NASA/TM—2008-215420

High Conductivity Carbon-Carbon Heat Pipes for Light Weight Space Power System Radiators

Albert J. Juhasz
Glenn Research Center, Cleveland, Ohio

October 2008

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NASA Aeronautics and Space Database and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include creating custom thesauri, building customized databases, organizing and publishing research results.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at *http://www.sti.nasa.gov*

- E-mail your question via the Internet to *help@sti.nasa.gov*

- Fax your question to the NASA STI Help Desk at 301–621–0134

- Telephone the NASA STI Help Desk at 301–621–0390

- Write to:
  NASA Center for AeroSpace Information (CASI)
  7115 Standard Drive
  Hanover, MD 21076–1320

NASA/TM—2008-215420

High Conductivity Carbon-Carbon Heat Pipes for Light Weight Space Power System Radiators

Albert J. Juhasz
Glenn Research Center, Cleveland, Ohio

Prepared for the
6th Annual International Energy Conversion Engineering Conference (IECEC)
sponsored by the American Institute of Aeronautics and Astronautics
Cleveland, Ohio, July 28–30, 2008

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

October 2008

Acknowledgments

This work was conducted at NASA Glenn Research Center Thermal Energy Conversion Branch.

This report is a formal draft or working paper, intended to solicit comments and ideas from a technical peer group.

Level of Review: This material has been technically reviewed by technical management.

Available from

NASA Center for Aerospace Information
7115 Standard Drive
Hanover, MD 21076–1320

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161

Available electronically at http://gltrs.grc.nasa.gov

High Conductivity Carbon-Carbon Heat Pipes for Light Weight Space Power System Radiators

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

Abstract

Based on prior successful fabrication and demonstration testing of a carbon-carbon heat pipe radiator element with integral fins this paper examines the hypothetical extension of the technology via substitution of high thermal conductivity composites which would permit increasing fin length while still maintaining high fin effectiveness. As a result the specific radiator mass could approach an ultimate asymptotic minimum value near 1.0 kg/m^2, which is less than one fourth the value of present day satellite radiators. The implied mass savings would be even greater for high capacity space and planetary surface power systems, which may require radiator areas ranging from hundreds to thousands of square meters, depending on system power level.

Nomenclature

A_i	inner surface area; A_o outer surface area
$A_{r(j)}$	incremental radiator area at section j
dA_i	elemental inner wall surface, or heat pipe evaporator area
dA_r	dA_o, is the elemental radiating outer wall surface, or heat pipe condenser area
h_r	heat transfer coefficient normalized to external or radiating area
L_{COND}	Condenser length
$\dot{m}$	radiator fluid mass flow rate
T_{wex}	wall temperature at duct outlet
T_{win}	wall temperature at duct inlet
$T = T(x)$	fluid bulk temperature at axial location x; T_{in}, T_{ex} = fluid temperatures at duct inlet and exit
$T_s = T_{space}$	equilibrium space sink temperature
$T_w = T_w(x)$	$T_{w(j)}$ wall temperature at arbitrary location x, or j
T_{weff}	effective radiator wall temperature
x	fractional distance along radiator flow path
γ	specific heat ratio of radiator heat transport fluid
σ	the Stefan-Boltzmann constant = $5.668*10^{-8}$ watts/m^{2}K^4
ε	the emissivity of the radiating surface

Introduction

By virtue of their inherent parallel redundancy, heat pipes (HP) are logical elemental building blocks for the construction of spacecraft radiators. In *pumped loop* space radiators, a micrometeoroid puncture of a cooling-fluid carrying tube would cause eventual loss of cooling fluid, thus leading to failure of the radiator. In contrast, space radiators composed of a large number of heat pipes would be relatively immune to puncture from micrometeoroids or small space debris because loss of an individual heat pipe, whose function is completely independent of that of its neighbors, would result only in the loss of that small fraction of total radiating area represented by the punctured heat pipe's radiating surface. Thus, overall radiator reliability can be significantly enhanced, even with lower wall thickness of its heat pipe elements, which also would reduce radiator mass. Increased survivability coupled with reduced mass is of strategic importance in spacecraft power system radiators, since past studies of power systems with either solar or nuclear heat sources have shown (Juhasz and Jones, 1986, Brandhorst et al., 1991) that radiator weight accounts for a significant portion of overall spacecraft launch mass. This is especially true for dynamic energy conversion systems utilizing the Brayton or Stirling thermodynamic cycles, since these systems have relatively low mean effective heat rejection temperatures. Thus, application of graphite-carbon composite technology to space radiator heat pipes will lead to even greater savings in the total Earth-to-orbit mass that needs to be launched for a given mission, and thereby contribute to the "low-cost access to space" initiative, which is a goal to be implemented during the early decades of the 21st century.

The purpose of this paper is to review, expand and extrapolate the results of space radiator research conducted by the NASA Glenn Research Center (GRC) and its contractors under the Civil Space Technology Initiative, (see Juhasz and Peterson (1994), Juhasz and Rovang (1995), and summary paper by Juhasz (2002)). The approach taken in extrapolating prototype C-C heat pipe test results to the design of full-scale space radiators is analogous to that taken by Groll in proposing the use of heat pipes as elemental units, or building blocks, for various thermal applications in industry (Groll, 1973). Such an extrapolation is especially appropriate, because the development of very high conductivity composites with the required mechanical and optical properties for space radiator use makes possible some highly attractive design options. Of these, the most impressive is one offering a radiator whose specific mass is less than one fourth that of a pumped loop design (<1.6 kg/m^2 compared to 6 to 10 kg/m^2) based on near term technology, while long term material development breakthroughs may lead to 1.0 kg/m^2 as an asymptotic low limit for radiator area specific mass expressed in kg/m^2, given that strength and durability of the fins during simulated launch conditions can be demonstrated. At the same time, heat pipe radiators provide significantly higher survivability to micrometeoroid damage, owing to the parallel redundancy of heat pipes.

Space limitations prevent an in-depth discussion of all aspects of the C-C heat pipe design, fabrication, and testing carried out under a joint program between NASA Glenn and the Rockwell International Division of the Boeing Company; however, this paper addresses the highlights and briefly analyzes radiating fin heat transfer, which is an essential feature of the proposed "integral fin" C-C heat pipe concept. Also included is a discussion of several potential radiator designs, based on the C-C heat pipe as an elemental unit of typical radiator panels, for space power systems ranging from multi-kilowatt to megawatt levels for space and lunar base applications.

Discussion

Integral Fin C-C Concept

If a heat pipe were a single element or building block of a spacecraft radiator consisting of a large number of similar devices, obviously, any measures taken to increase the reliability and survivability of each of these elemental units in the space environment would reduce the vulnerability of the entire radiator to micrometeoroid damage. One such measure is the addition of fins over the heat pipe condenser section, a provision that can easily be accomplished during the weaving of the C-C preform by using what is referred to as the *integrally woven fin* technique. To maximize radiation heat transfer at heat pipe operating conditions, the C-C shell condenser section, including the radiating fins, was exposed to an atomic oxygen (AO) ion source as part of the fabrication process. A total AO fluence of $4*10^{20}$ atoms/cm^2 raised the surface emissivity for heat radiation to a value of 0.85 to 0.90 at design operating temperatures of 700 to 800 K (Rutledge et al., 1989).

For a detailed analysis of heat transfer from a radiating fin, including derivation of the governing second-order, fourth-degree ordinary differential equation (ODE), the reader is referred to Juhasz (2002, Appendix A). The computer-coded numerical solution technique for this ODE was expanded as part of this study. This technique permits generation of solutions not only for constant material properties (i.e., thermal conductivity or surface emissivity) and rectangular fin profiles, but also for cases in which these properties are functions of temperature and in which the fin profile (i.e., the cross-sectional area normal to heat flow) varies with distance from the fin root along the main heat flow axis. Moreover, the option of heat transfer by combined radiation and convection, i.e., for atmospheric influence in planetary surface applications, can be readily implemented.

In addition to fins increasing the radiating surface area of the heat pipe condenser section, they are also impervious to damage from small particle impact since a punctured fin would not adversely affect the continued operation of the heat pipe. The ratio of the "vulnerable area of the heat pipe's working fluid containment portion" to "the overall heat pipe-plus-fin area" will thus decrease in inverse proportion to the fin width (which is defined as the linear dimension from the fin root to the fin tip). In addition to increasing the survivability, and thus the reliability, of individual heat pipe radiator elements, fins would also reduce the radiator's specific mass. Of course, increasing the fin width while keeping constant the fin thickness and fin efficiency (total heat transferred by the fin divided by the total heat transferred if the entire fin were at the fin root temperature) would be a design option only if the thermal conductivity of the fin in the root-to-tip direction could also be increased by using a higher conductivity material.

C-C Heat Pipe Design and Fabrication Details

As described in a prior report (Juhasz, 2002), to meet the radiator operating requirements for the SP-100 power system (nuclear reactor heat source coupled with thermoelectric energy conversion), a heat pipe evaporator temperature of 850 to 875 K was required. Since at this temperature the heat pipe's potassium working fluid undergoes an intercalation reaction with the C-C material, a barrier was needed between the inner surface of the C-C tube and the potassium working fluid. Thus, a thin-walled metallic liner produced by Pacific Northwest Laboratories (PNL) of Richland, Washington, was fabricated for this purpose. The external section of this liner, which was formed by a "Uniscan" rolling process, transitions to a larger wall thickness (0.020 in.). This section which protrudes beyond the C-C shell, as shown in figures 1 and 2, constitutes the "evaporator" part of the heat pipe, while the section inside the C-C shell constitutes the condenser of the heat pipe.

Figure 1(a) shows an isometric view of the C-C shell with integral fins and the Nb-1Zr (Niobium-1% Zirconium alloy) foil liner extension. A top view with dimensions for the heat pipe and thermocouple locations is shown in figure 1(b). The Nb-1Zr tubular liner fabrication was accomplished at PNL of Richland, Washington, by use of a tube roll forming and roller extrusion procedure which has the capability to reduce the wall thickness, and hence the tube outer diameter, but keeps the tube inner diameter constant. PNL developed this procedure, referred to as the *Uniscan* process, in an effort to produce flexible heat pipes, which could be rolled up and unfurled like a flat hose. Unfortunately, the thin walled metallic tubes developed creases when rolled into coils with reasonable radii of curvature. However, the "Uniscan" rolled thin walled tubes proved to function well as protective liners for the high conductivity integral fin C-C condenser shells. This is because when carbon-carbon (C-C) is exposed to the molten potassium HP working fluid, an intercalation reaction takes place causing swelling and eventual erosion of the C-C heat pipe wall.

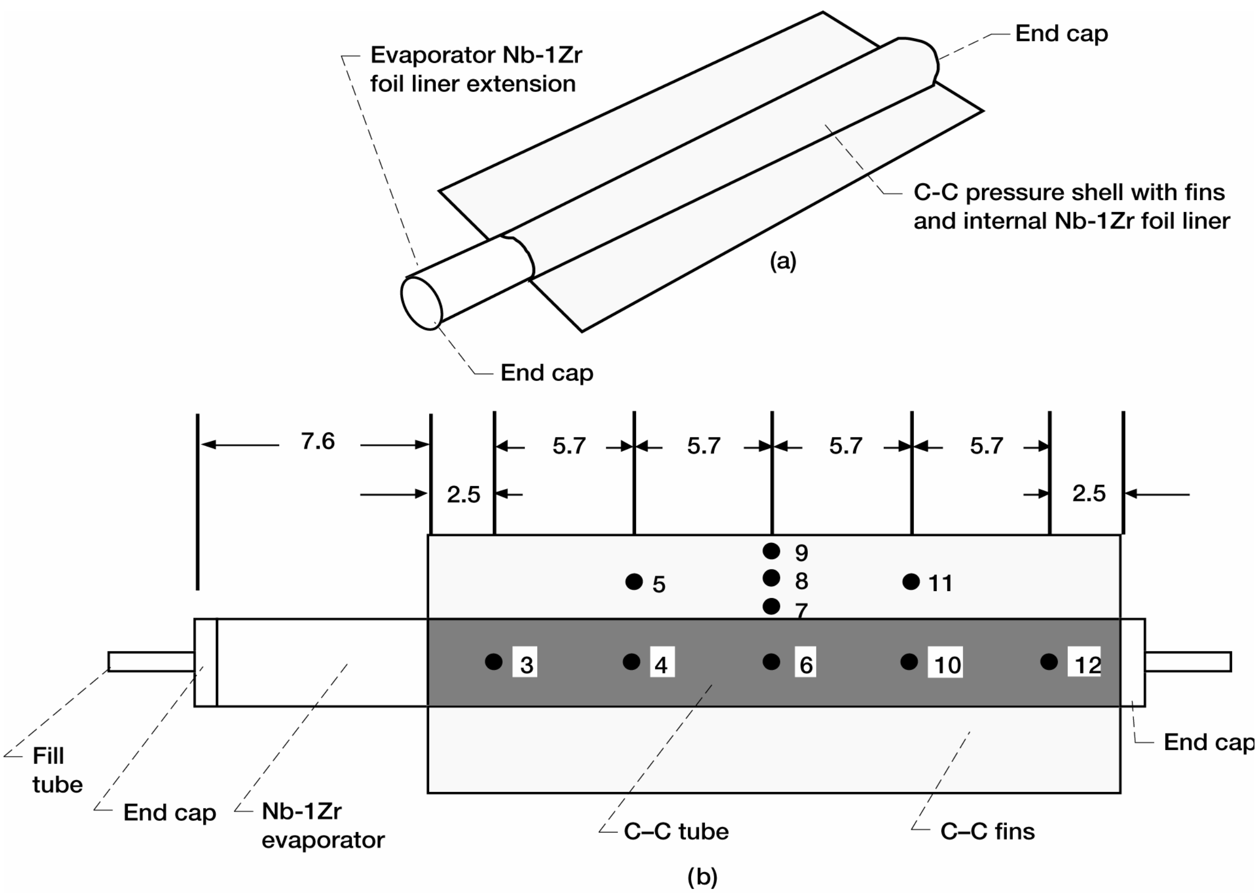


Figure 1.—Sketch of 2.5 cm diameter Carbon-Carbon heat pipe radiator element (dimensions in centimeters). (a) C-C shell with integral fins and metallic evaporator liner extension. (b) Top view of test article with thermocouple locations.

As shown in figure 2 liner had a 0.076-mm-thick wall with a thicker wall (0.76-mm) extension for the 2.5 cm diameter evaporator. While pressurized with argon gas, the liner was furnace-brazed into the C-C shell, as shown in the section view of figure 2. Prior to the furnace-brazing operation, a Molybdenum perforated foil wick was attached to the inner surface of the liner using 0.25 to 0.35 mm spacer tabs. End caps were welded to both ends of the liner, an especially significant accomplishment for the liner section that was only 0.076 mm thick. Fill tubes cut from 0.63-cm-diameter Nb-1Zr tubing were inserted into central holes in the end caps and welded in place.

The liner itself was furnace brazed into the C – C shell under inert gas (argon) pressure. For the brazing process silver ABA (ternary braze alloy) braze foil was wrapped around the pressurized thin walled liner cylinder and inserted into the inside diameter (ID) of the C – C shell. The braze assembly was then placed into the furnace for the braze operation, carried out at 1100 K, which was more than 200 K above the maximum design service temperature for the potassium heat pipe.

In the filling operation, the minimization of impurities, especially oxygen, in the potassium working fluid is of utmost importance, because the resulting oxides have been shown to be the principal cause of heat pipe corrosion at operating temperatures (Lundberg, 1987). In 1986 a process for achieving very low oxygen concentrations in liquid-metal fluids (DeVan, 1986) was demonstrated at the Oak Ridge National Laboratory (ORNL). This liquid-metal flow-through process with intermittent soak periods ensures that all wetted inner surfaces are free of adsorbed oxygen before the heat pipe is sealed. This procedure, with minor variations such as an initial vacuum bake out period, was selected as the way to fill the heat pipe with potassium working fluid. Since refractory metals were being used at elevated temperatures, all filling operations were performed in a glove box with an inert gas atmosphere. Prior measurements had shown that the equipment used was capable of keeping oxygen and moisture concentrations below 1 ppm, and nitrogen concentrations below 5 ppm. After completion of the filling operations, the fill tubes were pinched and welded. Figure 3 shows a photograph of completed heat pipe taken after testing, which will be discussed in the next section.

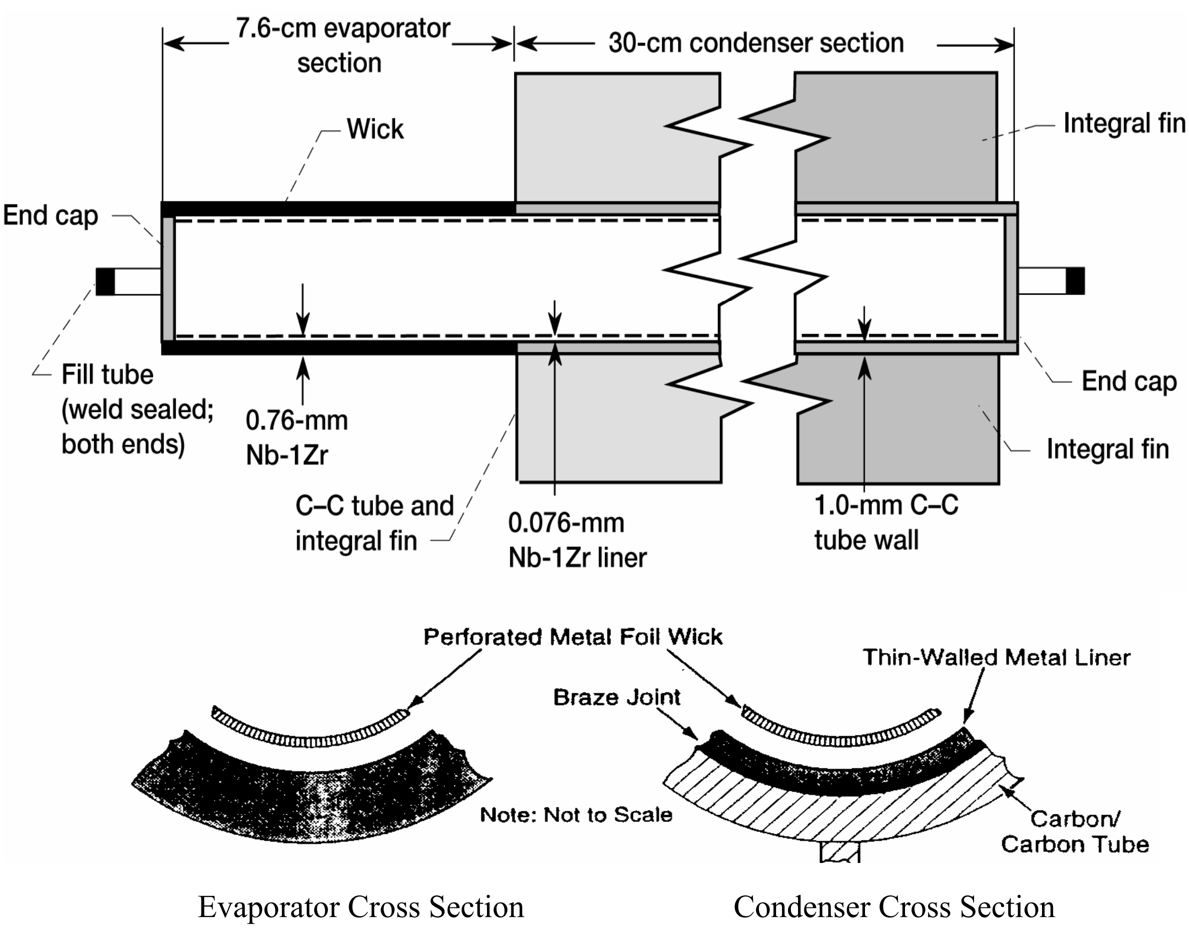


Figure 2.—Carbon—Carbon Heat Pipe Design Details.

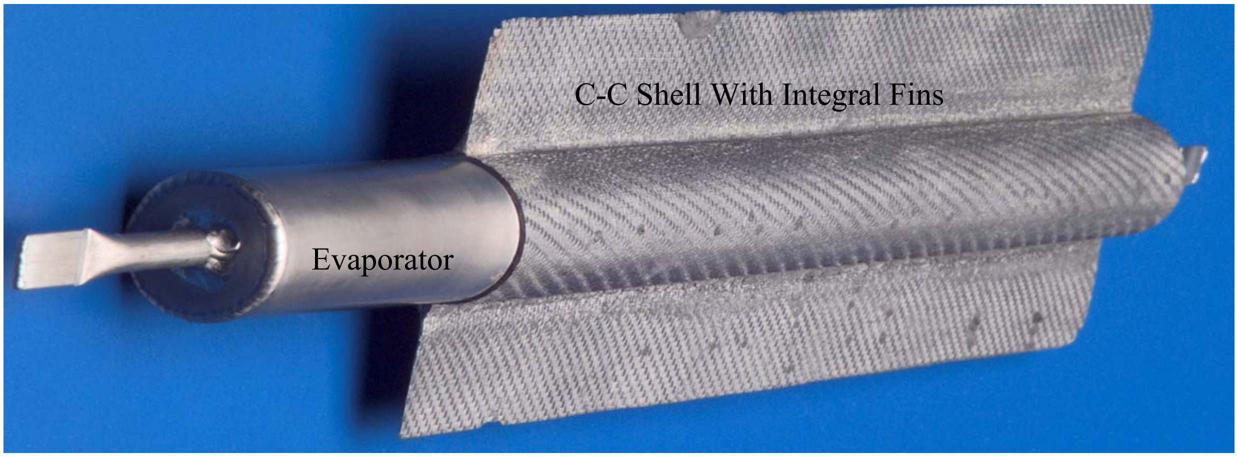


Figure 3.—Finned Carbon-Carbon Heat Pipe With Nb-1Zr Evaporator-Liner Photograph.

C-C Heat Pipe Test Summary

Since a more detailed account of the test program was reported previously (Juhasz and Rovang, (1995)), only some of the highlights are repeated here. Testing was conducted with the test article mounted in a horizontal vacuum chamber equipped with a water calorimeter wall shroud, as shown in figure 4.

To determine thermal performance, the heat pipe was instrumented with sheathed thermocouples 250 μm (10 mils) in diameter, as shown in figure 1. Thermocouples 3, 4, 6, 10, and 12 were intended to measure axial temperature distribution, whereas thermocouples 5 through 9 and 11 were intended to determine fin heat transfer and fin efficiency. Testing was carried out in a horizontal vacuum chamber equipped with a water calorimeter wall shroud, as shown in figure 4. Thermocouples were also installed inside the calorimeter cooling water inlet and outlet tubes to measure water temperature rise during testing. A vacuum of 10^{-5} torr was maintained within the chamber during testing. The input heat was supplied to the evaporator section by a radiation-coupled electrical resistance heater. To prevent degradation of the heater elements, an Inconel enclosure was used to isolate the heaters from the vacuum.

In addition, the inside surface of this cylindrical enclosure was surface-treated to raise its emissivity to a value above 0.9. To minimize heat losses to the vacuum chamber from the heaters, the heater elements were insulated with layers of ceramic fiber material. Multiple layers of highly reflective tantalum foil baffles were also installed to isolate the heaters from the condenser section, end flanges, and supports.

Testing was conducted over a 12 hr period, as indicated in figure 5, starting at ambient conditions, with the potassium working fluid in the solid state. To avoid possible evaporator dryout input power was increased gradually in 20 to 30 W increments every 15 min, starting with an initial heater temperature of 300 K.

Once temperatures in the first section of the condenser (thermocouples 3 to 5) rose above the melting point of the potassium working fluid (336.7 K), the rate of heat input was increased until the maximum heater limit of 770 W was reached near the end of the test period; at this point, the heater temperature was measured as 1270 K. Because of the low thermal absorptivity of the Nb-1Zr evaporator surface (~0.4), only about 300 W of heater power was actually absorbed by the evaporator. But cost and time constraints prevented raising the evaporator surface absorptivity. Note, however, that in the application intended by the original SP-100 power system design, as well as conceptual designs for future space power system radiators, the evaporator would be convectively heated by lithium fluid, and therefore, enhancement of evaporator surface absorptivity to radiation heat transfer would not be necessary.

Post-test examination of the heat pipe and associated test hardware showed all items to be in excellent condition. No changes could be detected in the C-C tube shell, braze joints, or liner. This shows that the overall design and the fabrication process were basically sound, considering that the test article was subjected to eight thermal cycles during fabrication, filling, and testing. These cycles included brazing and degassing at over 920 K, three potassium filling cycles ranging from 425 to 875 K, installing thermocouples at 575 K, checkout testing at 525 K, and performance testing at nearly 700 K. The ternary alloy braze bond between the C-C shell and liner, and the liner itself, both maintained their structural integrity throughout the thermal cycles and ambient temperature storage. On the basis of these results, the heatup rate during future testing and in actual service could be increased significantly.

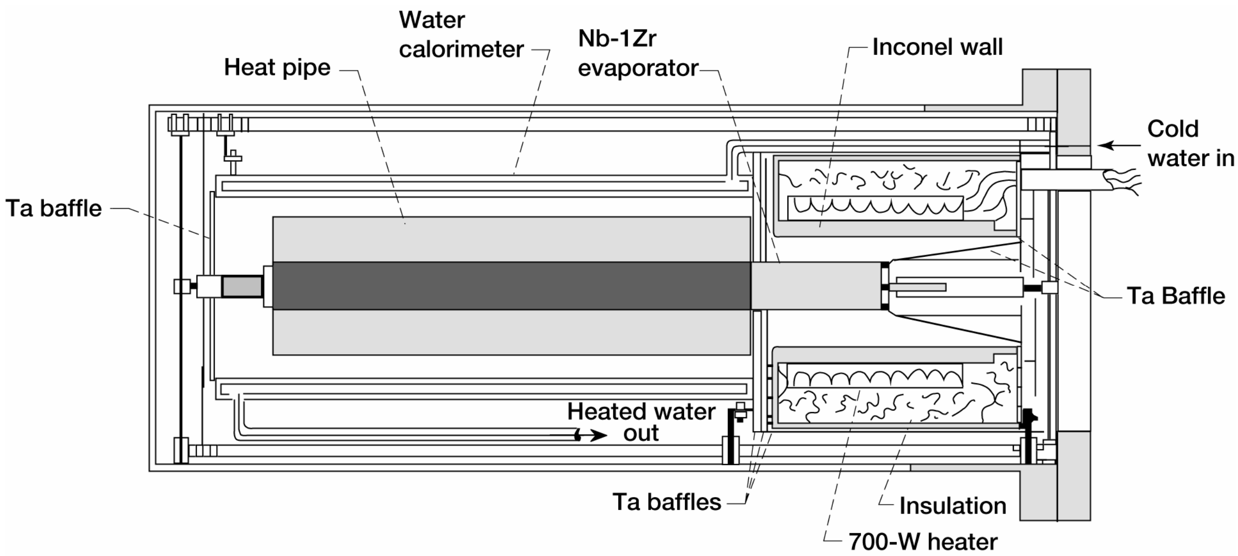


Figure 4.—C-C Heat Pipe installed in Vacuum Test Enclosure.

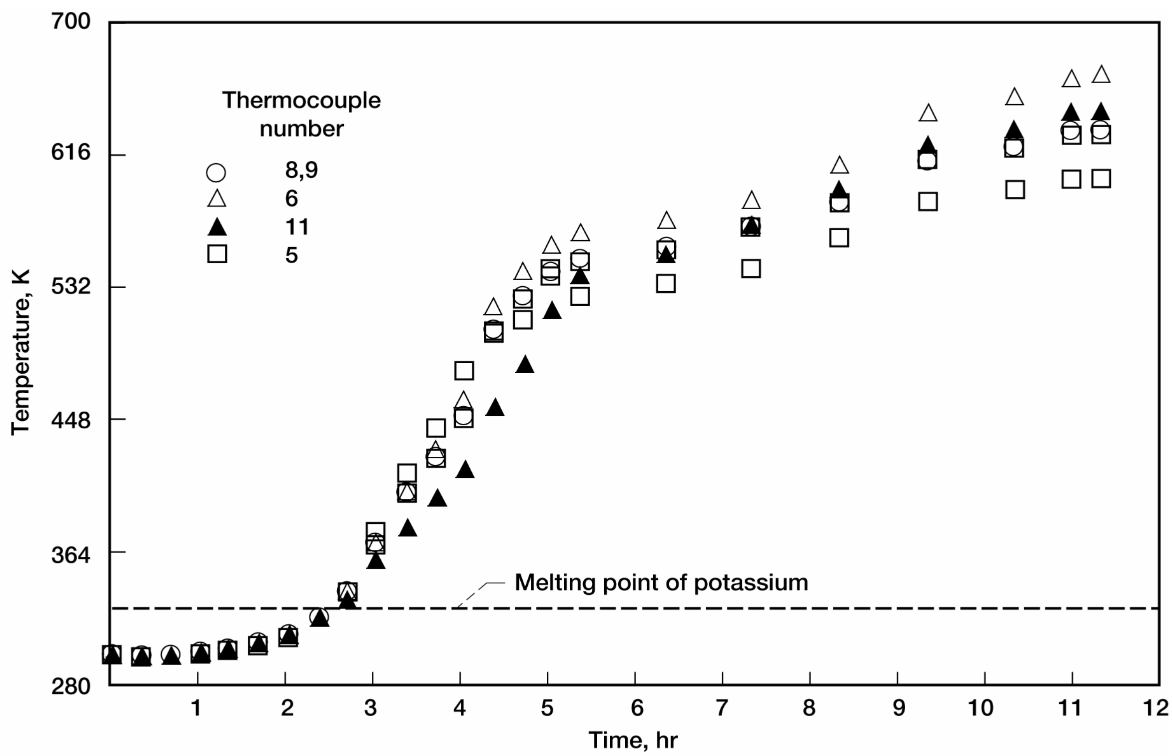


Figure 5.—C-C Heat Pipe Local Temperatures during Startup Period.

It should be pointed out that a limited amount of testing was also accomplished with a second heat pipe in the 400 to 450 K temperature range by using a stainless steel liner, with de-mineralized water serving as the heat pipe working fluid. A significant result from this test was that the liner remained intact (no leaks developed) at water vapor pressures of 16 bar, even though the recommended containment materials for water (Dunn and Reay, 1982) are either copper, Cupronickel alloy, or Monel metal.

Extension of Technology to C-C Heat Pipe Radiators

The C-C heat pipe fabricated and tested as described herein can be considered a potential element of a large multi-segment space radiator. As common sense would indicate, the literature on space radiator survivability (e.g., English and Guentert, 1961; Juhasz, 2002) indicates that if a space radiator is composed of a multiplicity of independently operating segments, a random micrometeoroid puncture of the radiator would result in the loss of only the punctured segment—not the entire radiator. Hence, the strategic advantage of segmented radiators for space service applications is obvious.

As an illustrative example figure 6 shows the trapezoidal radiator panels that were proposed for the SP-100 conical radiator configuration. Note that the radiator consists of 12 panels, each with 226 heat pipes, for a total of 2712 parallel redundant heat pipe radiator elements. Micro-meteoroid puncture of any heat pipe would hardly affect the operation of the complete radiator, especially if the design includes excess surface area at BOM (beginning of mission). A design which allows sacrificing a certain fraction of the initial radiator surface area results in lower wall thickness and weight. As shown in the references cited above, minimum radiator weight is obtained if the fraction of surviving- to- initial number of radiator segments, N_s/N, is approximately 0.75 (i.e., $e^{-1/4}>N_S/N>e^{-1/3}$). With over a thousand heat pipes the radiator weight could be decreased to less than 3 percent of the weight of a nonsegmented design for an overall survival probability of 0.999. Moreover heat pipe condenser fins are considered as "nonvulnerable" extended the heat transfer surfaces to micrometeoroid punctures, since a fin puncture will not even cause the loss of a single heat pipe element. Hence a large fin area fraction for each heat pipe increases overall reliability of the space radiator even further. Of course the central duct which carries the coolant fluid which transfers heat by convection to the evaporators needs to be protected against punctures by multi layer bumpering.

A typical space radiator panel consisting of a central duct and a number of finned heat pipes is shown in the annotated diagram of figure 7, which was used in a mathematical analysis (Juhasz, 2007) of a space radiator for a CCGT (Closed Cycle Gas Turbine) power plant. Although a gaseous cooling fluid was assumed in the analysis, the results are equally applicable to liquid coolants provided that the correct value of heat transfer coefficient, hr, is used in equation (1). As a main result of the analysis, equation (1) expresses the required radiating area, A_r, as a function of the input parameters, as shown in the diagram.

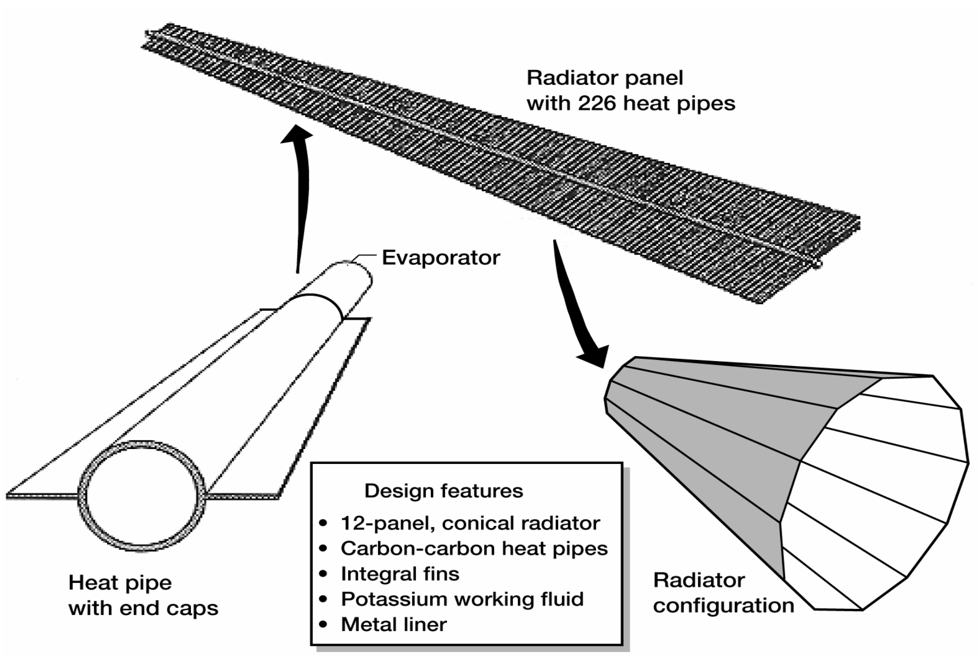


Figure 6.—Use of a C-C heat Pipe Radiator Element in Fabrication of a Radiator Panel and a 12-Panel Conical Radiator.

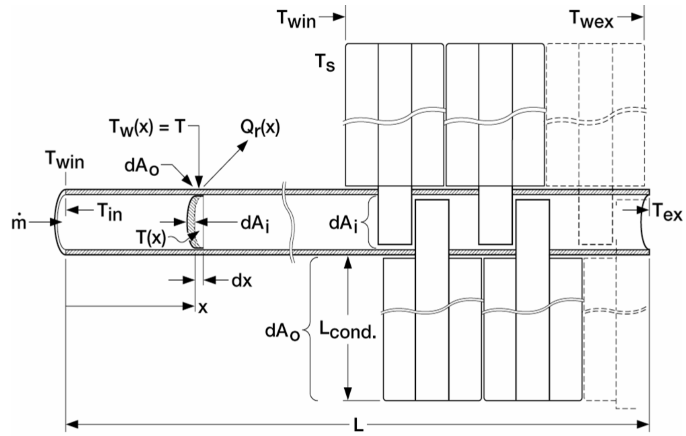


Figure 7.—Analysis of Space Radiator Duct with Cooled Gas Flow Flowing over Heat Pipe Evaporators.

$$A_r = \dot{m} \cdot C_p \cdot \left[\frac{1}{h_r} \cdot \ln\left(\frac{T_{win}{}^4 - T_s{}^4}{T_{wex}{}^4 - T_s{}^4} \right) + \frac{1}{\left(4 \cdot \sigma \cdot \varepsilon \cdot T_s{}^3\right)} \cdot \left[\ln \frac{\left(T_{win} - T_s\right) \cdot \left(T_{wex} + T_s\right)}{\left(T_{wex} - T_s\right) \cdot \left(T_{win} + T_s\right)} - 2 \cdot \left(\tan^{-1} \cdot \frac{T_{win}}{T_s} - \tan^{-1} \cdot \frac{T_{wex}}{T_s} \right) \right] \right] \quad (1)$$

Note that equation (1) can be extended to the case of variable heat transfer coefficients by dividing the radiator duct into a number of serial segments, each with its own input variables. The total required radiating heat transfer surface area may then be found by summing each of the serial elements from element *j* to element *n,* as shown in equation (2).

$$A_{tot} = \sum_{j=1}^{n} \int_{A_r(j)}^{A_r(j+1)} dA_r \quad (2)$$

Both equations (1) and (2) were programmed into a code which is used as a subroutine for space power systems using the Closed Brayton Cycle (CBC).

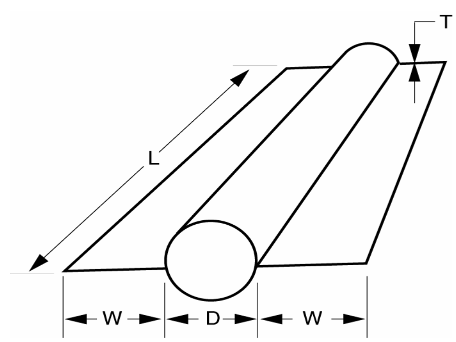
Extrapolation to Potential Future Breakthroughs in Materials

As discussed in the previous section, in addition to increasing the survivability, and thus the reliability, of individual heat pipe radiator elements, condenser fins would also reduce the radiator's specific mass. Of course, increasing the fin root-to-tip length while keeping a constant the fin thickness (1 mm) and fin efficiency (0.85, i.e., total heat transferred by the fin divided by the total heat transferred if the entire fin were at the fin root temperature) would be a design option only if the thermal conductivity of the fin in the root-to-tip direction could also be increased by using a higher conductivity material. An example is a thermal annealed pyrolytic graphite material (APG) that has been developed for encapsulation within a metallic structural shell; this material's thermal conductivity values range from 1200 to over 1600 W/m K (Montesano, 1996). A comparison of the effect of a range of fin thermal conductivities on radiator specific mass is illustrated in table I (with its accompanying dimensional sketch), which gives a breakdown of the integrated fin heat pipe component weights and surface areas for three C-C composite materials of increasing thermal conductivity: T-300, P95WG, and K-1100, the highest thermal conductivity composite.

A comparison of the specific mass values in table I shows that increasing the fin thermal conductivity of a heat pipe material leads to significant reductions in the specific mass of a heat pipe with integral fins. For the comparison the minimum fin effectiveness values were 85 percent. The T-300 heat pipe, whose values are shown in the first column, was built and tested (see fig. 1 (drawing) of prototype). Its specific mass of 2.1 kg/m^2 for two-sided heat rejection is a reduction of more than threefold over the specific mass of first-generation space station radiators. The actual graphitization density for the fins and C-C shell was 1.45, as shown.

TABLE I.—CARBON-CARBON HEAT-PIPE MASS FOR FOUR SHELL COMPOSITES

Material	T300	P95 WG	K 1100	APG
Thermal conductivity, W/mK	50–80	300–500	750–1000	1200–1600
Heat pipe dimensions, cm (See Dim. Sketch below)				
Length, L	91.4	91.4	91.4	91.4
Shell diameter, D	2.5	2.5	2.5	2.5
Width, W	2.5	5.0	7.5	10.0
Thickness, T	0.1	0.1	0.1	0.1
Heat pipe components mass, g				
C–C shell (Fin Density -FD = 1.45 g/cc)	170.4	237.0	302.9	369.1
C–C shell (Fin Density -FD = 1.00 g/cc)	117.5	163.2	208.9	254.6
Liner with evaporator	41.2	41.2	41.2	41.2
End caps	13.1	13.1	13.1	13.1
Fill tubes	7.2	7.2	7.2	7.2
Braze	22.5	22.5	22.5	22.5
Foil wick	24.0	24.0	24.0	24.0
Working fluid	13.5	13.5	13.5	13.5
Total mass, g (FD = 1.45 g/cc)	291.9	358.5	424.4	490.6
(FD = 1.00 g/cc)	239.0	284.7	330.4	376.1
One-sided radiating area, m^2	0.0691	0.114	0.16	0.206
Specific mass, kg/m^2 (FD = 1.45 g/cc)	4.22	3.14	2.65	2.38
Specific mass, kg/m^2 (FD = 1.00 g/cc)	3.46	2.50	2.07	1.83
Two-sided radiating area, m^2	0.1382	0.228	0.32	0.412
Specific mass, kg/m^2 (FD = 1.45 g/cc)	2.11	1.57	1.32	1.19
Specific mass, kg/m^2 (FD = 1.00 g/cc)	1.73	1.25	1.04	0.92



The heat pipe specified by the values in the second column (P-95 WG) was also fabricated, but it has not yet been tested because of funding limitations. Its equivalent specific mass would be 1.57 kg/m^2, shown in a light grey tone to indicate a not yet fabricated design, albeit available in the near term. The third and fourth column values are for potential long term material breakthroughs, especially values for hypothetical graphitization fin densities as low as 1 g/cc while maintaining sufficient strength and rigidity to endure launch vibrations. Radiator specific mass values in these columns are seen to approach 1 kg/m^2 for fin densities between 1.45 and 1.0 g/cc. Of course strength and ruggedness of the low density fin materials needs to be demonstrated.

Concluding Remarks

A lightweight C-C prototype liquid-metal heat pipe for space applications has been designed, fabricated, and successfully tested. The actual specific mass of the built and tested heat pipe with integrally woven T300 C-C fins was 2.1 kg/m^2 for two-sided heat radiation that would occur with flat plate radiator configurations and double that value (~4.2 kg/m^2) for single sided radiators. For a P95 WG shell material, which was built but not tested, the specific mass for the two sided heat rejection was 1.57 kg/m^2. These specific mass values are approximately one fourth of the values commonly found in current space radiators, averaging 6 to 10 kg/m^2. It was also shown that the very high conductivity C-C materials currently being developed may lead to radiator specific mass values approaching 1.0 kg/m^2, if survivability to launch vibrations can be demonstrated.

Although the heat pipe tested was designed to operate in the 700 to 850 K temperature range with its potassium working fluid, the technology can be extended to cover a broad range of temperatures by properly selecting alternate heat pipe working fluids and compatible liner material. As indicated in the text, the technology was also demonstrated for the 400 to 450 K temperature range, albeit without extensive instrumentation and data collection, by using a stainless steel liner and water as the working fluid. The advantage of using the lightweight C-C heat pipes in the design of segmented space radiators was also demonstrated from two points of view: (1) survivability in a micrometeoroid space environment and (2) efficient radiation heat transfer by utilizing the high thermal conductivity of C-C material in a finned condenser configuration.

References

Brandhorst, H.W., Jr.; Juhasz, A.J.; and Jones, B.I. (1991): Alternative Power Generation Concepts for Space. NASA TM–88876

DeVan, J.H. (1986): Purification Procedure for Sodium Working Fluid in a Stainless Steel Heat Pipe. ORNL Letter No. 0828/05/86.

Dunn, P; and Reay, D.A. (1982): Heat Pipes. Pergamon Press Inc., Maxwell House, Fairview Park, Elmsford, New York 10523, USA.

English, R.E.; and Guentert, D.C. (1961): Segmenting Radiators for Meteoroid Protection. Ars J., Aug. 1961, pp. 1162–1164.

Groll, M. (1973): Waermerohre als Bauelemente in der Waerme-und Kaeltetechnik. Brennstoff-Waerme-Kraft. vol. 25, no. 1, pp. 11–14.

Juhasz, A.J.; and Jones, B.I. (1987): Analysis of Closed Cycle Megawatt Class Space Power Systems With Nuclear Heat Sources. Proceedings of the Third Symposium on Space Nuclear Power Systems, M.S. El-Genk, and M.D. Hoover, eds., Orbit Book Co., Malabar, FL.

Juhasz, A.J.; and Peterson, G.P. (1994): Review of Advanced Radiator Technologies for Spacecraft Power Systems and Space Thermal Control. NASA TP–4555.

Juhasz, A.J.; and Rovang, R.D. (1995): Composite Heat Pipe Development Status: Development of Lightweight Prototype Carbon-Carbon Heat Pipe with Integral Fins and Metal Foil Liner. NASA TM–106909.

Juhasz, Albert J. (2002): “Design Considerations for Lightweight Space Radiators Based on Fabrication and Test Experience With a Carbon-Carbon Prototype Heat Pipe” NASA/TP-1998-207427/REV1, September, 2002.

Juhasz, A.J. (2007): “Heat Transfer Analysis of a Closed Brayton Cycle Space Radiator” NASA/TM—2007-215003, August 2007.

Lundberg, L.B. (1987): Alkali Metal Heat Pipe Corrosion Phenomena. Sixth International Heat Pipe Conference, May 1987, Grenoble, France.

Montesano, M.J. (1996): New Material for Thermal Management Has Four Times Thermal Conductivity of Copper. Mater. Tech., vol. 11, no. 3, pp. 87–91.

Rutledge, S.K.; Hotes, D.L.; and Paulsen, P.E. (1990): The Effects of Atomic Oxygen on the Thermal Emittance of High Temperature Radiator Surfaces. NASA TM–103224.

REPORT DOCUMENTATION PAGE					*Form Approved* *OMB No. 0704-0188*
The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.					
1. REPORT DATE *(DD-MM-YYYY)* 01-10-2008		**2. REPORT TYPE** Technical Memorandum			**3. DATES COVERED** *(From - To)*
4. TITLE AND SUBTITLE High Conductivity Carbon-Carbon Heat Pipes for Light Weight Space Power System Radiators					**5a. CONTRACT NUMBER**
					5b. GRANT NUMBER
					5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Juhasz, Albert, J.					**5d. PROJECT NUMBER**
					5e. TASK NUMBER
					5f. WORK UNIT NUMBER WBS 850661.04.01.03
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration John H. Glenn Research Center at Lewis Field Cleveland, Ohio 44135-3191					**8. PERFORMING ORGANIZATION REPORT NUMBER** E-16584
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001					**10. SPONSORING/MONITORS ACRONYM(S)** NASA
					11. SPONSORING/MONITORING REPORT NUMBER NASA/TM-2008-215420
12. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified-Unlimited Subject Categories: 24, 34, and 20 Available electronically at http://gltrs.grc.nasa.gov This publication is available from the NASA Center for AeroSpace Information, 301-621-0390					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT Based on prior successful fabrication and demonstration testing of a carbon-carbon heat pipe radiator element with integral fins this paper examines the hypothetical extension of the technology via substitution of high thermal conductivity composites which would permit increasing fin length while still maintaining high fin effectiveness. As a result the specific radiator mass could approach an ultimate asymptotic minimum value near 1.0 kg/m^2, which is less than one fourth the value of present day satellite radiators. The implied mass savings would be even greater for high capacity space and planetary surface power systems, which may require radiator areas ranging from hundreds to thousands of square meters, depending on system power level.					
15. SUBJECT TERMS Carbon-carbon heat pipes; Space power system radiators					
16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** STI Help Desk (email:help@sti.nasa.gov)
a. REPORT U	**b. ABSTRACT** U	**c. THIS PAGE** U	UU	16	**19b. TELEPHONE NUMBER** *(include area code)* 301-621-0390

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18