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*Design and Development of a
Titanium Heat-Pipe Space Radiator*

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Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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Design and Development of a Titanium Heat-Pipe Space Radiator

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DESIGN AND DEVELOPMENT OF A TITANIUM HEAT-PIPE SPACE RADIATOR

by

Steven P. Girrens

ABSTRACT

A titanium heat-pipe radiator has been designed for use in a 100-kW_e nuclear-thermoelectric (TE) space power plant. The radiator is required to have a 99% probability of remaining functional at full power at the end of a seven-year mission. The radiator has a conical-cylindrical shape and is compatible for launch in the space shuttle. The radiator heat pipes are arranged into panel segments and each reactor-core thermoelectric heat-pipe unit has four radiator heat pipes for redundancy. Radiator mass was minimized based on acceptable losses due to micrometeoroid impact. Results of studies on various design parameters are presented in terms of radiator mass. Developments on the design and testing of the radiator heat pipes are also presented. Prototype titanium (potassium working fluid) heat pipes were fabricated and tested in space-simulating conditions. Testing results are compared to analytical performance predictions.

I. INTRODUCTION

The Los Alamos National Laboratory is involved in a program to develop a small, compact, nuclear reactor power system for space applications. The power plant is being designed to produce 100 kW of electrical power for seven years and to be fully compatible for safe launch into low Earth orbit by the Space Transportation System (STS). Potential use for the reactor system is the production of electric power needed for space surveillance, communications, and propulsion.

The space reactor electric power plant has four major subassemblies: an enriched uranium-oxide-fueled reactor cooled by 90 sodium-filled molybdenum heat pipes; a lithium-hydride shield that protects other parts of the spacecraft from reactor radiation; silicon-germanium thermoelectric converters that produce electricity from the reactor-supplied thermal energy; and a titanium heat-pipe radiator that rejects waste heat from the converter system into space. This report is concerned with describing the design and development of the radiator subassembly.

A heat-pipe radiator was selected based on results from a previous study¹ that indicated that such a system would be lighter and more reliable than a conventional pumped-fluid system. Table I contains a list of the basic design criteria to be satisfied by the radiator design developed for a 100-kW_e space power system. The only failure mechanism considered in determining the radiator survival probability was damage incurred from micrometeoroid impact. In conjunction with the radiator development, an experimental program was performed by the University of Dayton Research Institute (UDRI) to study the hypervelocity impact resistance of titanium, titanium alloys, and beryllium. The results from this study² were incorporated into the radiator design in order to obtain a minimal mass configuration.

II. RADIATOR DESIGN

A. Configuration and Material

The radiator configuration chosen for study and compatibility with the nuclear-thermoelectric power system utilizes a system of potassium-filled titanium heat pipes to remove heat from the cold junction of the thermoelectric (TE) modules and radiate the waste heat to space. To obtain system redundancy, each core heat-pipe thermoelectric module package is in direct

TABLE I
RADIATOR DESIGN CRITERIA

Radiator power (kW)	1010
Operating temperature (K)	775
Mission time (yr)	7
Radiator survival probability	0.99

thermal contact with either three or four radiator heat pipes through the TE module heat pipes. As Fig. 1 illustrates, three core heat-pipe thermoelectric modules are grouped together, along with their radiator heat pipes, to form a basic panel segment. The manner in which the radiator panels are arranged to form the full radiator is illustrated in Fig. 2. With a total of 30 segments, the array has a conical-cylindrical shape with a diameter compatible with the bay of the Space Shuttle launch vehicle, 4.5 m.

Fig. 1. Individual radiator heat-pipe panel.

Fig. 2. Multiple panel heat-pipe radiator design.

The exterior surface of the radiator panels is flat with the remaining portion of the individual heat-pipe containers being D-shaped. Other panel designs considered included circular-finned and rectangular heat pipes. The D-shape was selected because it minimized radiator mass. Titanium was selected for the radiator material because of its relatively low density, ease of fabrication, good impact resistance, and durability at high temperatures. Beryllium was also considered because of its low density but was not chosen due to its very high cost, difficulty in fabrication, brittle impact behavior and toxicity.

B. Meteoroid Threat

A major environmental hazard to be considered in the design of space vehicle systems is meteoroid impact. Since meteoroids are solid particles moving in interplanetary space, they can be quantified with average density, velocity, and mass-flux models. The National Aeronautics and Space Administration (NASA) Near Earth to Lunar Surface Meteoroid Environment Model³ was selected for use in the design of the radiator. This model was also selected to establish the meteoroid environment criteria in the STS design.⁴ The near-Earth average total meteoroid (average sporadic plus average stream) mass-flux model is as follows:

$$\log_{10} N_t = -14.37 - 1.213 \log_{10} m, \quad \text{for } 10^{-6} \leq m \leq 1, \quad (1)$$

where

$$\begin{aligned} N_t &= \text{number of particles of mass } m \text{ or greater/m}^2\text{-s, and} \\ m &= \text{particle mass (g).} \end{aligned}$$

The average particle density and velocity associated with this mass-flux model are 0.5 g/cm^3 and 20 km/s , respectively. To correct for the Earth's gravitational effect at a given distance above the Earth, N_t is multiplied by the defocusing factor, G_e , which is obtained from Fig. 3. To correct for planetary body shielding, the unshielded defocused flux is multiplied by the shielding factor, E . The shielding factor is determined as described in Fig. 4.

Since the radiator surface is composed of several heat pipes, the radiator area is essentially segmented into many individual, independent units. With the previously described mass-flux model and the Poisson distribution equation,

$$P_{x \leq n} = \sum_{r=0}^{r=n} \left[\frac{e^{-N_t A \tau} (N_t A \tau)^r}{r!} \right], \quad (2)$$

Fig. 3. Defocusing factor due to Earth's gravity for average meteoroid velocity of 20 km/s.

where

- $P_{x \leq n}$ = probability of impact by n meteoroids or less,
- N_t = expected flux (particles/m²-s)
- A = exposed area (m²), and
- τ = exposure times (s),

the probability of impact by n particles of mass m or greater can be established. Thus, by armoring the heat pipes to withstand impacts from a specified mass of meteoroid, the number of impacts from larger particles can be predicted, and the probability of heat pipes being penetrated can be determined.

C. Heat Pipe Failure and Micrometeoroid Protection

The radiator heat pipes are titanium containers filled with potassium working fluid that circulates between the container's heated (evaporator) and cooled (condenser) regions. Heat is absorbed by the working fluid in the evaporator where the liquid is vaporized. The vaporized working fluid flows to the condenser region where the heat absorbed is released to the surroundings as the fluid condenses. The liquid working fluid is then pumped back to the evaporator through a porous wick or screen arteries by capillary action.

BODY SHIELDING FACTOR, E: (Defined as ratio of the shielded to unshielded flux)

$$E = \frac{1 + \cos \theta}{2} ,$$

where $\sin \theta = \frac{R}{R+H}$

R = radius of shielding body
H = altitude above surface

Fig. 4. Method for determining body shielding factor for randomly oriented spacecraft.

A heat-pipe failure mechanism that can result in a meteoroid environment is penetration of the heat-pipe container. A puncture in an operating heat pipe immediately results in a loss of both the liquid and vaporized working fluid. Meteoroid impacts on heat pipes that result in dimples or spalling do not adversely affect heat-pipe operation. Therefore, when armoring the surface of a heat-pipe container exposed to space, concern is directed towards determining the thickness of material required to prevent penetration by a specified mass meteoroid.

The radiator system of individual heat pipe units must be designed to absorb predicted losses and function at full heat load for the entire 7-yr mission. With the aid of the NASA meteoroid environment model and the Poisson distribution equation, the probability of impact by n particles of mass m or greater can be established. Since impacts by particles of mass m or greater

will penetrate the armor protection of the heat pipes, the radiator may lose n heat pipes due to the impact of the n meteoroids. If the radiator can withstand without failure the impacts of these meteoroids, then the Poisson distribution probability, $P_{x \leq n}$, becomes the radiator survival probability, and the number of heat pipes surviving the mission can be predicted. With this information, the radiator can be designed so that the surviving heat pipes adequately reject the waste heat.

An area of concern in designing the radiator is optimizing the number of radiator heat pipes required to provide adequate system redundancy while absorbing predicted micrometeoroid impact losses. However, of even greater importance is selecting a meteoroid mass, which will quantify the meteoroid threat and is required to calculate the protective armor thickness. Several equations exist for predicting the infinite-penetration thickness, p_{∞} , to defeat a specified mass particle traveling at hypervelocities. The armor equation selected for use in the radiator design was developed by Charters and Summers⁵ (C-S) and may be written in the form

$$p_{\infty} = \left(\frac{81}{8\pi} \frac{\rho_p}{\rho_t} m_p u_p^2 \right)^{1/3} \frac{1}{S_t^{1/3}}, \quad (3)$$

where

- m_p = meteoroid mass (kg),
- u_p = meteoroid velocity ($u_p = 20\,000$ m/s),
- ρ_p = meteoroid density ($\rho_p = 0.5$ g/cm³),
- ρ_t = density of target material (g/cm³), and
- $S_t^{1/3}$ = experimentally determined target material property factor (J/mm³)^{1/3}.

The hypervelocity impact behavior of commercial pure, Grade 2 Ti and pure beryllium were studied at UDRI by impacting targets of these materials with millimeter-sized spheres of glass, copper, aluminum, and cadmium propelled from a light-gas gun at velocities ranging from 4.5-7.6 km/s. Target temperatures ranged from 295-775 K when impacted. Titanium was found to behave in a ductile manner when impacted, but beryllium was found to be brittle even at 775 K. The material property factor in Eq. (3), $S_t^{1/3}$, was quantified for

titanium to be 3.82 and 3.20 (J/mm³)^{1/3} at 293 and 775 K, respectively. Since we are interested in the material thickness capable of preventing penetration by a specified-mass particle, we can define a threshold penetration thickness (TPT) as that thickness of plate that just provides protection against a particle impact. The plate may spall, but it must not be perforated. Empirical experience in ballistics and hypervelocity impact^{2,5} supports the approximation

$$\text{TPT} = 1.5 p_{\infty}. \quad (4)$$

Equations (3) and (4) were used along with the UDRI impact data to calculate the radiator's protective armor thickness.

D. Thermal Design and Radiator Sizing

The thermal environment assumed in the radiator design is as follows:

solar radiation	1399 W/m ² , and
space sink temperature	0 K.

At geosynchronous orbit, the effect of Earth albedo was assumed negligible. The effective area, A_{eff} , required to reject the total heat load at the design temperature is given by

$$A_{\text{eff}} = Q_R / (\sigma \epsilon T^4 - I), \quad (5)$$

where

Q_R	= radiator waste heat load (W),
σ	= Stefan-Boltzman constant ($5.67 \times 10^{-8} \text{ W/m}^2\text{-K}^4$),
ϵ	= radiator surface emissivity (0.9),
T	= radiator operating temperature (775 K), and
I	= product of solar radiation and radiator solar absorptivity (W/m ²).

The effective area represents the radiating area, which must remain undamaged during the entire mission to reject the full power waste heat load. Therefore, if during the mission heat pipes are lost due to micrometeoroid penetration, the remaining operating pipes must be longer than would be required without any loss of heat pipes in order to compensate for the lost radiating area.

The radiator configuration may be considered to consist of two right-circular geometric shapes: a frustum of a cone and a cylinder. The conical portion allows for additional radiating area while increasing the diameter of the radiator to its maximum value of 4.5 m and minimizing radiator and payload shielding requirements. Both the conical and cylindrical sections are 30-sided figures since the exterior surface of the individual panel segments is flat. Sizing the width of the panels was performed with the following expression

$$W_{\text{seg}} = \{2r^2[1 - \cos(2\pi/30)]\}^{1/2}, \quad (6)$$

where r is the radiator radius. Upon selecting a small cone radius and cone half angle, the area of the conical section remains constant, and the remaining required radiating area is obtained in the cylindrical section.

The values of A_{eff} , particle flux, and mission time are substituted into the Poisson distribution equation to determine the number of impacts at a probability of 0.99. If the initial number of radiator heat pipes is N , and A_{eff} is equally divided among N heat pipes, the Poisson distribution will predict the number of heat pipes lost, N_L . An initial beginning-of-mission area approximation is calculated by multiplying A_{eff} by $N/(N-N_L)$. The new area, A_{new} , becomes the corrected radiator area and again a Poisson distribution calculation is performed. The operating area at the end of the mission time is

$$A_{\text{eom}} = A_{\text{new}} \frac{(N-N_L')}{N}, \quad (7)$$

where N_L' is the number of losses corresponding to the target area A_{new} . If $A_{\text{eom}} < A_{\text{eff}}$, the total radiator area is increased by $A_{\text{eff}} - A_{\text{eom}}$ and the Poisson calculation repeated. However, if $A_{\text{eom}} \geq A_{\text{eff}}$, the mission heat-pipe losses are predicted and the area iteration process ends. A flow chart illustrating the area sizing procedure is shown in Fig. 5. Heat-pipe length is therefore increased by increasing the length of the cylindrical portion of the radiator until the above described area criterion is satisfied.

Fig. 5. Flow chart of procedure to calculate radiator design area and number of heat pipes surviving mission.

The individual heat pipes are sized based on the sonic limit criterion⁶ because satisfying this condition minimizes axial-temperature variation. Sizing the cross-sectional area available for vapor flow at twice the sonic limit value is the technique used to design isothermally operating heat pipes. The sonic limit criterion is described by

$$q_{\text{sonic}} = 0.474 L (\rho_v p_v)^{1/2}, \quad (8)$$

where for potassium at 775 K,

$$\begin{aligned} \rho_v &= \text{vapor density (0.025 kg/m}^3\text{)}, \\ p_v &= \text{vapor pressure (4124 N/m}^2\text{)}, \text{ and} \\ L &= \text{latent heat of vaporization (2097 kJ/kg)}. \end{aligned}$$

The heat-pipe vapor area is thus established by

$$A_v = 2 Q_p / (1.01 \times 10^7 \text{ W/m}^2), \quad (9)$$

where Q_p is the power to be transported per heat pipe.

The curved portion of the D-shaped heat pipes acts as the enclosure for the vapor flow area. At present, the interior surface of the radiator is closed to the space environment and therefore the curved shell sections will be constructed to the minimum allowable thickness determined by fabrication and structural considerations. Also, since the vapor flow area is kept constant for performance, the curved shells have larger height-to-width ratios at the small cone radius end than at the large-cone-radius cylindrical section interface.

III. RADIATOR SYSTEM STUDIES

Having established the basic equations used to calculate the size and mass of the radiator, various parameter studies were performed to determine the optimum reference design characteristics. The first study performed was to determine the effect of selecting a micrometeoroid mass to defend against and varying the number of heat pipes. As can be seen in the results presented in Fig. 6, radiator masses are minimized for a meteoroid mass $\sim 1.5 \times 10^{-5}$ g and total number of radiator heat pipes set at either 270 or 360. Increases in the radiator mass curves to the left of their minima are due to increases in impact losses while mass increases to the right of the minima are due to increased armor thicknesses.

For the current reactor design, the radiator heat load corresponds to a TE conversion efficiency of 0.09. Setting the small cone radius at 1.0 m, Fig. 7 presents results indicating the effects of cone half angle and reduced TE

Fig. 6. Radiator mass vs meteoroid mass for various numbers of radiator heat pipes.

Fig. 7. Radiator mass vs cone angle for various converter efficiencies supplying 100 kW_e.

efficiencies (increased radiator heat loads) on overall radiator mass. A decrease in efficiency from 0.09 to 0.07 results in a mass penalty of 175 kg at a cone half angle of 30° . Final selection of the cone half angle is also dependent upon spacecraft shielding requirements.

Sensitivity studies were also performed on the reference design. The effect that operating temperature and radiator emissivity have on radiator mass is illustrated in Fig. 8. One important observation that can be made is that a drop in emissivity from 0.90 to 0.85 will not result in a mass penalty if the operating temperature is increased 10 K. Figure 9 is a plot of radiator mass vs mission life and micrometeoroid survival probability. As is evident, the radiator mass is more sensitive to mission time than to the selected system survivabilities of 0.98, 0.99, and 0.998. For a survival probability of 0.99, an increase in mission life from 7 to 10 yr results in a 23-kg increase in radiator mass. Table II contains a listing of radiator characteristics for the current reference design configuration.

Fig. 8. Radiator mass vs operating temperature for various radiator emissivities.

Fig. 9. Radiator mass vs mission life at three survival probabilities.

IV. HEAT-PIPE DEVELOPMENT

A. Design and Predicted Performance

The radiator heat pipes are designed to attain minimum mass while transporting the prescribed heat loads isothermally. The cross-sectional configuration of the titanium heat pipes varies from the view shown in Fig. 10a at the smallest conical section radius to the view shown in Fig. 10b at the large-cone radius cylindrical section interface. The configuration in Fig. 10b remains constant in the cylindrical radiator section. The cross-sectional area available for vapor flow is constant along the entire length of the heat pipe and equal to 582 mm^2 . The flat armored side radiates the waste heat to space. The TE modules are mounted on the flat side; both evaporation and condensation occur on this surface. Current designs assume a TE evaporator section 0.6 m long and a condenser 4.55 m in length. The resulting evaporator input heat flux is 24.4 W/cm^2 ; the condenser heat flux is 1.8 W/cm^2 .

TABLE II
TITANIUM RADIATOR SIZE AND MASS DATA FOR 100-kW_e POWER

<u>Parameter</u>		
Radiator power (kW)		1010
Total number of heat pipes		360
Number of heat pipes per TE module		4
Number of heat pipes surviving mission		321
Q _{max} /heat pipe (kW)		2.94
Critical meteoroid mass (g)		1.5 x 10 ⁻⁵
Heat-pipe armor thickness (mm)		0.60
Cone half angle (deg)		30
Small radiator radius (m)		1.0
Large radiator radius (m)		2.25
Heat-pipe length (m)		5.15
Overall radiator length (m)		4.85
Armor (flat section) mass (kg)	170	
Container (curved section) mass (kg)	140	
Artery screen mass (kg)	9	
Distribution wick mass (kg)	35	
Fluid mass (kg)	30	
Total radiator mass (kg)		384

The fluid wicking system uses arteries to transport potassium from the condenser to the evaporator and a distributive wick to transport the liquid to and from the arteries. Two single-layer 80-mesh titanium-screen arteries supply the liquid return mechanism. Design of the distributive wicking system is concentrating on nonscreen wicking surfaces that include steel shotblasting, machined V-grooving, and pyramid-shaped embossing. These types of fluid distribution systems eliminate the need to insert and attach a separate screen mesh to the inside of the irregularly shaped heat pipe. They also increase the strength and rigidity of the heat-pipe wall while decreasing weight.

Performance predictions for heat pipes consisting of evaporator and condenser sections have been calculated with the aid of a Los Alamos developed computer code HTPIPE.⁷ Calculations are based on a laminar-flow model using

Fig. 10. Portion of radiator panel segment.
 a. Cross-section at small cone radius.
 b. Cross-section at large-cone-radius cylindrical section interface.

the two-dimensional Navier-Stokes equations and include compressibility effects. The hydrodynamic model of the heat pipe is essentially a pressure balance on the recirculating flow of the working fluid.

Computer calculations were made, utilizing this model, to predict performance limits of the titanium/potassium heat pipes. Figure 11 is a plot of the maximum powers obtainable for different artery sizes. Since the screen pore size determines the capillary force that supports the liquid-vapor pressure difference in the heat pipe, finer mesh screens allow for higher performance. Presently, titanium screens are available in 50- and 80-mesh weaves. For the current heat pipe design, 80-mesh screen would provide a heat transport performance margin of 1.9. Selecting the artery radius at 2.3 mm would allow the heat pipe to maintain its design power even if one of the two arteries becomes

inoperable. Figure 12 is a plot of maximum heat pipe power vs evaporator exit temperature. As is evident in both Figs. 11 and 12, the design heat-pipe power of 2.94 kW is well below the sonic limit, thus indicating minimal axial-temperature variation. Also shown in Figs. 11 and 12 is that maximum heat-pipe performance is confined by the wicking limit (screen pore size dependence limit). Figure 13 illustrates the predicted axial-temperature variation for the radiator heat-pipe design. Calculations indicate a 4-K temperature drop in the evaporator and a temperature recovery of 3 K in the condenser section. Note that at all locations in the condenser, the operating temperature is above the radiator design temperature of 775 K.

B. Prototype Fabrication and Testing

Fabrication of prototype titanium heat pipes progressed in three stages from 0.3-m to 2-m to 5.5-m-long units. This sequence served the dual purpose of developing fabrication procedures while providing heat pipes for evaluation. The design features of a 2-m Ti heat pipe are shown in Fig. 14. Heat pipe

Fig. 11. Performance limits of radiator heat pipes with various screen meshes vs artery size.

Fig. 12. Performance limits of radiator heat pipes vs operating temperature (temperature of evaporator exit).

Fig. 13. Axial-temperature variation of radiator heat pipes.

Fig. 14. Design features of prototype titanium radiator heat pipe.

components include the curved half-shell, 0.56 mm thick, the flat top plate, 0.56 mm thick, the two 50-mesh-Ti screen wick arteries, and two end caps with one containing the fill tube. These parts are fabricated separately and then welded together. Figure 15 illustrates the assembled components before welding on the end caps. The material used for the body of the heat pipe was Grade 2 Ti; the top plate and half-shell were fabricated from sheet stock, and the end caps were machined from plate. The single-layer screen arteries for the pipes were formed over a mandrel and then spot welded to the flat top plate before welding the flat and curved sections together in order to control artery dimension. The cross-sectional area available for vapor flow is 6.3 cm^2 while the arteries are each 12 mm^2 in cross section. The distributive wicking surface on the interior of all heat pipes was provided by steel shotblasting the titanium sheet prior to forming. Figure 16 shows a completed 2-m heat pipe. Using the fill tube in one of the end caps, the heat pipe is evacuated and then enough potassium is added by vacuum distillation to fill the arteries and saturate the distribution wick. The 5.5-m heat pipe was filled with 260 g of potassium. After completion of the potassium transfer, the fill tube is weld sealed and the heat-pipe fabrication thereby finished.

Heat-pipe testing is performed under space-simulating conditions in a vacuum chamber at 10^{-7} torr. Heat input to the evaporator was provided by conduction heating in the 2-m tests and rf coupling for the 5.5-m heat pipe.

Fig. 15. Titanium heat pipe (30 cm) before welding on end caps.

Fig. 16. Assembled 2-m Ti heat pipe.

Figure 17 shows the 5.5-m heat pipe instrumented and ready for assembly into the vacuum chamber. The attainment of design power was not expected in these early experiments because of the uncoated condition (that is, a high-emissivity coating is required on the condenser exterior surface for the testing of performance limits) of the heat pipes.

Fig. 17. Instrumented 5.5-m Ti/K heat pipe before assembly into vacuum chamber.

Testing of the 2-m heat pipes produced valuable fabrication experience but minimal heat-pipe operating characteristics. However, the 2-m pipes did operate isothermally at 775 K and low power. Testing of the 5.5-m heat pipe generated data invaluable to the design of future radiator heat pipes. Figures 18 and 19 illustrate the good correlation acquired between operating and start-up power measurements and analytical predictions using the HTPIPE code. As is evident in Fig. 18, data was obtained covering a wide operating temperature range of 180 K. The maximum heat-pipe power attained was 1.86 kW at an evaporator exit temperature of 753 K. The average condenser temperature at this power level was 760 K. This data point, 63% of design power, was a significant result since the heat pipe reached a heat input dry-out limitation. This limitation was a result of the shotblasted distribution wick's inability to

distribute enough working fluid for evaporation. This result thus indicates the necessity for wire screen supplementation in the evaporator section of the heat pipe to increase the fluid distribution capability. Figure 19 shows that the start-up capability of the heat pipe is very stable and predictable in the low power range. A comparison between the analytically predicted axial-temperature variation and the measured profile is shown in Fig. 20. The heat pipe was also operated successfully against gravity (pipe tilted so that condenser section is higher than evaporator), thus demonstrating artery fill and operation.

V. RADIATOR EMISSIVITY COATINGS

The titanium radiator surface requires a high-emissivity coating to obtain the assumed emissivity value of 0.9. The high-emissivity coatings are necessary if radiator mass is to be minimized. Very few high-temperature, long-life-tested emissivity coatings exist. Various thermal control materials have

Fig. 18. Comparison of measured operating powers with predicted performance for 5.5-m Ti heat pipe.

Fig. 19. Comparison of measured start-up powers with predicted performance for 5.5-m Ti heat pipe.

been developed for lower-temperature space applications and a few are described in Ref. 8. Two coatings under consideration are Z-93, developed at Illinois Institute of Technology Research Institute (IITRI), and RADIFRAX RC-356, developed at General Electric (GE).

The Z-93 coating is mixed and applied like a paint. The pigment in Z-93 is zinc oxide and the binder is potassium silicate. The coating developers feel that the paint will maintain its high emissivity of 0.90 and adhesion properties at 775 K on metal substrates that are wettable though data supporting this statement has yet to be obtained. Experiments involving zincorthotitanate (a descendent coating of Z-93) have been performed at Los Alamos. The zincorthotitanate coating (applied also as a paint) was sprayed on titanium samples and underwent thermal cycling to 775 K in a vacuum. Metallography of the coated samples indicates favorable adhesion between the zinc paint and titanium substrate. Hemispherical total emissivity measurements in air at room temperature, after specimen heating, indicated a

Fig. 20. Comparison of measured and predicted axial temperatures for 5.5-m Ti heat pipe.

value of 0.89. It is felt that the performance of the Z-93 coating will be similar to that of the zincorthotitanate.

The RADIFRAX coating maintains an emissivity greater than 0.85 at temperatures up to 1120 K while remaining optically and chemically stable for one year. The coating is plasma arc sprayed and compatible with substrates titanium 6-2-4-2 alloy and Inconel. Testing remains to be done to determine possible life, temperature, and thermal cycling limits of the RADIFRAX coating.

VI. SUMMARY

The major objective of the 100-kW_e power plant program at Los Alamos is to demonstrate the technological feasibility of building high-power-level space reactor systems. In support of this objective a high-temperature, light-weight radiator was designed to reject a 100-kW_e power system's waste heat. The radiator design utilizes a system of 360 Ti heat pipes, arranged in 30 identical panel segments, each of which is 5.15-m long and can dissipate 2.9 kW of

power at 775 K. The radiator is designed to reject the full waste heat load for 7 yr with a micrometeoroid survival probability of 0.99. The radiator is compatible for launch in the space shuttle with an overall length of 4.82 m and a mass of 384 kg.

The radiator heat pipes are arterial in design and use potassium for the working fluid. The heat pipes are designed to transport their design power isothermally. Prototype heat pipes have been fabricated in 2-m and 5.5-m lengths. The successful design, fabrication, filling, and testing of the 5.5-m heat pipe represents an important technological advance in the development of very long, light-weight, high-temperature heat pipes for space applications. Its length of 5.5 m makes it the longest alkali metal heat pipe ever tested. The fabrication and testing of this heat pipe include the following significant accomplishments.

1. Successful completion of a major advance in heat-pipe design, incorporating several design and fabrication procedures (thin sheet material, D-shaped cross-section and long axial welds) not previously demonstrated.
2. Successful filling and wet-in procedures developed for very long, thin-walled heat-pipe structures.
3. Stable start-up of very long arterial liquid-metal heat pipes demonstrated.
4. 1.86 kW of heat transported at 760 K demonstrating overall capability of the pipe.
5. Successful heat-pipe operation against gravity demonstrating artery fill and operation.
6. Data indicating an input heat dry-out limit for the shot-blasted distribution wick showing the necessity for wire screen supplementation in the evaporator section.
7. Excellent correlation between analytical predicted performance and actual test data.

Experiments involving titanium impact resistance and emissivity coatings were also performed concurrent with radiator development work. Results from impact testing were used to calculate required thickness of titanium for micrometeoroid protection. Radiator emissivity coating studies indicate that Z-93 (zinc oxide) and RADIFRAX (iron titanate) are good high-temperature candidates for emissivities above 0.85.

VII. RECOMMENDATIONS

A heat-pipe radiator is a technologically feasible candidate for use with nuclear space power systems. Developing a heat pipe to provide a light-weight, high-temperature, reliable, and efficient heat-transfer device is the primary concern of this radiator concept. Future work should involve continued investigation into various heat-pipe designs. More heat pipes should be fabricated to obtain information on performance limits, bending and life testing. Possible design variations to be considered as a result of this study include inserting a screen in the evaporator to support higher input heat flux and varying the cross-sectional configuration to investigate titanium forming techniques. Experiments involving the candidate emissivity coatings need also to be performed to verify adhesion and property stability.

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