**FACTORS WHICH AFFECT HEAT REJECTION SYSTEM DESIGN FOR LUNAR PRODUCTION SYSTEMS**

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## Abstract

This paper presents a radiation model of radiators on the surface moon. The driving factors on radiator area are the operating temperature and solar radiation. In addition five types of radiators are examined. Heat pipe radiators are currently the best type available due to its light mass, high reliability and wide operating temperature range. However liquid droplet radiators show tremendous potential because of its light mass, simple design and immunity to meteoroid puncture.

## Nomenclature

- $A_e$ earth's albedo, assumed to be 0.35. The albedo of an object is the fraction of incident solar radiation reflected by the object
- $A_m$ moon's albedo, assumed to be 0.07
- $A_r$ radiator area
- F's shape factors of the radiator towards the various radiation sources
- $G_s$ solar incident radiation per unit area, assumed to be 1.4 $kW/m^2$
- P power to be dissipated in kW
- T operating temperature of the radiator
- $T_e$ effective temperature of the earth-atmosphere system, equals 255°K assuming the albedo of the combined system to be 0.35
- $T_m$ ambient temperature on the surface of the moon, assumed to be 110°K during lunar night and 390°K during lunar day
- $\alpha$'s absorptivities of the radiator material to the various incident radiation
- $\epsilon$ emissivity of the radiator material
- $\sigma$ Stefan-Boltzmann constant, equals $5.67 \times 10^{-11}$ $kW/m^2/K^4$

## Introduction

Heat rejection on the moon may be accomplished either individually or in combinations through: heat integration which recuperates the waste heat to process streams in the system which require heating; cogeneration which uses the heat from hot exhaust streams to produce power; or direct radiation which radiates the waste heat into the lunar environment and outer space. This paper will concentrate on heat rejection by radiation. A radiation model of radiators on the surface of the moon is proposed to examine factors which affect radiator area requirement. Since lift-off mass from earth is an important design consideration, in general large area implies more equipment complexity and higher mass. In addition five types of radiator designs are examined with emphasis on light mass and high reliability.

## Radiator Model

An energy balance on a radiator is depicted in Figure 1. The radiator is assumed to be elevated from the surface of the Moon so that heat exchange with the environment occurs in all directions.

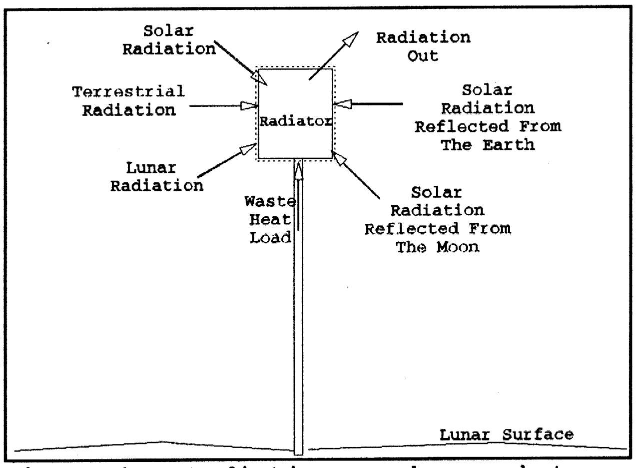


**Figure 1** Radiation exchange between radiator and the lunar environment

Equating Power In = Power Out under steady state, the net power released by the radiator is given by equation (1).

$$\alpha_s F_s G_s + \alpha_{e1} F_{e1} \sigma T_e^4 + \alpha_{e2} F_{e2} A_e G_s + \alpha_{m1} F_{m1} \sigma T_m^4 + \alpha_{m2} F_{m2} A_m G_s + \frac{P}{A_r} = \epsilon F_{ra} \sigma T_r^4 \quad (1)$$

$\alpha_s F_s G_s$ is the solar radiation per unit area absorbed by the radiator. $\alpha_{e1} F_{e1} \sigma T^4_e$ is the terrestrial radiation per unit area absorbed by the radiator. $\alpha_{e2} F_{e2} A_e G_s$ is the solar radiation per unit area reflected from Earth absorbed by the radiator. $\alpha_{m1} F_{m1} \sigma T_m{}^4$ is the lunar radiation per unit area absorbed by the radiator. $\alpha_{m2} F_{m2} A_m G_s$ is the solar radiation per unit area reflected from the surface of the Moon absorbed by the radiator. $\epsilon F_{ra} \sigma T^4$ is the rate of heat per unit area released from the radiator into the lunar environment. The radiator material is assumed to have high thermal conductivity so that the surface temperature is also the operating temperature. $P/A_r$ is the rate of process waste heat supplied to the radiator per radiator area. Rearrange (1) to obtain $A_r/P$:

$$\frac{A_r}{P} = \{\epsilon F_{ra} \sigma T_r^4 - \alpha_{e1} F_{e1} \sigma T_e^4 - \alpha_{m1} F_{m1} \sigma T_m^4 - [\alpha_s F_s + \alpha_{m2} F_{m2} A_m + \alpha_{e2} F_{e2} A_e] G_s\}^{-1}, \quad T_r > T_m \quad (2)$$

This equation shows the controllable factors which may have significant impact on the required radiator surface area are: (1) the radiator temperature, (2) lunar night or day operation, (3) far- or near-earth face process plant location, (4) the absorptivities of the radiator to the various radiation sources, (5) the emissivity of the radiator at the radiator temperature and (6) latitude and local surface features for site selection. Using generic values of absorptivity (0.3), and emissivity (0.9) for radiator material, a parametric analysis was performed to determine the impact of the first three factors on $A_r/P$. The lunar night/day factor was controlled by setting $F_s$ and $F_{m2}$ to either 0 or 0.5, and $T_m$ to 110°K or 390°K respectively. The far/near-earth factor was controlled by setting $F_{e1}$ and $F_{e2}$ to either 0 or 0.5 Radiator temperatures range from 390°K to 1200°K. Table I and Figure 2 show the analysis results. The main conclusions are:

**Table I** Radiator area per unit power vs radiator temperature, lunar night/day operation, and far/near-earth face location.

| $T_r$ °K | Night Far | Night Near | Day Far | Day Near |
|---|---|---|---|---|
| | $A_r/P$, $m^2/kW$ | | | |
| 1200 | 0.0095 | 0.0095 | 0.0095 | 0.0095 |
| 1000 | 0.0196 | 0.0196 | 0.0198 | 0.0198 |
| 800 | 0.0479 | 0.0480 | 0.0489 | 0.0491 |
| 750 | 0.0620 | 0.0624 | 0.0636 | 0.0641 |
| 700 | 0.0817 | 0.0824 | 0.0846 | 0.0854 |
| 650 | 0.1099 | 0.1112 | 0.1152 | 0.1166 |
| 600 | 0.1513 | 0.1539 | 0.1616 | 0.1645 |
| 550 | 0.2143 | 0.2195 | 0.2355 | 0.2418 |
| 500 | 0.3138 | 0.3250 | 0.3615 | 0.3764 |
| 450 | 0.4784 | 0.5049 | 0.5988 | 0.6408 |
| 440 | 0.5235 | 0.5553 | 0.6710 | 0.7242 |
| 420 | 0.6306 | 0.6773 | 0.8579 | 0.9467 |
| 400 | 0.7666 | 0.8368 | 1.1308 | 1.2905 |
| 390 | 0.8484 | 0.9352 | 1.3183 | 1.5405 |

1. As expected by the fourth power law of radiation, operating the radiator at higher temperature would reduce the radiator array size. Referring to Table I the radiator size ranges from about .010 $m^2$/kW at 1200°K to 0.15 $m^2$/kW at 600°K and about .35 $m^2$/kW at 500°K. In general the radiator temperature is governed by the process temperature such as in a chemical reactor, thus the choice of radiator temperature may be constrained by other system requirements. At a given operating temperature $T_r$ and waste heat rate to be rejected P, the $A_r/P$ values may be used to compare with heat exchanger area requirements of other heat rejection schemes. For example if radiation is used in conjunction with heat

integration, the minimum operating radiator temperature at which the increased radiator area, together with increased heat exchangers and equipment, might balance out energy savings may be determined.

2. At operating temperatures above 900°K the area increase with temperature decrease is not as significant as at lower temperatures. Therefore opportunities may exist for combined radiation with heat integration or cogeneration for high temperature (above 1000°K) waste heat streams before radiating at 800-900°K without too large a penalty in area increase.

3. The area between the two curves in Figure 2 is bounded by the upper and lower limits of radiator area as a function of operating temperature based on the assumptions used in the analysis: the top curve corresponds to a plant designed to operate during lunar day on the side of the moon which faces the earth; the lower curve corresponds to one designed to operate during lunar night on the side which never sees the earth. The two curves approach together and coincide above 800°K. Therefore lunar night vs day operation and far-earth vs near-earth face location have negligible effects on the radiator area at radiator temperatures above 800°K: 0.0479 vs 0.0491 $m^2$/kW respectively. At radiator temperature of 600°K and on the far-earth face, lunar night operation requires about .151 $m^2$/kW while day operation and near-earth face requires around 0.165 $m^2$/kW, an increase in area of 9%.

4. The far-earth vs near-earth face location by itself has negligible effects on radiator area down to operating radiator temperature of 500°K. They differ by about 4% for day operation.

## Radiator Type And Selection

The analysis in the previous section shows that radiator temperature, the time of operation and site selection all affect radiator design for lunar application. In addition, the amount of heat to be rejected also dictates the type of radiator to be employed, since some radiators have higher capacity than others for equivalent radiator surface areas. Radiator material should have high thermal conductivity, high infrared emissivity but low solar absorptivity, high strength to mass ratio, high resistance to meteoroid damage, and good structural integrity. For oxygen application, material compatibility becomes an important design consideration as well. Radiator shape and configuration is not important so long as the radiator could fit in the spacecraft or be deployable.

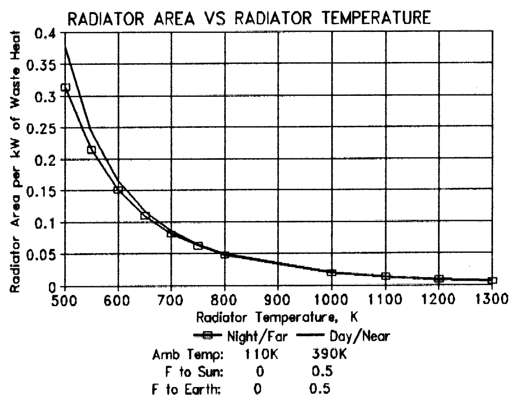


**Figure 2** Radiator Area per unit waste heat, $m^2$/kW, vs radiator temperature, lunar/day operation, far/near-earth face location.

The radiators that are either being used currently or are under investigation include: simple finned radiators, liquid metal pumped-looped radiators, heat pipe radiators, liquid-droplet radiators and moving belt radiators.

### Finned Radiators

The finned radiator is simply a radiator made of material with high thermal conductivity and high emissivity, and fins to increase the heat transfer area. Heat transfer is accomplished through conduction from the fluid to the interior of the radiator, conduction through the radiator material, and radiation from the exterior surface of the radiator to the environment. This method is limited to low radiative loads. Figure 3 is a block diagram of a finned radiator array with several panels of finned tube sheet operating in parallel. $T_{hi}$ and $T_{ho}$ are the temperature of the radiator working fluid entering and leaving the radiator respectively.

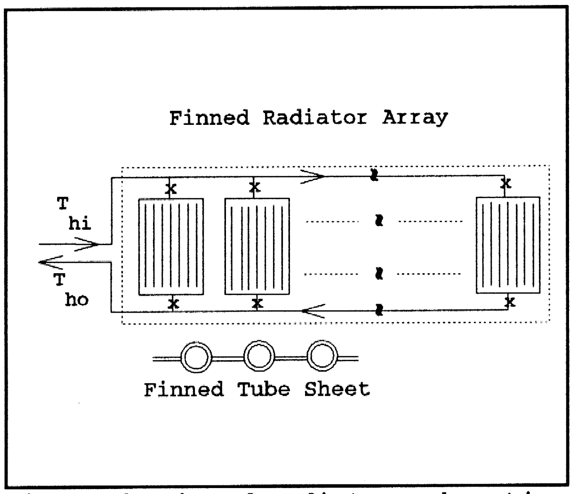


**Figure 3** Finned radiator schematic.

<u>Liquid Metal Pumped-Loop Radiators</u>

The liquid metal pumped-loop radiator is designed for use in high temperature applications such as cooling of a nuclear reactor. Figure 4 is a schematic of a pumped loop radiator. It consists of a waste heat exchanger, a high emissivity radiating surface, a volume accumulator and an electromagnetic pump(2:102). The volume accumulator is used to compensate for thermal expansion of the fluid from start up to operating temperature as well as maintaining the proper pressure in the loop. Due to heat losses from the waste heat exchanger to the radiator, the radiator operating temperature is lower than the waste heat exchanger temperature, thus lowering the radiator effectiveness and increasing radiator area.

<u>Heat Pipe Radiators</u>

The heat pipe radiator is currently the most popular heat rejection method. Figure 5 illustrates the basic principles of operation of a heat pipe. Heat is transferred to the evaporator section of the heat pipe. The heat evaporates the liquid phase of the working fluid in the radiator. The gas flows toward the cold end of the radiator, which is cooled by radiating into the environment. The working fluid condenses and is pumped back toward the evaporator along capillary channels lined with wick material along the

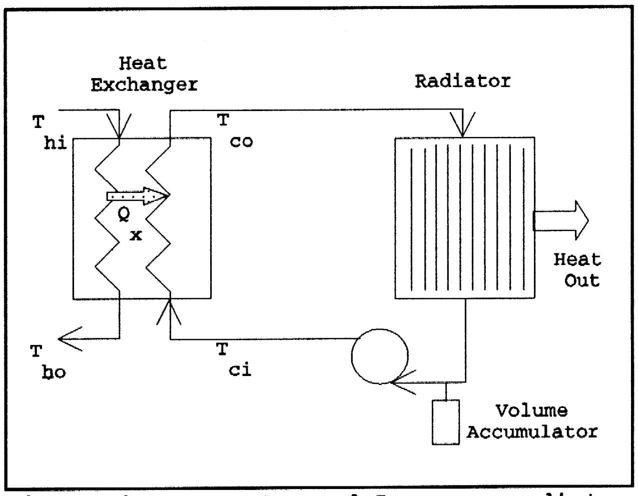


**Figure 4** Pumped-Loop radiator schematic.

interior walls of the heat pipe. Advantages of heat pipes include: high heat transfer capability, high temperature capability, and high reliability because the system has no moving parts and it can be a series of self-contained parallel units. The choice of the working fluid is governed by the desired radiator operating temperature. Operating temperatures for heat pipes range from cryogenic temperature to liquid metal temperature. Magnesium, sodium and lithium are some examples of working fluid for high temperature applications.

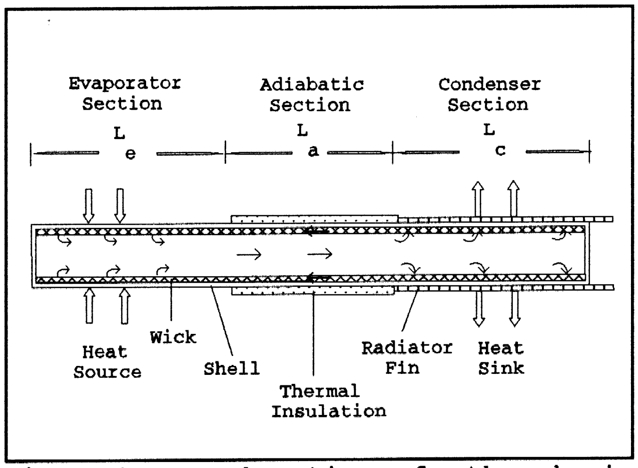


**Figure 5** Schematic of the basic operating principles of a heat pipe.

Liquid Droplet Radiators

This method is being studied very closely by many researchers because of its light mass and relatively simple hardware. Figure 6 shows the basic concept of a liquid droplet radiator. Waste heat is transferred to a liquid working fluid in the heat exchanger. The liquid is then ejected through a pressurized nozzle into the environment. The sheet of droplets are radiatively cooled while in flight and is collected at the other end to begin the cycle again. Since the mass of the radiator area is only the mass of the working fluid, it leads to a significant mass reduction over other more conventional radiators such as fins or heat pipes. Moreover protection against meteoroid puncture in the radiator area is unnecessary. Operating temperature ranges from 300°K to 1000°K. Some evaporation losses may take place and the fluid will have to be replenished. Tin appears to be a good candidate fluid for 1000°K rejection temperature because of its low vapor pressure[5]. In addition it does not degrade due to temperature cycling or ionizing radiation, it has high heat conductivities and high surface tensions.

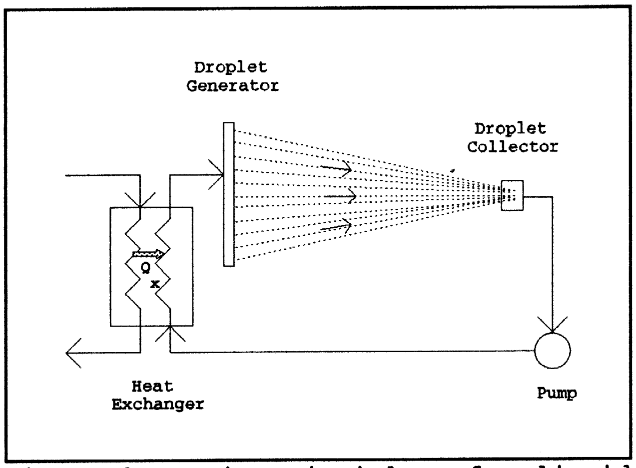


**Figure 6** Basic principles of a liquid droplet radiator.

In general the emissivity values for liquid droplet radiator fluids are quite low: about 0.15 for tin. Therefore given the same power output, the radiative area may be seven times that of heat pipes. However the mass reduction more than compensate for the area increase. Current predictions for the mass density of liquid droplet radiators are on the order of 0.11 to 0.15 $kg/m^2$ of radiator area. By contrast, the mass densities of well designed heat pipe radiators for space applications are about 5 $kg/m^2$.

Moving Belt Radiators

The moving belt radiator runs a belt around a waste heat exchange drum. Heat is conducted away through direct contact between the belt and the heat exchanger. The belt then radiates the heat into the environment. The advantages of this concept are its light weight, and its nonsusceptibility to meteoroid impact. This method is still in the early conceptual stage.

## Summary

A radiation model has been proposed to estimate radiator area requirement based on radiator operating temperature, the lunar environmental conditions and radiator surface material properties. Using some generic values for radiator material's emissivity in the infrared wavelength and absorptivity in the solar wavelength, the radiator area per unit power of waste heat was estimated as a function of radiator operating temperature, and the presence or absence of sunshine and earthshine. The model predicted that opportunities exist for heat integration or cogeneration to be used with radiation without significant radiator area increase if the temperature of the waste heat stream is above 1000°K and the minimum radiator temperature is above 800°K. The model also showed that the radiator area requirement is independent of the time and location of operation, i.e. during lunar night vs lunar day and far-earth vs near-earth side if the radiator operating temperature is above 800°K.

Five radiator designs were briefly examined to review the current status of space radiator development. Although still in the early development stage, liquid droplet radiators appear to be the best candidate for high power radiative load because of its light mass, simple design and immunity to meteoroid puncture. However until the liquid droplet radiator has been tested at the system level, heat pipe radiators are still the best option for the moment because of the relatively light mass, high reliability and wide operating temperature range.

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