Variable Conductance Heat Pipe Radiators for Lunar and Martian Environments

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Abstract. Long-term Lunar and Martian surface systems present challenges to thermal system design, including changes in thermal load, and large changes in the thermal environment between Lunar (or Martian) day and night. For example, the heat sink temperature at the Lunar equator can vary from 210 to 315 K. The radiator must be sized to reject the design power at the maximum temperature, but must also be able to accommodate both the changing heat sink temperature, as well as changes in power. Variable Conductance Heat Pipe (VCHP) radiators were examined for the main reactor of a fission surface power system, as well as the cavity cooling radiator. A VCHP radiator was designed for Lunar Equator that is capable of maintaining a 16K temperature drop with a 4% addition to overall mass. Without the VCHP the radiator would experience a 43K drop in temperature. This design is also capable of handling turndown on the power without an effect to the outlet temperature. At Shackleton Crater, the temperature drop for a conventional heat pipe radiator is small enough that a VCHP is not beneficial at constant power. However, a VCHP will allow turndown ratios of 5:1 or more. A conventional radiator can not be turned down more than 2:1, without valves to bypass part of the radiator. VCHPs are also easier to start than conventional radiators, since the gas-loading prevents sublimation from the evaporator when the condenser is frozen.

Keywords: Variable Conductance Heat Pipes, VCHPs, titanium/water heat pipes, Lunar Surface Power, Heat Pipe Radiator

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INTRODUCTION

Long-term Lunar and Martian systems present challenges to thermal systems, including changes in thermal load, and large changes in the thermal environment between day and night. During the day, the heat rejection sink can be 330 K, while it can drop at night or in dark craters down to 50 K (Swanson and Butler, 2006). The Apollo landings were timed for lunar morning, so the environment was relatively benign. In contrast, future missions will need to operate over the entire temperature range. The radiator to reject the waste heat must be sized for the maximum power at the highest sink temperature. This radiator is then oversized for other conditions, such as the Lunar/Martian night, or periods when the power to be rejected is low. One method to allow turndown ratios is to add a series of valves to bypass a portion of the radiator at low power. Alternately, Variable Conductance Heat Pipes (VCHPs) can be used to passively adjust to changes in power and sink temperature.

In a VCHP, a non-condensable gas is added that blocks a portion of the condenser. As power is reduced, the gas charge blocks more of the condenser. This allows the heat pipe evaporators (and any attached heat exchanger) to remain at an almost constant temperature. In addition to passively controlling the thermal load, the gas allows the fluid in the heat pipe to freeze in a controlled fashion as the heat pipe is shut down, avoiding damage. In addition, the gas in the VCHP will help with start-up from a frozen condition. A companion paper examines the experimental freeze/thaw behavior in radiator VCHPs, and demonstrates that the VCHP can be successfully thawed after being frozen for 15 days (Ellis and Anderson, 2009)

NASA is currently considering Brayton Power Conversion Systems for surface power applications. The typical operating condition for the radiator is in the range of 300 to 550 K, with one design operating between 370 and 400 K (Mason, Poston and Quails, 2008). In these power systems, a single phase water or NaK loop carries waste heat from the energy convertors to a heat pipe radiator. Titanium/water heat pipes have been shown to give the best performance in this temperature range (Anderson, Dussinger, Bonner and Sarraf, 2006).

RADIATOR DESIGN

There are a number of significant differences between VCHPs for Lunar and Martian radiators, and standard spacecraft VCHPs:

- Gravity Aided
- Higher Power
- Possibly freezing fluid in the condenser during normal operation
- Possibly freezing fluid in the entire VCHP
- Operation of a large number of VCHPs linked by a heat exchanger.
- Large variation in reservoir temperature

A VCHP radiator design for Lunar or Martian environments must take all of these factors into account.

Lunar Environment

One of the first steps in developing a radiator design is to determine the effective sink temperature. The effective sink temperature was calculated for a site near Shackleton Crater, since it is currently under consideration for a moon base. The other location that was examined was the equator, since it will have the maximum variation in sink temperature. A radiator operating on a planetary surface will be exposed to three sinks: the sun, the planet surface, and open space (Dallas, Diaguila and Saltsman, 1971). For the lunar radiator sink temperature, both the lunar surface and open space are treated as black bodies. Furthermore, the albedo of the moon is considered low enough to neglect solar absorption by surface reflection and only direct solar absorption is considered. The effective sink temperature for a vertical, 2-sided radiator is then given by equation (1) (Dallas, Diaguila and Saltsman, 1971).

$$T_{\sin k} = \left(\frac{T_M^4}{2} + \frac{G_s}{2\sigma_{SB}} \frac{\alpha}{\varepsilon} \cos(\theta_n) \right)^{\frac{1}{4}} \tag{1}$$

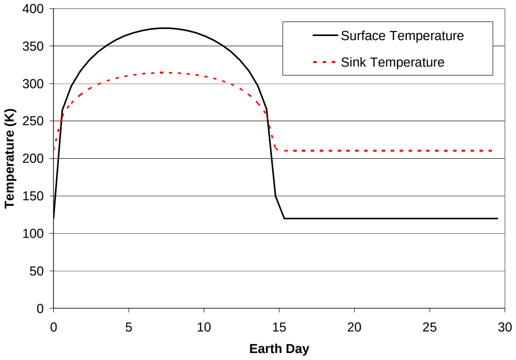

FIGURE 1. Surface and Sink Temperature for a Two-sided Radiator at the Equator.

The solar heat flux can be calculated from the average solar luminosity and average distance of the moon to the sun. Solar luminosity is 3.83×10^{26} W and the average solar distance from the moon is 1 AU or 1.5×10^{11} m. This gives a value of 1.36×10^{3} W/m^2 for the solar heat flux at the moon. Neglecting the effects of surface heterogeneity, the lunar surface temperature varies depending on moon phase and latitude. An accepted correlation for calculating surface temperature in degrees Kelvin as a function of Earth days, D, and latitude, θ_l, is shown as equation (2) (Dallas, Diaguila and Saltsman, 1971).

$$T_M = 364 \sin^{\frac{1}{6}}\left(\frac{90D}{7}\right)\cos(\theta_l) \tag{2}$$

At the Shackleton Crater location, the radiator was assumed to be in a sunlit location for the entire lunar rotation. This assumption is reasonable considering data from the 1994 Clementine probe (Fincannon, 2007). For solar incidence, the sun is assumed to rotate 360° around the axis of a fixed, two-sided, vertical radiator. The sink temperature can now be calculated from lunar sunrise to sunset and is shown for the lunar equator in Figure 1 and for Shackleton Crater (89° S) in Figure 2.

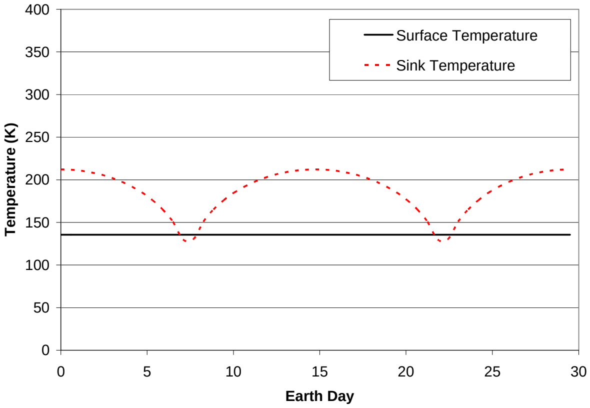

FIGURE 2. Surface and Sink Temperature for a Two-sided Radiator at Shackleton Crater.

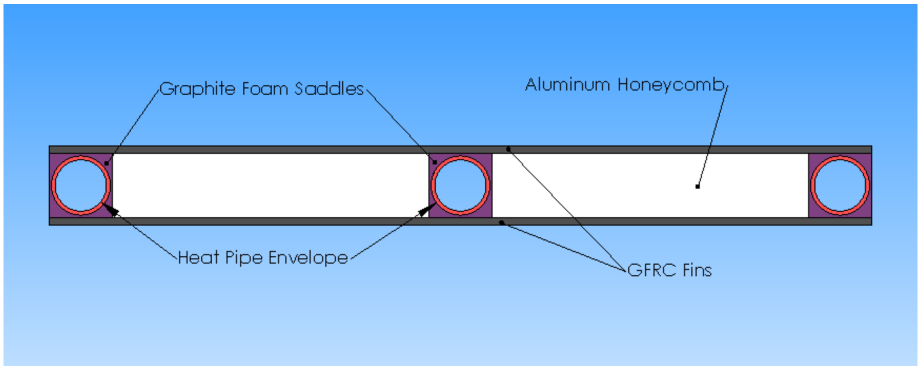

FIGURE 3. Radiator Panel Cross-Section, with Titanium Heat Pipes and POCO Foam Saddles.

Heat Pipe Radiator Optimization

The radiator requirements are based on those in Mason, Poston, and Qualls (2008). The radiator design is based on the high temperature titanium/water radiator fabricated and tested by Anderson, Sarraf, Garner, and Barth (2006). As shown in Figure 3, the radiator panel has the following. The panel design has the following:

- A series of titanium/water heat pipes (or VCHPs) to transfer heat from the secondary fluid to the radiator panel.
- High conductivity Poco foam saddles to form an interface between the circular heat pipe and the flat fin.
- High conductivity fins – Graphite Fiber Reinforced Composites (GFRC)
- Aluminum honeycomb to provide stiffness to the structure.

- Bonding material applied at the heat pipe/foam interface and the foam/fin interface

A trade study for an individual heat pipe was conducted to optimize the radiator design, based on the procedure documented in Anderson and Stern (2005). The results are shown in Table 1.

TABLE 1. Optimized Nuclear Reactor Radiator Parameters.

Parameter	Value
Lunar Equator Sink Temperature	210 to 314 K
Shackleton Crater Sink Temperature	130 to 212 K
Operating Temperature	370 to 400 K
Thermal Energy Rejected	30 kW
Pipe O.D.	0.952 cm (3/8 in.)
Pipe I.D.	0.902 cm
Evaporator Length	15.2 cm
Condenser Length	2 m
Overhanging Fin Width	7.62 cm
Fin Width	8.674 cm
Fin Thickness	0.41 mm
Minimum Foam Thickness	0.51 mm
Adhesive Thickness	0.13 mm

After determining the best individual heat pipe/radiator design, the radiator was divided up into three 10K sections rejecting equal 10 kW powers:

370 to 380K
380 to 390K
390 to 400K

The results are shown in Tables 2 and 3 for the Lunar Equator and Shackleton Crater, respectively.

TABLE 2. Overall Radiator Design at Lunar Equator, Designed for 310K (Maximum) Sink Temperature, 30 kW power.

Operating Temp (K)	Total Radiator Area (m^2)	Total Radiator Length (m)	Number of Heat Pipes	Total Radiator Mass (kg)
375	9.30	4.65	54	23.95
385	7.69	3.85	44	19.82
395	6.49	3.24	37	16.71
TOTAL =	23.48	11.74	135	60.49

TABLE 3. Overall Radiator Design at Shackleton Crater, Designed for 210K (Maximum) Sink Temperature, 30 kW power.

Operating Temp (K)	Total Radiator Area (m^2)	Total Radiator Length (m)	Number of Heat Pipes	Total Radiator Mass (kg)
375	5.50	2.75	32	14.16
385	4.89	2.45	28	12.61
395	4.37	2.19	25	11.27
TOTAL =	14.76	7.38	85	38.04

Behavior of a Heat Pipe Radiator at the Minimum Sink Temperature

The radiator design was sized for the highest sink temperature, since that requires the maximum radiator area. At the minimum sink temperature, the radiator is oversized. The two cases that bound the change from the maximum to the minimum heat sink are:

1. The power is increased to maintain the operating temperature range. This allows the converters to operate at a constant temperature
2. The power remains constant, and the radiator (and coolant) temperatures are allowed to drop.

Table 4 shows the increase in power required to maintain a constant coolant temperature for the Lunar Equator and Shackleton Crater. For the equator, the required power increases by more than 58%, while it increases by roughly 8% for Shackleton Crater. The equator case has a much larger change because the maximum sink temperature is 314K, which is relatively close to the minimum radiator temperature of 360 K. Since the back radiation from the environment changes with T_{sink}^4, the lunar equator radiator is much larger than the Shackleton Crater radiator, and is much more strongly affected by the change in sink temperature.

TABLE 4. Constant Temperature, Variable Power Case. 30 kW Power with High Temperature Sink.

Location	Lunar Equator	Location	Shackleton Crater
Sink Temperature	210K	Sink Temperature	130K
Inlet Temperature	400K	Inlet Temperature	400K
Outlet Temperature	370K	Outlet Temperature	370K
Total Radiated Power	47,470 W	Total Radiated Power	32,500 W

The second case that was considered was allowing the radiator and coolant temperature to drop as the sink temperature drops. The results are shown in Table 5. Again, the coolant temperatures are strongly affected at the equator, with the outlet coolant temperature dropping from 370 to 327K, a ΔT of 43K. On the other hand, the Shackleton Crater case is less strongly affected, with the outlet temperature dropping to 362K, a ΔT of only 8K.

TABLE 5. Constant Power, Variable Temperature Case, 400 to 370 K Heat Pipe Temperatures with High Temperature Sink.

Location	Lunar Equator	Location	Shackleton Crater
Sink Temperature	210K	Sink Temperature	130K
Total Radiator Power	30kW	Total Radiator Power	30kW
Inlet Temperature	368K	Inlet Temperature	393K
Outlet Temperature	327K	Outlet Temperature	362K

VCHP RADIATOR DESIGN

The VCHP radiator design is based on the optimized conventional heat pipe radiator design discussed above, with identical heat pipe dimensions and spacing. The only change is the addition of a VCHP reservoir.

VCHP Radiator Design Equations

In many spacecraft, the VCHP temperature is controlled either by tying it to another portion of the spacecraft, or adding electrical heaters. Reservoir temperature control is required when the VCHP temperature must be tightly controlled. In contrast, the VCHP reservoir in a Lunar or Martian radiator will be located at the top of the heat pipe, and is assumed to operate at the sink temperature. Due to the wide variation in sink temperature, there is a minimum ΔT_{VCHP}, even with an infinite reservoir. To size the VCHP reservoir, the following assumptions are made:

1. Sharp front between the working fluid and the gas.
2. Reservoir operates at the sink temperature.
3. Non-condensable gas in the heat pipe is also at the sink temperature.

The first step is sizing the VCHP reservoir is to select the difference in heat pipe vapor temperature between the hot sink and cold sink cases.

$$T_{RadLow} = T_{RadHigh} - \Delta T_{VCHP} \tag{3}$$

The required active radiator length for the hot and cold cases is then

$$Length_{High} = \frac{q}{2 \cdot \sigma_{SB} \cdot \varepsilon \cdot \eta_{Panel} \cdot \left(T^4_{RadHigh} - T^4_{SinkMax}\right)} \tag{4}$$

$$Length_{Low} = \frac{q}{2 \cdot \sigma_{SB} \cdot \varepsilon \cdot \eta_{Panel} \cdot \left(T^4_{RadLow} - T^4_{SinkMin}\right)} \tag{5}$$

The inactive condenser length at the low temperature is the difference between the two lengths:

$$Length_{CondInactive} = Length_{High} - Length_{Low} \tag{6}$$

The volume of non-condensable gas at the minimum temperature is related to the reservoir volume by:

$$Vol_{GasLow} = Vol_{\mathrm{Re}servoir} + Length_{CondInactive} \cdot A_{Pipe} \tag{7}$$

Assuming that the non-condensable gas behaves as a perfect gas, the volume filled with gas at the high and low sink temperatures is:

$$P_{VaporHigh} \cdot Vol_{\mathrm{Re}servoir} = m_{NCG} \cdot R \cdot T_{SinkMax} \tag{8}$$

and

$$P_{VaporLow} \cdot Vol_{GasLow} = m_{NCG} \cdot R \cdot T_{SinkMin} \tag{9}$$

Combining equations 3 through 9, the reservoir volume can be calculated:

$$Vol_{\mathrm{Re}servoir} = \frac{A_{Pipe} \cdot P_{VaporLow} \cdot T_{SinkMax} \cdot Length_{CondInactive}}{T_{SinkMin} \cdot P_{VaporHigh} - T_{SinkMax} \cdot P_{VaporLow}} \tag{10}$$

ΔT EFFECTS ON VCHP RADIATOR DESIGN

The heat pipe radiator design discussed above was used as a baseline for the VCHP radiator design. There are two benefits to a VCHP radiator as opposed to a heat pipe radiator:

1. The VCHP radiator can maintain a relatively constant temperature from the lowest to the highest sink.
2. The VCHP radiator can passively handle power turn-down without having the radiator freeze.

These benefits allow the radiator to passively accommodate to the extreme highs and lows of the surrounding environment while maintaining a relatively steady operating power and temperatures.

The sink temperature at the equator can vary from 210 to 314 K. This roughly 100 K change in reservoir temperature sets the minimum allowable vapor temperature ΔT that is required for the VCHP to operate. At lower ΔTs, the change in the water vapor pressure is not sufficient to accommodate the change in the NCG temperature. Radiator mass as a function of the design ΔT is shown in Figure 4 and Table 6. For this radiator, there are no solutions for $\Delta T < 14$ K. Table 6 shows the mass breakdowns as a function of operating temperature, while Figure 4 shows the overall mass. The masses assume a spherical VCHP reservoir, and include the mass of the reservoir and the NCG.

As seen in Figure 4, the optimum ΔT for this design would be roughly 16 K, as this maintains a fairly low change in temperature as well as a relatively low mass. The masses for the heat pipe radiator as well as the VCHP radiator are shown in Table 7, based on a ΔT of 16K. The VCHP radiator is approximately 4% heavier then the heat pipe radiator. As discussed below, the benefits of using a VCHP radiator are worth the cost in mass.

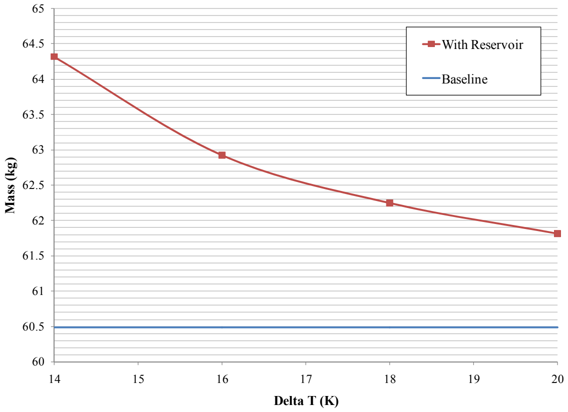

FIGURE 4. Effect of design ΔT on total VCHP radiator mass at the Lunar Equator, main radiator panel, 30 kW power.

TABLE 6. The Effect of ΔT on Total VCHP Radiator Mass at the Lunar Equator, 30 kW power. The Baseline Non-VCHP radiator would weigh 60.49 kg.

ΔT (K)	VCHP Radiator Mass, 390-400 K (kg)	VCHP Radiator Mass, 380-390 K (kg)	VCHP Radiator Mass, 370-380 K (kg)	Total VCHP Radiator Mass (kg)	Increase in Mass (%)
14	17.91	21.07	25.35	64.32	6.3
16	17.38	20.62	24.92	62.92	4.0
18	17.20	20.40	24.65	62.24	2.9
20	17.06	20.26	24.49	61.81	2.2

TABLE 7. Radiator Mass for Lunar Equator, Design ΔT of 16 K, 30 kW power.

Operating Temp (K)	Number of Heat Pipes	Total Radiator Mass (kg)	Reservoir Mass Per Heat Pipe (kg)	Total Reservoir Mass (kg)	Total VCHP Radiator Mass (kg)	Increase in Mass (%)
375	54	23.95	0.0184	0.985	24.94	4.1
385	44	19.82	0.0180	0.796	20.62	4.0
395	37	16.71	0.0176	0.656	17.37	3.9
TOTAL =	135	60.49	0.0539	2.437	62.92	4.0

For a conventional radiator, the temperature drop at Shackleton Crater was only 8 K. Due to this low ΔT, a VCHP radiator at Shackleton has very little benefit as the sink temperature is varied. As discussed below, the major benefit of a VCHP radiator at Shackleton Crater is that it allows very large turndown ratios.

TURN-DOWN RATIO

A major benefit of a VCHP radiator is that it allows a large turn-down ratio. Figure 5 shows the effect of the turndown ratio on delta T for a conventional radiator without a reservoir. This is based on a nominal outlet temperature of 370K. As seen in Figure 5, the heat pipe will stop carrying power at delta Ts greater then 60K. The heat pipe will freeze at delta Ts greater then 100K. If a turndown ratio of more then 2:1 is desired, a series of valves will be required to bypass a portion of the conventional radiator. VCHPs can passively accommodate a large turndown ratio, without requiring valves.

For the Equator, the required mass to allow a given turndown ratio is shown in Table 8 and Figure 6, assuming a constant ΔT of 16 K. At Shackleton Crater, VCHPs also allow a large turndown ratio. The results can be seen in Table 9 and Figure 7, again for a constant ΔT of 16 K. The additional mass can be reduced by allowing a larger ΔT. Results from the analysis of how the ΔT affects the overall mass were performed earlier and showed that as the delta T increased, the mass decreased.

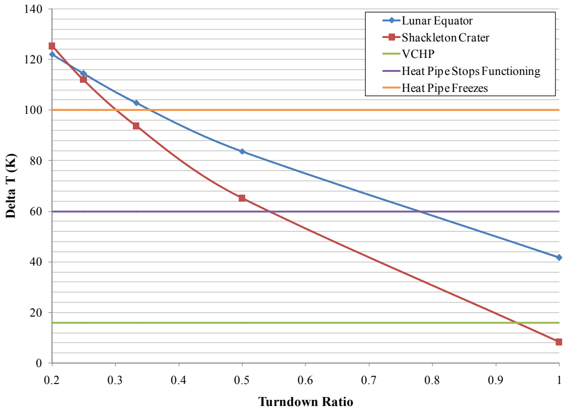

FIGURE 5. Effect of Turndown Ratio on Outlet Temperature for Conventional Radiator at both the Lunar Equator and Shackleton Crater.

TABLE 8. The Effect of Turndown Ratio on Total VCHP Radiator Mass for Lunar Equator, ΔT=16K, 30 kW power. The mass for a non-VCHP radiator is 60.49 kg.

Turndown Ratio	Total VCHP Radiator Mass, 395K (kg)	Total VCHP Radiator Mass, 385K (kg)	Total VCHP Radiator Mass, 375K (kg)	Total VCHP Radiator Mass (kg)	Increase in Mass (%)
1	17.40	20.62	23.95	61.97	2.5
1/2	18.19	21.36	23.95	63.502	5.0
1/3	18.41	21.57	23.95	63.930	5.7
1/4	18.52	21.67	23.95	64.136	6.0
1/5	18.58	21.72	23.95	64.256	6.2

TABLE 9. The Effect of Turndown Ratio on Total VCHP Radiator Mass for Shackleton Crater, ΔT=16K, 30 kW power. The mass for a non-VCHP radiator is 38.04 kg.

Turndown Ratio	Total VCHP Radiator Mass, 395K (kg)	Total VCHP Radiator Mass, 385K (kg)	Total VCHP Radiator Mass, 375K (kg)	Total VCHP Radiator Mass (kg)	Increase in Mass (%)
1/2	13.08	14.00	15.34	42.43	11.6
1/3	13.57	14.37	15.64	43.58	14.6
1/4	13.80	14.54	15.78	44.12	16.0
1/5	13.93	14.64	15.86	44.43	16.8

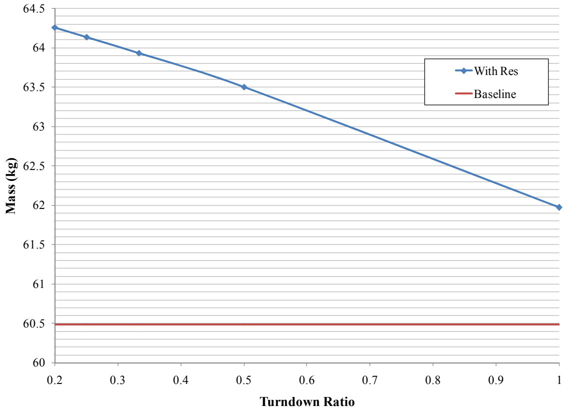

FIGURE 6. Effect of turndown ratio on total VCHP radiator mass at lunar equator with a ΔT of 16 K, 30 kW power, main radiator panel.

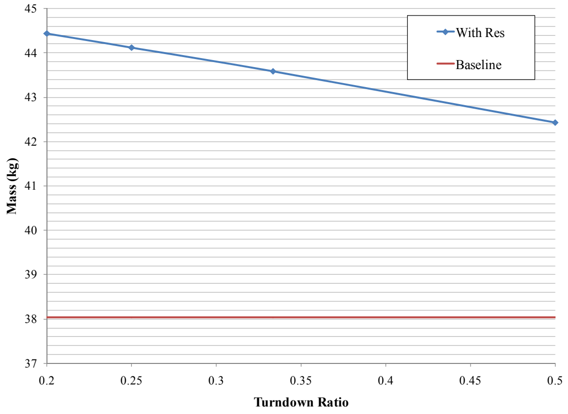

FIGURE 7. Effect of turndown ratio on total VCHP radiator mass at Shackleton Crater with a ΔT of 16 K, 30 kW power, main radiator panel.

At the equator, the VCHP radiator is approximately 4% heavier then the heat pipe radiator for a constant power system. This is a minimal increase and mass, and allows the energy conversion equipment to operate with more nearly constant temperatures. With a 16 K ΔT, a roughly 6% increase in mass will allow a turndown ratio of 5:1. At Shackleton, a 17% increase in mass is required for the same turndown ratio. In both cases, there is no need for a complex valve system to accommodate these shifts in temperature and power, as would be necessary for a standard heat pipe radiator. Note that the valve system would still add extra mass to the radiator.

CONCLUSIONS

A Lunar or Martian radiator must be size to reject the waste heat at the maximum power and the highest sink temperature. The radiator is then oversized for other conditions, such as the Lunar/Martian night, or periods when the power to be rejected is low. One method to allow turndown ratios is to add a series of valves to bypass a portion of the radiator at low power. Alternately, a VCHP radiator can be used to passively adjust to changes in power and sink temperature. Optimized radiators, both conventional and VCHP, were designed for a fission surface power system operating at the Equator, or at the South Pole.

A VCHP radiator was designed for Lunar Equator that is capable of maintaining a 16K temperature drop with a 4% addition to overall mass. Without the VCHP the radiator would experience a 43K drop in temperature. This design is also capable of handling power turndown with a minimum effect on the outlet fluid temperature. At Shackleton Crater, the temperature drop for a conventional heat pipe radiator is small enough that a VCHP is not beneficial. However, if power turndown is needed, a VCHP radiator will passively adjust to high turndown ratios. In contrast, a conventional radiator will stop working at turndown ratios of roughly 2:1. In addition, the non-condensable gas makes it easier to start the system up from a frozen state.

NOMENCLATURE

A_{Pipe} = heat pipe internal area (m^2)
D = earth days (day)
G_s = solar heat flux at the average lunar distance from the sun (W/m^2)
$Length_{CondInactive}$ = inactive condenser length at the minimum sink temperature (K)
$Length_{High}$ = active heat pipe length with maximum sink temperature (m)
$Length_{Low}$= active heat pipe length with minimum sink temperature (m)
m_{NCG} = mass of non-condensable gas in the VCHP (kg)
$P_{VaporHigh}$ = working fluid vapor pressure at the maximum sink temperature (Pa)
$P_{VaporLow}$ = working fluid vapor pressure at the minimum sink temperature (Pa)
q = power carried by a single heat pipe (W)

R = gas constant (J/kg K)
T_M = surface temperature of the moon (K)
T_{RadLow} = radiator (heat pipe) temperature with the minimum sink temperature (K)
$T_{RadHigh}$ = radiator (heat pipe) temperature with the maximum sink temperature (K)
T_{sink} = effective sink temperature (K)
$T_{SinkMax}$ = maximum sink temperature (K)
$T_{SinkMin}$ = minimum sink temperature (K)
ΔT_{VCHP} = difference in heat pipe temperatures between the maximum and minimum sink temperature cases (K)
Vol_{GasLow} = volume filled with non-condensable gas at the minimum sink temperature (m^3)
$\mathrm{Vol}_{\mathrm{Reservoir}}$ = reservoir volume filled with non-condensable gas at the maximum sink temperature (m^3)
α = radiator panel absorptivity
ε = radiator panel emissivity
η_{Panel} = radiator panel efficiency
θ_l = latitude
θ_n = incidence angle of solar radiation
σ_{SB} = Stefan Boltzmann constant ($W/(m^2\ K^4)$)

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