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# Carbon-Carbon Heat Pipe Testing and Evaluation

Albert J. Juhasz
*Lewis Research Center*
*Cleveland, Ohio*

and

Richard D. Rovang
*Rockwell International*
*Canoga Park, California*

National Aeronautics and
Space Administration

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Albert J. Juhasz
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

and

Richard D. Rovang
Rockwell International
Canoga Park, California 91303

## ABSTRACT

This report discusses development and proof-of-concept testing of a new lightweight carbon-carbon (C-C) space radiator heat pipe developed under the NASA Civil Space Technology Initiative (CSTI) High Capacity Power Program. The heat pipe was filled with potassium working fluid and tested for 11 hours including startup from ambient temperature with the working fluid initially in the frozen state to near 700 K condenser temperature. Steady-state heat pipe input power during testing was facility limited to about 300 watts, representing about 50% of the design input power. Post test inspection showed the heat pipe to be in excellent condition after eight thermal cycles from ambient to steady-state operating temperature. Potential applications, ranging from small spacecraft heat rejection to aircraft and terrestrial uses, are discussed.

## INTRODUCTION

Space power system analysis and subsystem mass tradeoff studies for systems with nuclear and solar heat sources conducted at the NASA Lewis Research Center have shown [1,2] that radiator mass comprises a significant fraction of the overall power system mass. This is especially true for dynamic power systems such as the Closed Brayton Cycle (CBC) or the Free-Piston Stirling (FPS) that reject non-convertible cycle heat at the relatively low temperature range of 350 to 550 K as compared to space sink temperatures (200-250 K). While passive power conversion systems such as the Thermoelectric (TE) and the Thermionic (TI) have the advantage of the fourth power radiation law due to their higher heat rejection temperatures (800 to 900 K), they need to reject more heat due to their lower thermal efficiency. Hence, these systems may still require large radiating surface areas and thus would also benefit from advances in lightweight radiator technology, even though the mass savings would be lower than for dynamic systems.

To explore new technologies which could lead to significant reductions in space radiator and heat rejection subsystem mass, a program was initiated at the NASA Lewis Research Center aimed at the development of innovative radiator concepts, applicable to space heat rejection subsystems operating over a range of temperatures which would meet the needs of both dynamic and passive power conversion systems. This report reviews salient results of the effort to develop a lightweight C-C radiator designed for the heat rejection requirements of the SP-100 TE power system [3]. Extension of the technology to other temperature ranges are also discussed briefly.

## LIGHTWEIGHT C-C RADIATOR DEVELOPMENT

Development of this technology was con-ducted under an "Advanced Radiator Concepts" (ARC) contract between the NASA Lewis Research Center and Rockwell International Co. as a major effort of the CSTI Thermal management program [4]. As indicated in Figure 1 (a), the basic element of a C-C radiator is a carbon-carbon heat pipe consisting of a tubular C-C pressure shell with integrally woven fins and a thin walled (0.064 mm) metallic liner of niobium-1% zirconium (Nb-1Zr) alloy which has been furnace brazed to the inner surface of the composite shell for containment of the heat pipe working fluid. A short extension of this liner protruding beyond one end of the shell forms the evaporator section which is in thermal contact with the power system heat rejection loop fluid. The wall thickness for the evaporator and the two welded end caps is about 0.4 mm, permitting a structurally rigid radiator panel assembly. The surface emissivity, $\varepsilon$, of the C-C shell and fins

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was 0.85. Further details on the fabrication and assembly of the heat pipe, using the originally available T-300 C-C composite for the finned shell have been reported previously [5,6]. A 35 cm long heat pipe with 2.5 cm wide fins was successfully tested [7], starting from room temperature with the potassium working fluid in the frozen state to temperatures near 700 K. A sketch of the instrumented test article is shown in Figure 1 (b). Further details on the heat pipe filling and test procedures are given in later sections under the pertinent headings.

Because the "along the fiber" thermal conductivity (fin root-to-tip direction) of the heat pipe tested was limited to a maximum of 80 W/m-K, an additional task was added to study methods of fabricating the woven preform finned shells using higher conductivity fiber yarn, which is more difficult to weave. Several lengths of P-95 WG composite shells were successfully fabricated under this task. Since the conductivity of this composite was about 300 W/m-K at the operating temperature range of 750 to 800 K, the fin length (root-to-tip dimension) could be increased from 2.5 to 5 cm, without any loss in fin efficiency. A comparison of the two fin designs and a detailed heat pipe component weight breakdown is given in Table 1, which shows that the long finned P-95 WG heat pipe achieves a 69 percent increase in radiating area at a mere 15 percent increase in mass. As a result the areal, specific mass decreases from 2.1 to 1.45 kg/m$^2$. The one sided heat rejection capacity with view factor (VF) = 1, computed as function of fin root temperature by the use of a specially written radiating fin code for the two C-C composites, Figure 2, shows that the higher conductivity P-95 WG composite heat pipe is capable of rejecting over 60 percent more heat than the T-300 composite, due to the higher radiating area.

## HEAT PIPE FILLING PROCEDURE

The process of adding the potassium working fluid was initiated after a 20 hour vacuum bake out and degassing of the heat pipe at a temperature of 820 K. To insure purity of the potassium working fluid a meticulous fill procedure was followed, consisting of a repetitive potassium filling, soaking, and flushing sequence. For a detailed schematic of the filling system the reader is referred to a prior report [7]. Since the heat pipe liner was made from a refractory material, all filling operations were performed in an inert glovebox atmosphere.

A supply tank (located inside the glovebox) provided potassium for flushing and filling. Although this potassium was commercially pure, a final distillation was performed to guarantee ultra-high purity starting material. Potassium was transferred from the supply tank to the distillation tank using 0.999999 argon (Ar6) pressure in the supply tank and evacuating the distillation tank. After transfer, heat was supplied to the distillation tank and cooling to the feed tank until the required amount of potassium was distilled.

Ar6 pressure was used again to push the purified potassium from the feed tank through the heat pipe and into the overflow tank. When sufficient overflow was observed, the feed valve was closed and the heat pipe soaking process initiated. The temperature of the heat pipe was raised to its maximum operating condition of 875 K and held for 6 hours. This soaking period allowed time for diffusion of impurities into the potassium and conditioning of the wick. At the end of the 6 hours, a fresh volume of potassium was pushed through the heat pipe, displacing the previous volume. This cycle was repeated three times. On the fourth cycle, the pipe was filled with fresh potassium then excess drained back into the feed tank with the required inventory remaining in the wick and reservoir. A temperature histogram of the three potassium fill-soak cycles is also shown in reference 7.

Potassium in the heat pipe was then allowed to freeze under vacuum conditions. Fill tubes were crimped using pinch block techniques, and then cut and seal-welded. The final step in the filling process was inspecting and weighing of the heat pipe to ensure that the correct amount of potassium had been charged. Analysis of the final oxygen concentration in the potassium working fluid showed the oxygen level to be below the detectable limit of 8 ppm.

## HEAT PIPE TESTING

Functional tests were run on the filled C-C heat pipe to verify that the potassium containment boundary would remain intact under operating conditions, that the C-C to liner bond was stable through multiple thermal cycles, and to determine first-order operating characteristics of the heat pipe. As shown in Figure 1b, the heat pipe was instrumented with thermocouples (TCs), to determine axial temperature distribution

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(TCs 3, 4, 6, 10, and 12) and to determine fin temperature profile and efficiency (TCs 6, 7, 8, and 9), with TCs 5 and 11 added at mid-fin locations as a check on fin profile readings.

## Test Setup

Testing was performed in a horizontal vacuum chamber as shown in Figure 5. A vacuum of 1.3 x $10^{-3}$ Pa ($10^{-5}$ Torr) was maintained within the chamber to limit heat losses from the condenser to radiation mechanisms (similar to a space environment) and to protect the Nb-1Zr and C-C components from oxygen attack. Heat was supplied to the evaporator section of the pipe by a radiation-coupled, electrical resistance heater. Since the heater elements could not be operated in a vacuum without experiencing rapid degradation, an Inconel can was used to isolate the heaters from the vacuum. A surface treatment was performed on the heater can inside diameter to produce an emissivity above 0.9. To minimize heat losses to the vacuum chamber from the heaters, the back side of the heater elements were insulated by a ceramic fiber insulation inside the can. Multiple layers of highly reflective tantalum foil baffles were used to isolate the heater from the condenser section, end flanges, and supports.

The C-C condenser section was surrounded by a water-cooled calorimeter to measure heat rejected from the pipe. The inside diameter of the calorimeter was also treated to enhance thermal absorptivity. Sheathed thermocouples 250 μm (10 mils) in diameter were attached to the condenser to measure surface temperatures. Thermocouples were also installed inside the calorimeter-cooling water inlet and outlet tubes to measure temperature rise of the water during operation.

## Test Results

The heat pipe test was conducted over an 11.3 hour (680 minute) period, starting with the pipe at ambient temperature and the potassium in the frozen state. For this first test, a conservative approach was taken, supplying initial power to the heater at a low level, then gradually increasing power until the maximum heater limit of 770 W was reached. Temperatures measured at various locations (see Figure 1b) are shown as a function of time in Figure 4. The scale on this figure may give the impression that temperatures continue to increase at the end of the test. However, over the last 20 minutes of operation

only a 1°C temperature rise was measured, indicating that, for all practical purposes, steady-state conditions had been achieved.

As mentioned above, the test was conducted by incremental addition of power to the evaporator radiant heater, transitioning from an initial level of 20 W, at 300 K heater temperature, to a final level of 770 W, at a heater temperature of 1269 K. Unfortunately, less than half of the heater power was absorbed by the heat pipe evaporator because of the low thermal absorptivity of the Nb-1Zr evaporator surface. This was recognized as a problem before testing. However, an absorptivity enhancement coating was not applied to the evaporator surface, because the coating could potentially react with the liner, thereby jeopardizing the primary objective of the test. If the Nb-1Zr liner or an end cap weld were to fail during the test, it would be difficult to determine if failure was due to faulty design and fabrication methods or to a compatibility issue associated with the coating. Moreover, this heat pipe was designed for convective coupling of the evaporator in flowing liquid metal. Therefore, low-radiative thermal coupling efficiencies between the evaporator and the heat source are not problematic, except for testing purposes. Future tests may use a direct contact resistance heater to control evaporator heat input. Heat output, as measured by the water calorimeter, was 300 W at the maximum heater power setting.

Getting thermocouples to adhere to the C-C tube and fins without impacting the test results was found to be difficult. Several techniques were tried with the most successful being the use of a graphite paste. Even with this method, five of the ten thermocouples, which had been attached to the C-C tube, separated during testing. Four of these were located on the tube (TCs 3, 4, 10, and 12) and one at the fin root (TC 7). Because of this, an accurate axial temperature profile was not obtained at the final power throughput; however, some significant axial performance results can be inferred from the fin temperatures.

A fin efficiency of 80% (actual heat rejected divided by theoretical heat rejected if the entire fin were at the root temperature) was calculated for the heat pipe at the final operating conditions, based on temperature measurements made from the tube to the edge of the fin perpendicular to the pipe axis. Three TCs 6, 8, and 9, located midway along the condenser, measured surface temperatures of 670 K, 635 K, and 634 K, respectively. The temperature profile formed

by the readings from these three thermocouples suggests that most of the thermal resistance is concentrated near the base of the fin. This is most likely due to the low conductivity filler material used in the cusp area located under the fin root, which would explain the large temperature drop between TCs 6 and 8. In a second generation C-C tube and fabrication process design this cusp area, and hence the need for filler material, has been eliminated. Thus the thermal coupling between the liner and the fin should be improved considerably. Moreover, the new design uses the higher conductivity P-95 WG C-C composite. However, fabrication and testing of a new heat pipe with the improved C-C tube design has been deferred until additional funding can be obtained.

Visual post-test inspection of the heat pipe showed it to be in excellent condition, thus validating the soundness of the overall design and fabrication process. No changes in the C-C tube shell, braze joints, or liner were apparent, considering that the test article underwent eight thermal cycles. These included the brazing and degassing at 820 K, three fill cycles from about 425 to 875 K, thermocouple installation at 575 K, checkout testing at 525 K, and performance testing at near 700 K. The Nb-1Zr liner with the high temperature welded end caps, forming the potassium containment envelope, maintained its structural integrity throughout these thermal cycles, and it remains intact at room temperature storage.

## CONCLUDING REMARKS

Design validity, fabrication quality and successful operation of a C-C , liquid metal heat pipe with integrally woven fins has been demonstrated. Cleaning and filling of the heat pipe with potassium to a final oxygen concentration below 8 ppm was successfully carried out. After eight thermal cycles the heat pipe has shown no signs of degradation of the C-C shell, tube-to-liner bond or weld joints.

Due to facility limitations, initial performance tests were conducted at an evaporator temperature of nominally 700 K and a total thermal power throughput of 300 W, less than half of design power. Higher power tests using induction, conductive, or convective evaporator heat input coupling, are ready to be performed under potential follow-on programs.

Although the heat pipe tested was designed for operation in the 700 to 850 K temperature range with the potassium working fluid, the technology can be readily extended to cover a much broader range of operating temperatures, ranging from cryogenic to hypersonic aircraft leading edge cooling applications. This can be accomplished by proper selection of the composite architecture (including fin length and thickness), a working fluid compatible liner material, and the working fluid applicable to the desired service temperature range. For terrestrial applications, where oxidation protection needs to be considered, the C-C shell would have to be covered with a protective coating; or the C-C composite material could be replaced by a non-oxidizing ceramic composite.

## References

1. Juhasz, A. J. and Jones, B. I., "Analysis of Closed Cycle Megawatt Class Space Power Systems with Nuclear Heat Reactor Sources," Proceedings of the Third Symposium on Space Nuclear Power Systems, Albuquerque, NM, Jan. 13-16, 1986.

2. Brandhorst, H. W., Juhasz, A. J., and Jones, B. I., "Alternative Power Generation Concepts in Space," NASA TM-88876, 1986.

3. Mondt, J. F., Truscello, V. C., and Marriott, A. T., "SP-100 Power Program," 11th Symposium on Space Nuclear Power and Propulsion, Albuquerque, NM, Jan. 9-13, 1994.

4. Juhasz, Albert J., "An Overview of the Lewis Research Center Thermal Management Program," Conference on Advanced Space Exploration Initiative Technologies, co-sponsored by AIAA, NASA, and OAI, Cleveland, OH, Sept. 4-6, 1991.

5. Rovang, R. D., et al., "Advanced Radiator Concepts for SP-100 Space Power Systems - Phase III Final Report, NASA CR-187170, Aug. 1990.

6. Rovang, R. D., et al., "Carbon-Carbon Heat Pipe Assembly," Proceedings of 10th Symposium of Space Nuclear Power and Propulsion," CONF-930103, American Institute of Physics, AIP Conf. No. 271, 1:539-543.

7. Rovang, R. D., Hunt, M. E., and Juhasz, A. J., "Testing of a Liquid Metal Carbon-Carbon Heat Pipe," 11th Symposium on Space Nuclear Power and Propulsion, Albuquerque, NM, Jan. 9-13, 1994.

Table 1: Carbon-Carbon Heat Pipe Mass Breakdown

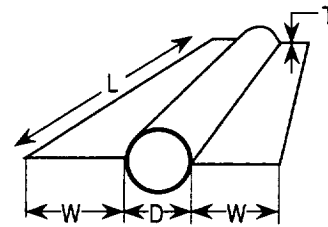| COMPONENT | T-300 Composite | P-95 WG Composite |
|---|---|---|
| DIMENSIONS (SEE SKETCH) | L = 91.4 cm; D = 2.5 cm W = 2.5 cm; T = 0.1 cm | L = 91.4 cm; D = 2.5 cm W = 5 cm; T = 0.1 cm |
| C-C SHELL | 169.5 | 214.0 |
| LINER W, EVAPORATOR | 41.2 | 41.2 |
| END CAPS | 13.1 | 13.1 |
| FILL TUBES | 7.2 | 7.2 |
| BRAZE | 22.5 | 22.5 |
| WICK | 24.0 | 24.0 |
| WORKING FLUID | 13.5 | 13.5 |
| TOTAL MASS (G) | 291.0 | 335.5 |
| TWO SIDED RADIATING AREA - $m^2$ | 0.1383 | 0.2335 |
| SPECIFIC MASS - $kg/m^2$ | 2.1 | 1.45 |
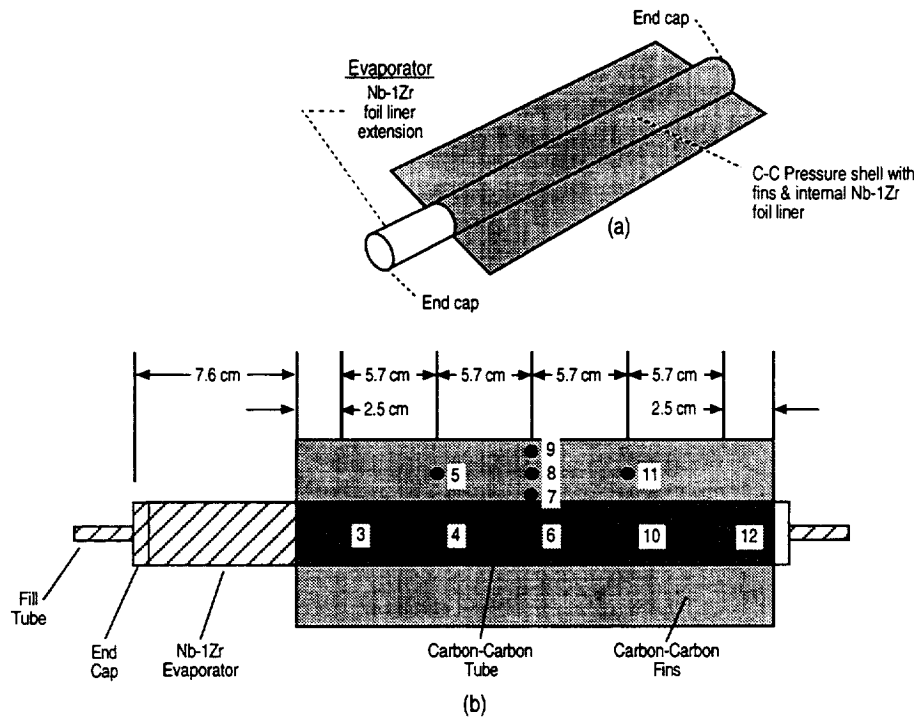
Figure 1: Carbon-Carbon Heat Pipe Radiator Element

(a) Sketch showing C-C shell and Metallic Liner/Evaporator Extension
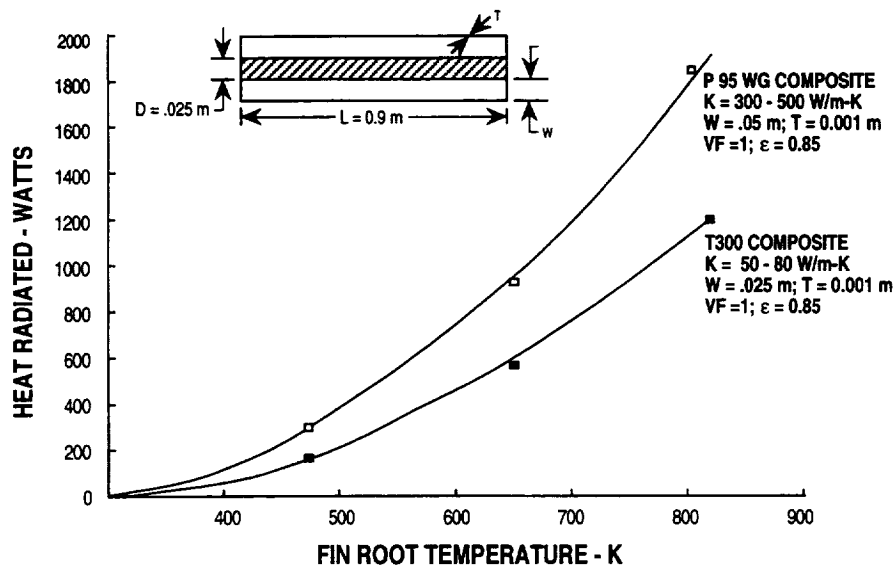(b) Test Article (top view) showing Thermocouple Locations

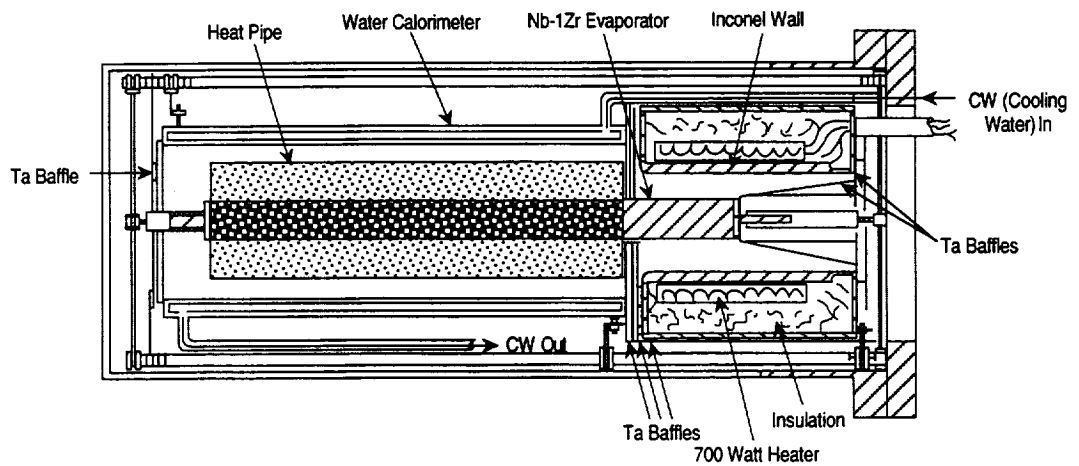Figure 2: Thermal Conductivity Effect on Finned Heat Pipe Performance
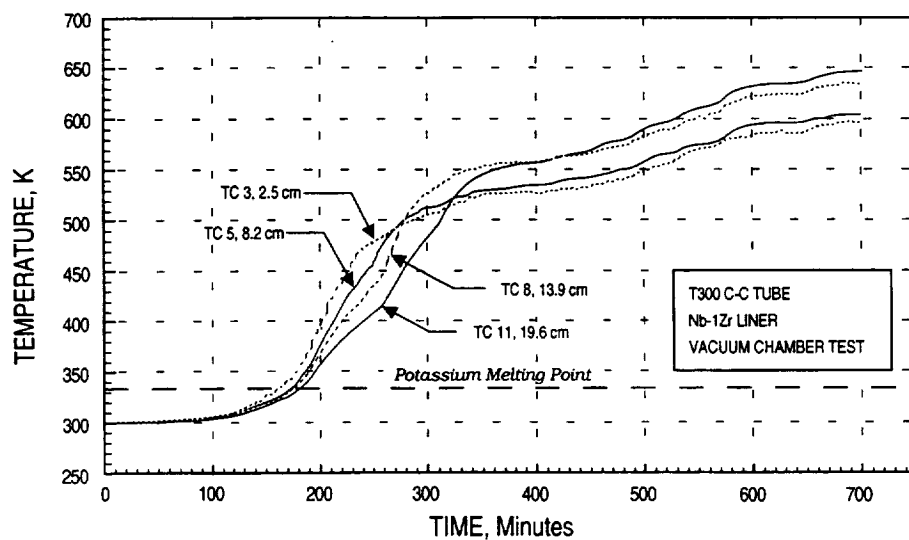


Figure 3: Heat Pipe Test Setup and Vacuum Enclosure



Figure 4: Heat Pipe Temperature Profile Development

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Lewis Research Center
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