 MPa	228 MPa	312. MPa
0-Degree Compression Modulus	ASTM D695	197. GPa	181. GPa	199. GPa	376. GPa
90-Degree Compression Strength	ASTM D695	95.8 MPa	124. MPa	107. MPa	46.2 MPa
90-Degree Compression Modulus	ASTM D695	13.0 GPa	12.9 GPa	13.9 GPa	13.4 GPa
0-Degree Inplane Shear Strength	ASTM D5379	121. MPa	134. MPa	124. MPa	67.6 MPa
0-Degree Inplane Shear Modulus	ASTM D5379	57.6 GPa	57.2 GPa	63.9 GPa	

The laminate thermal conductivities were also measured after thermal cycling. The results are shown in Figures 6 to 8. The thermal is measured in three directions:

- X in plane, perpendicular to the heat pipe (the direction of heat conduction)
- Y in plane, along the heat pipe axis
- Z transverse to the fin

Table 3. Estimated Laminate Thermal Conductivity at 500 K.

Matrix	A, HFPE W/m K	B, 5250-4 BMI W/m K	C, Cyanate Ester W/m K
X (in plane) Long	251	226	255
Y (in plane) Trans.	63	57	65
Z (through plane)	0.96	0.72	1.22

Table 3 shows the laminate thermal conductivity, extrapolated to the maximum normal operating temperature of 500 K. The X and Y thermal conductivities decrease with temperature, while the Z thermal conductivity increases slightly with temperature (but still remains very low, less than 1 W/m K)

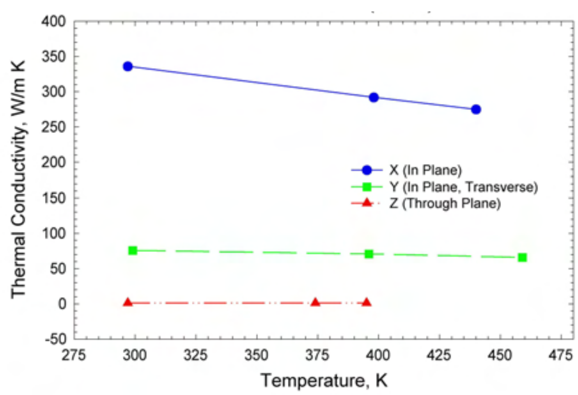


Figure 6. Panel A Laminate (HFPE) Thermal Conductivity vs. Temperature.

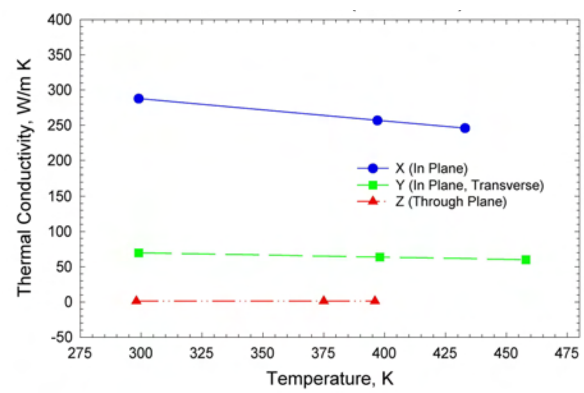


Figure 7. Panel B Laminate (5250-4 BMI) Thermal Conductivity vs. Temperature.

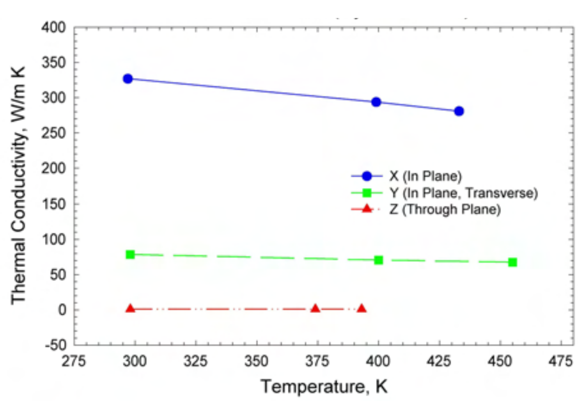


Figure 8. Panel C Laminate (Cyanate Ester) Thermal Conductivity vs. Temperature.

Figure 9. Close-up of Cured Sandwich Panel with High Thermal Conductivity skins.

Sandwich panels with all three resins were also fabricated. Figure 9 shows one of the panels, with the aluminum honeycomb and the high thermal conductivity laminates. All of the panels were postcured at 530 K for 2 hours. Prior to testing, all of the materials were thermal cycled for 20 cycles with a 2 minute dwell at the temperature extremes. The temperature was varied from 150 K to 530 K (-190 ºF to 495 ºF)

The results are shown in Table 4. Material A had low skin shear values. The fabrication process was modified to correct this problem.

Table 4. Summary of Panel Mechanical Test Results / Predicted Properties. Thermal Cycling All Test Specimens: (20 Cycles, 2 Minute Dwell at temp extremes, ambient thermocouple only): (150ºK to 530ºK) (-123ºC to 260ºC) (-190ºF to 495ºF). All tests at room temperature.

Sandwich Testing (Post Thermal Cycling)	Test Method	Material A HFPE	Material B 5250-4	Material C EX1551
0-Degree Edgewise Compression	ASTM C364	114.5 MPa Avg	86.0 MPa Avg	86.0 MPa Avg
90-Degree Edgewise Compression	ASTM C364	16.4 MPa Avg	46.1 MPa Avg	51.8 MPa Avg
0-Degree Flexure	ASTM C393	49.4 MPa Av Skin Shear	131.9 MPa Av Skin Shear	140.2 MPa Av Skin Shear
90-Degree Flexure	ASTM C393	4.6 MPa Av Skin Shear	39.5 MPa Av Skin Shear	37.9 MPa Av Skin Shear
Flatwise Tension	ASTM C297	0.052 MPa Avg	0.393 MPa Avg	0.379 MPa Avg

VI. Small Heat Pipe Test Panels

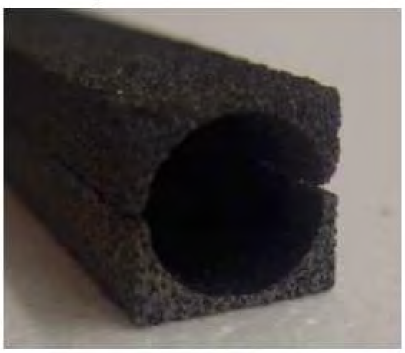


Figure 10. Close-up of Poco Foam Saddles.

Finally, three small heat pipe test panels were fabricated, one for each material. The panels have an area of 30.5 cm x 30.5 cm (12 in. x 12 in.). Each panel has a 1.91 cm (0.75 inch) O.D. titanium/water heat pipe. Since the minimum foam thickness is 0.317 cm (0.125 in.), the panel thickness is 2.62 cm (1.032 in).

Panel fabrication began with the construction of CP titanium heat pipes at ACT. The heat pipes have a sintered wick, and are designed to operate gravity aided. The heat pipes were charged with water, then run at 500 K for about 1 month to help passivate the heat pipes. The pipes were vented to remove non-condensable gas, resealed, and shipped to ATK for integration into the composite panels. Table 5 shows the materials used in each panel. Figure 10 is a close-up of the Poco foam saddles used as an interface between the heat pipe and fins.

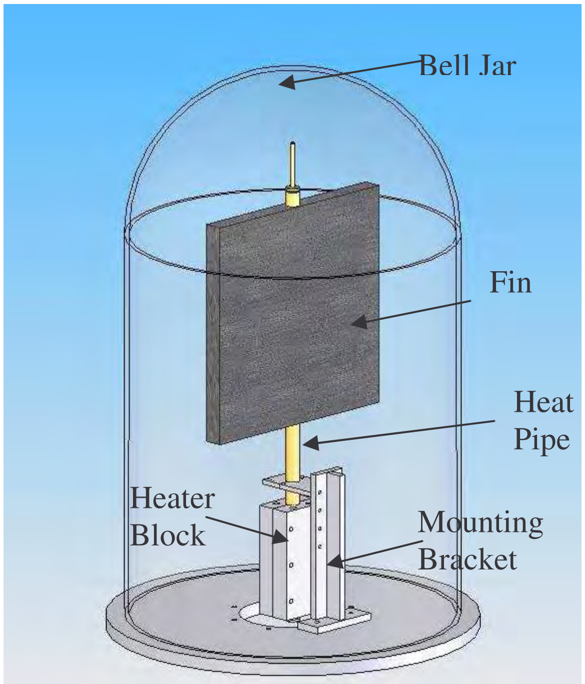
The panels were thermally cycled to demonstrate the ability of the radiator panels to operate at temperatures up to 530 K, and withstand thermal cycling between 500 K and 250 K.

The following test plan was used:

1. Operate the heat pipe at 500 K for 5 days
2. Cycle the radiator panels between 500 K and room temperature. (15 cycles total)
3. After the 500 K cycles are complete, run two cycles where the peak heat pipe temperature is 530 K. 530 K is the maximum design temperature during an upset.
4. Run a cycle to 500 K, measure temperatures, and compare with the baseline.
5. Remove the panels from the vacuum chamber. Place them horizontally. Conduct 10 freeze/thaw cycles, with the temperature going down to roughly 250 K.
6. Place the panels back in the vacuum chamber. Run a cycle to 500 K, measure temperatures, and compare with the baseline.

Table 5. Small Heat Pipe Panel Materials.

Panel	Fiber	Resin Matrix	Adhesive	Saddle	Heat Pipe	Heat Pipe Wick
Panel A	K13D2U	HFPE	5250-4 BMI	Poco Foam	CP-Ti	CP-Ti Screen
Panel B	K13D2U	5250-4 BMI	5250-4 BMI	Poco Foam	CP-Ti	CP-Ti Screen
Panel C	K13D2U	EX-1551 Cyanate Ester	EX-1551 Cyanate Ester	Poco Foam	CP-Ti	CP-Ti Screen



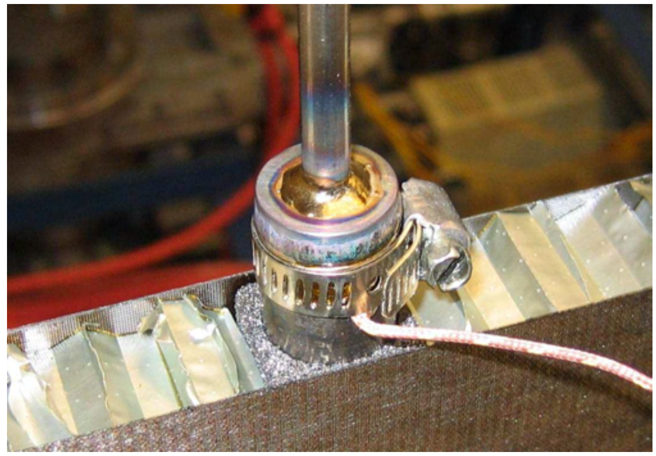


Figure 12. Panel A after testing – View of the heat pipe condenser, and the Poco graphite saddles. The panel is basically unchanged.

Figure 11. Panel Test Set-up.

The test set-up for the hot thermal cycles is shown in Figure 11. The heat pipe panels are mounted in a vacuum jar, and allowed to radiate to room temperature. A vacuum system is required, since titanium reacts with oxygen and nitrogen at the operating temperature. During the cold cycles, the ten 300 K to 250 K cycles were carried out with the panels in a horizontal position. The horizontal position is required, since the heat pipes are gravity aided pool boilers, and have a large amount of liquid. The minimum temperature of 250 K was chosen, since it is achievable by our chiller. The test chamber was purged with dry nitrogen, to prevent damage or alteration of the system due to condensation.

Figure 12 is a picture of Panel A after all of the thermal tests, showing that the panel was basically unchanged. All of the panels showed no signs of cracking or disbonding after the thermal cycles.

VII. Conclusions

A Graphite Fiber Reinforced Composite (GFRC) radiator with high temperature titanium-water heat pipes is currently under development. Three candidate fin materials have been evaluated: K13D2U fibers with 5250-4, EX1551, and HPFE resin. Titanium was selected over Monel as the baseline envelope material, due to its lower mass and previous experience with bonding titanium into honeycomb panels.

Poco graphite foam saddles are used to bond the heat pipes to the radiator fins. In addition to providing a heat transfer path between the round heat pipes and flat fins, the graphite saddle also provides micrometeroid protection, and reduces the effects of the coefficient of thermal expansion difference between the heat pipe and the fin.

Laminate and panels have been fabricated with the three candidate materials. The fin material is 0.38 mm thick, and uses a lay-up pattern that gives a C.T.E. along the heat pipe that matches the C.T.E. of titanium. Thermal conductivity and mechanical properties have been measured after thermal cycling.

Three 30.5 cm by 30.5 cm test panels using the three fin materials, aluminum honeycomb, POCO foam saddles, and titanium heat pipes were fabricated. After 120 hours at 500 K, the panels were successfully exposed to 15 thermal cycles between 300 and 500 K, two cycles to 530 K, and 10 cycles from 300 to 250 K. Visual observation and thermal test data showed no degradation, debonding or cracking.

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