NASA TM X-1729

A METHOD FOR REDUCING THE EQUIVALENT SINK TEMPERATURE OF A VERTICALLY ORIENTED RADIATOR ON THE LUNAR SURFACE

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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ABSTRACT

An aluminized plastic cover sheet over the lunar surface immediately surrounding a vertical radiator offers a simple, light-weight method for reducing the radiator equivalent sink temperature. A simplified analysis predicts equivalent sink temperature as a function of cover surface coating properties, cover length, and radiator elevation for a radiator in the lunar equatorial plane. Results indicate that equivalent sink temperature can be reduced from over 600° R (333 K) (no cover) to about 400° R (222 K) (with cover). The corresponding reduction in required radiator area is about 50 percent for a radiator temperature of 700° R (389 K). The effect of operation off the lunar equator is also discussed.

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SUMMARY

A simple light-weight method for reducing the maximum equivalent sink temperature of a vertically oriented radiator on the lunar surface is investigated. It is proposed that a thin aluminized plastic sheet be used as a cover over the natural lunar surface in the area immediately surrounding the radiator. The proposed cover has low solar absorptivity and thermal emissivity as opposed to high values for the natural lunar soil.

The radiator is alined in the lunar equatorial plane. This alinement results in negligible direct solar energy incident on the radiator because of the small angle between the ecliptic plane and the lunar equatorial plane.

An approximate analysis is presented which shows that the maximum equivalent sink temperature for a vertically oriented radiator at the lunar equator can be reduced from over 600° R (333 K) to about 400° R (222 K) with a cover spread out to a distance equal to eight times the radiator height. With a radiator temperature of 700° R (389 K), this reduction in equivalent sink temperature permits a 50 percent reduction in radiator area.

Elevation of the radiator above the lunar surface increases the equivalent sink temperature for a reasonable cover length. Elevation by an amount equal to the radiator height increases the equivalent sink temperature from 396° to 434° R (220 to 241 K) at a radiator operating temperature of 700° R (389 K) and a cover length equal to eight times the radiator height.

It is concluded that substantial reduction in required radiator area for lunar surface operation can be achieved. This reduction is especially significant for low-temperature radiators typified by Brayton-cycle primary radiators and radiators used for secondary-equipment cooling. The effect of operation at locations off the lunar equator is briefly discussed. For these locations the radiator is alined in a plane parallel to the lunar equatorial plane in order to minimize direct solar energy input to the radiator.

INTRODUCTION

The capability of a radiator to reject waste heat is limited by the temperature of its surroundings. Low-temperature radiators for lunar based power generation systems are sensitive to the high temperature of the lunar surface. Typical low-temperature systems are the Brayton cycle, fuel cell, and low-temperature organic Rankine cycle systems. Other applications are secondary equipment cooling, environmental control, and life support.

Equivalent sink temperature is the steady-state equilibrium temperature reached by the radiator because of incident energy from its surroundings. It is a convenience used to account for energy arriving at the radiator from a heat sink. A low value of equivalent sink temperature is especially desirable for low temperature space radiators.

The equivalent sink temperature of a horizontal radiator on the lunar surface is near 500° R (278 K). For a vertical radiator the equivalent sink temperature is over 600° R (333 K). These temperatures are based on the conditions that the sun is directly overhead, the lunar surface absorptivity is 0.90, and the radiator is coated with a material having a ratio of solar absorptivity to thermal emissivity of 0.25. A horizontal radiator receives no energy from the lunar surface. A vertical radiator receives no direct solar energy but receives both reflected solar and thermal energy from the lunar surface. A vertical orientation allows a flat radiator to reject heat from both sides. Thus, there is a desire to reduce the high equivalent sink temperature of a vertical radiator.

A simple, light-weight method for reducing the equivalent sink temperature of a vertical radiator on the lunar surface is proposed. An approximate analysis for the resulting equivalent sink temperature is included.

DESCRIPTION

A radiator similar to that shown in figure 1 is assumed. A flat radiator is either assembled on the lunar surface or deployed from a lunar landing vehicle. The radiator is alined in the Moon's equatorial plane. This alinement results in negligible direct solar energy incident on the radiator because the inclination of the mean lunar equator to the ecliptic is a maximum of only 1.6° (ref. 1).

It is proposed that an aluminized sheet of thin plastic, such as Mylar, be spread out over the lunar surface near the radiator. The aluminized plastic sheet serves as a lightweight, easily packaged and deployed covering. Its low solar absorptivity (approx. 0.12) replaces the natural lunar surface absorptivity (approx. 0.9) (ref. 2) in the region near the radiator. It is the high solar absorptivity of the Moon which is primarily responsible for the high equivalent sink temperature of a vertical radiator on the lunar surface when the Sun is directly overhead. Because of the specular characteristics of the aluminized coating, the cover contributes no solar energy to the radiator if extended perpendicular to the radiator in a flat manner without wrinkles.

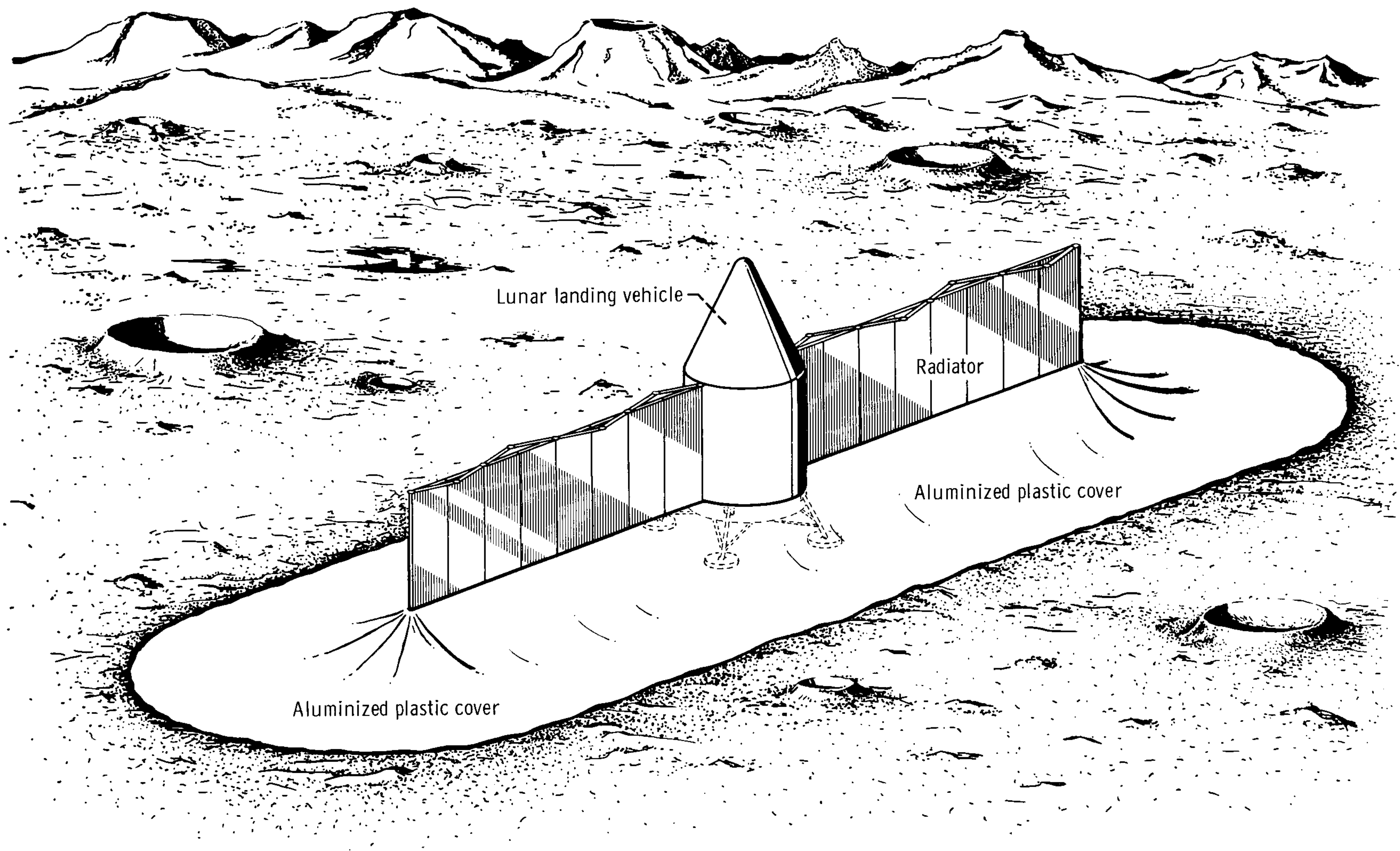

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Figure 1. - Radiator and cover on the moon.

The equilibrium temperature of the plastic sheet is determined by its ratio of solar absorptivity to thermal emissivity. In order to control the temperature of the plastic sheet to an acceptable level, it may be necessary to apply a coating such as silicon oxide. Such a coating is transparent to solar energy and is used with controlled thickness over aluminized surfaces to vary the solar absorptivity to thermal emissivity ratio over a wide range (0.2 to 6) as a temperature control device (ref. 3). The cross section of the coated aluminized plastic sheet is shown in figure 2.

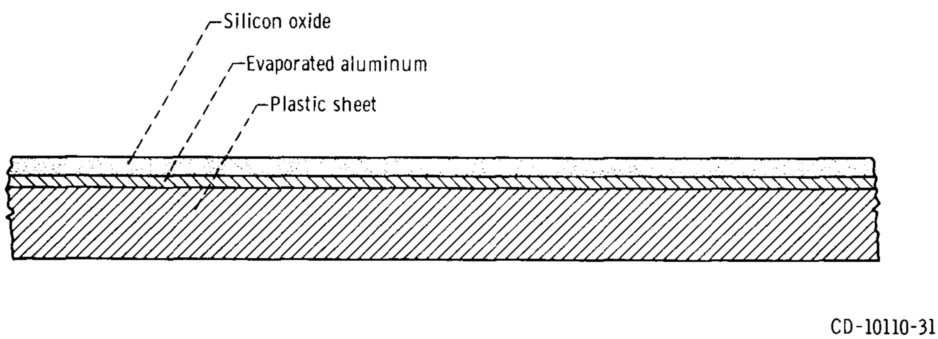


Figure 2. - Cross section of aluminized plastic cover sheet with coating.

METHOD OF ANALYSIS

An approximate analysis to determine the reduction in equivalent sink temperature that can be realized with the proposed aluminized plastic cover sheet is described. Included in the analysis are the effects of radiator temperature, cover length and emissivity, and elevation of the radiator above the lunar surface on equivalent sink temperature. The effect of cover emissivity on cover temperature is also considered. It is assumed that the radiator is located at the equator with the Sun directly overhead, a condition resulting in maximum equivalent sink temperature.

The equation for equivalent sink temperature is based on the steady-state heat balance among the radiator, lunar surface covering, and the lunar soil. These surfaces are designated radiator, cover, and Moon, respectively (fig. 3).

To simplify the analysis, end effects are neglected by considering the radiator and cover to be semi-infinite planes. The radiator is assumed to be isothermal. Conversely, the cover and lunar soil are nonisothermal. Nonisothermal surfaces are analyzed numerically by subdivision into incremental strips which are assumed to be isothermal. An isothermal strip of the lunar cover is designated i and is a semi-infinite rectangle of normalized length ΔL_i; all dimensions are normalized to the radiator height. Similarly, ΔL_j is the normalized length of an incremental strip j of the uncovered lunar surface.

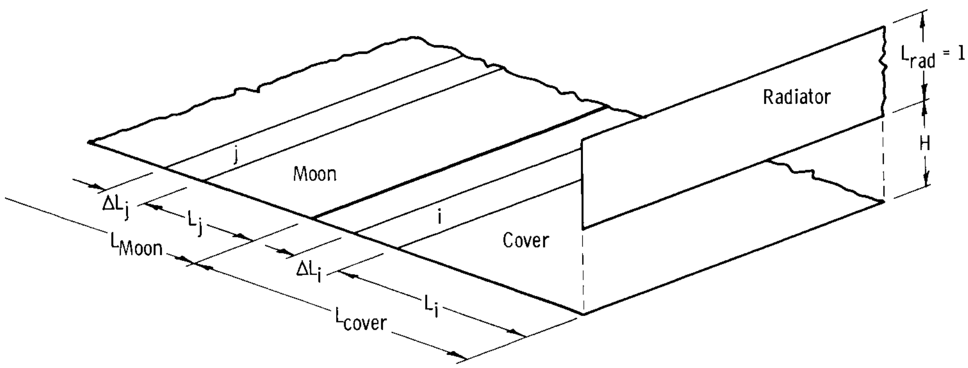


Figure 3. - Surface designation for heat-transfer analysis.

The heat input to the radiator is the sum of thermal radiation from the cover, thermal radiation from the lunar soil, and reflected solar radiation from the lunar soil. In the steady-state, the sum of these input energies is equal to the thermal emission of the radiator. Assuming that the cover has a specular aluminized coating, is arranged normal to the plane of the radiator, and is deployed in a flat manner without wrinkles, the solar energy reflected from the cover will not reach the radiator.

In equation form, the heat balance is

$$\sigma\epsilon_{rad,th}L_{rad}T_{sink}^4$$

$$= \alpha_{rad,th}\left(\sigma\epsilon_{cover,th}\sum_{cover}\Delta L_i F_{i-rad}T_i^4 + \sigma\epsilon_{Moon,th}\sum_{Moon}\Delta L_j F_{j-rad}T_j^4\right)$$

$$+ \alpha_{rad,s}S\rho_{Moon}L_{Moon}F_{Moon-rad} \tag{1}$$

Using the reciprocity rules for configuration factors

$$\Delta L_i F_{i-rad} = L_{rad}F_{rad-i} \tag{2}$$

$$\Delta L_j F_{j-rad} = L_{rad}F_{rad-j} \tag{3}$$

and

$$L_{Moon}F_{Moon-rad} = L_{rad}F_{rad-Moon} \tag{4}$$

equation (1) becomes

$$\sigma\epsilon_{rad,th}L_{rad}T_{sink}^4$$

$$= \alpha_{rad,th}\left(\sigma\epsilon_{cover,th}\sum_{cover} L_{rad}F_{rad-i}T_i^4 + \sigma\epsilon_{Moon,th}\sum_{Moon} L_{rad}F_{rad-j}T_j^4\right)$$

$$+ \alpha_{rad,s}S\rho_{Moon}L_{rad}F_{rad-Moon} \tag{5}$$

Rearranging equation (5) and using $\alpha_{rad,th} = \epsilon_{rad,th}$, the fourth power of the equivalent sink temperature is

$$T_{sink}^4 = \epsilon_{cover,th}\sum_{cover} F_{rad-i}T_i^4 + \epsilon_{Moon,th}\sum_{Moon} F_{rad-j}T_j^4$$

$$+ \frac{\alpha_{rad,s}}{\epsilon_{rad,th}}\frac{S}{\sigma}\rho_{Moon}F_{rad-Moon} \tag{6}$$

To obtain an equation for the temperature of the incremental strip of the cover, it is necessary to write a heat balance on the increment. It is noted that the strip receives direct energy from the Sun and thermal energy from the radiator. Since the cover and lunar surface are in the same plane, there is no direct energy exchange between these two surfaces. The heat balance on the increment of cover is thus

$$\sigma\epsilon_{cover,th}(\Delta L_i)T_i^4 = \alpha_{cover,s}S(\Delta L_i) + \alpha_{cover,th}\sigma\epsilon_{rad,th}L_{rad}F_{rad-i}T_{rad}^4 \tag{7}$$

where T_{rad} is the operating temperature of the radiator and is to be distinguished from T_{sink}, the equivalent sink temperature of the radiator. Rearranging equation (7) and using $\alpha_{cover,th} = \epsilon_{cover,th}$, the fourth power of the temperature of the cover increment is

$$T_i^4 = \frac{\alpha_{cover,s}}{\epsilon_{cover,th}}\frac{S}{\sigma} + \frac{L_{rad}}{\Delta L_i}\epsilon_{rad,th}F_{rad-i}T_{rad}^4 \tag{8}$$

The analogous heat balance on the incremental strip of bare lunar soil results in the following equation:

$$T_j^4 = \frac{\alpha_{\text{Moon, s}}}{\epsilon_{\text{Moon, th}}} \frac{S}{\sigma} + \frac{L_{rad}}{\Delta L_j} \epsilon_{\text{rad, th}} F_{\text{rad-j}} T_{rad}^4 \tag{9}$$

Combining equations (8) and (9) with equation (6) results in the following equation:

$$T_{sink} = \left(\alpha_{\text{cover, s}} \frac{S}{\sigma} F_{\text{rad-cover}} + \epsilon_{\text{rad, th}} \epsilon_{\text{cover, th}} \frac{L_{rad}}{\Delta L_i} T_{rad}^4 \sum_{\text{cover}} F_{\text{rad-i}}^2 \right.$$

$$+ \alpha_{\text{Moon, s}} \frac{S}{\sigma} F_{\text{rad-Moon}} + \epsilon_{\text{rad, th}} \epsilon_{\text{Moon, th}} \frac{L_{rad}}{\Delta L_j} T_{rad}^4 \sum_{\text{Moon}} F_{\text{rad-j}}^2$$

$$\left. + \frac{\alpha_{\text{rad, s}}}{\epsilon_{\text{rad, th}}} \frac{S}{\sigma} \rho_{\text{Moon}} F_{\text{rad-Moon}} \right)^{1/4} \tag{10}$$

The sink temperature contains five separate contributions. The first term is the contribution from the cover which results from solar energy absorbed by the cover. The second is the thermal energy which originated at the radiator and is reradiated by the cover. The third term is the contribution from the lunar soil which, like the first term, results from solar energy absorbed. The fourth term, like the second, is the thermal energy from the radiator which is reradiated by the lunar soil. The contribution of this term beyond a distance of 100 L_{rad} is negligibly small and therefore is ignored in the sink temperature calculations. The last term is the solar energy incident upon the radiator as the result of diffuse reflection from the lunar soil.

The equations for $F_{\text{rad-cover}}$, $F_{\text{rad-Moon}}$, $F_{\text{rad-i}}$, and $F_{\text{rad-j}}$ are needed. Because of the semi-infinite common dimension of all surfaces, the configuration factors are based on two-dimensional geometries. This allows the use of Hottel's crossed-string method (ref. 4).

Referring to figure 3, the equation for $L_{rad} F_{\text{rad-i}}$ can be written by the crossed-string method as follows:

$$L_{rad} F_{\text{rad-i}} = \frac{1}{2} \left[\sqrt{L_i^2 + (H + L_{rad})^2} + \sqrt{(L_i + \Delta L_i)^2 + H^2} - \sqrt{L_i^2 + H^2} \right.$$

$$\left. - \sqrt{(L_i + \Delta L_i)^2 + (H + L_{rad})^2} \right] \tag{11}$$

where H is the elevation of the radiator above the cover normalized to radiator height L_{rad}. Since L_{rad} is the normalized radiator height and is equal to 1, the configuration factor F_{rad-i} is

$$F_{rad-i} = \frac{1}{2}\left[\sqrt{L_i^2 + (1+H)^2} + \sqrt{(L_i + \Delta L_i)^2 + H^2} - \sqrt{L_i^2 + H^2} - \sqrt{(L_i + \Delta L_i)^2 + (1+H)^2}\right] \tag{12}$$

The equation for $F_{rad-cover}$ can be obtained by summing equation (12) over all cover increments. Also the equation can be obtained directly from Hottel's crossed-string method as

$$F_{rad-cover} = \frac{1}{2}\left[(1 + H) + \sqrt{L_{cover}^2 + H^2} - H - \sqrt{L_{cover}^2 + (1 + H)^2}\right] \tag{13}$$

or

$$F_{rad-cover} = \frac{1}{2}\left[1 + \sqrt{L_{cover}^2 + H^2} - \sqrt{L_{cover}^2 + (1 + H)^2}\right] \tag{14}$$

The equation for F_{rad-j} is

$$F_{rad-j} = \frac{1}{2}\left[\sqrt{(L_{cover} + L_j)^2 + (1 + H)^2} + \sqrt{(L_{cover} + L_j + \Delta L_j)^2 + H^2}\right.$$

$$\left. - \sqrt{(L_{cover} + L_j)^2 + H^2} - \sqrt{(L_{cover} + L_j + \Delta L_j)^2 + (1 + H)^2}\right] \tag{15}$$

The equation for $F_{rad-Moon}$ can be obtained by summing equation (12) over all increments of the lunar surface. It can also be obtained directly from Hottel's crossed-string method as

$$F_{rad-Moon} = \frac{1}{2}\left[\sqrt{L_{cover}^2 + (1 + H)^2} + \sqrt{(L_{cover} + L_{Moon})^2 + H^2}\right.$$

$$\left. - \sqrt{L_{cover}^2 + H^2} - \sqrt{(L_{cover} + L_{Moon})^2 + (1 + H)^2}\right] \tag{16}$$

If it is assumed that the lunar soil extends infinitely far in the direction perpendicular to the radiator, it can be written that

$$F_{rad\text{-}cover} + F_{rad\text{-}Moon} = 0.5 \tag{17}$$

Hence, $F_{rad\text{-}Moon}$ can be simply written

$$F_{rad\text{-}Moon} = 0.5 - F_{rad\text{-}cover} \tag{18}$$

RESULTS

Table I lists the assumed values for the solar absorptivity α_s and thermal emissivity ϵ_{th} of the radiator coating, cover coating (ref. 3), and lunar surface (ref. 2). The values assumed for the radiator coating are conservatively representative of a zinc oxide/potassium silicate coating for the temperatures up to 760° R (422 K). Above this temperature this coating degrades and the assumption of constant radiator coating properties results in somewhat optimistic values of equivalent sink temperatures. However, comparative results showing the reduction in equivalent sink temperature resulting from the use of the cover should be valid.

TABLE I. - ASSUMED PROPERTIES OF RADIATOR COATING, COVER COATING, AND LUNAR SURFACE

	Solar absorptivity, α_s	Thermal emissivity, ϵ_{th}
Radiator coating	0.22	0.88
Cover coating	.12	Variable, 0.06 to 0.60
Lunar surface	.90 (ρ = 0.10)	1.00

Figure 4 presents radiator equivalent sink temperature as a function of cover length for a radiator on the lunar surface for radiator temperatures of 600° R (333 K), 700° R (389 K), and 800° R (444 K). A cover thermal emissivity of 0.12 and an elevation of zero are assumed. This temperature range is representative of the effective radiating temperature of nonisothermal radiators rejecting the primary waste heat of power systems such as Brayton cycle, fuel cell and low-temperature organic Rankine systems. It is also a temperature range of interest for the secondary cooling requirements of power systems with high primary radiator temperatures as well as the cooling requirements

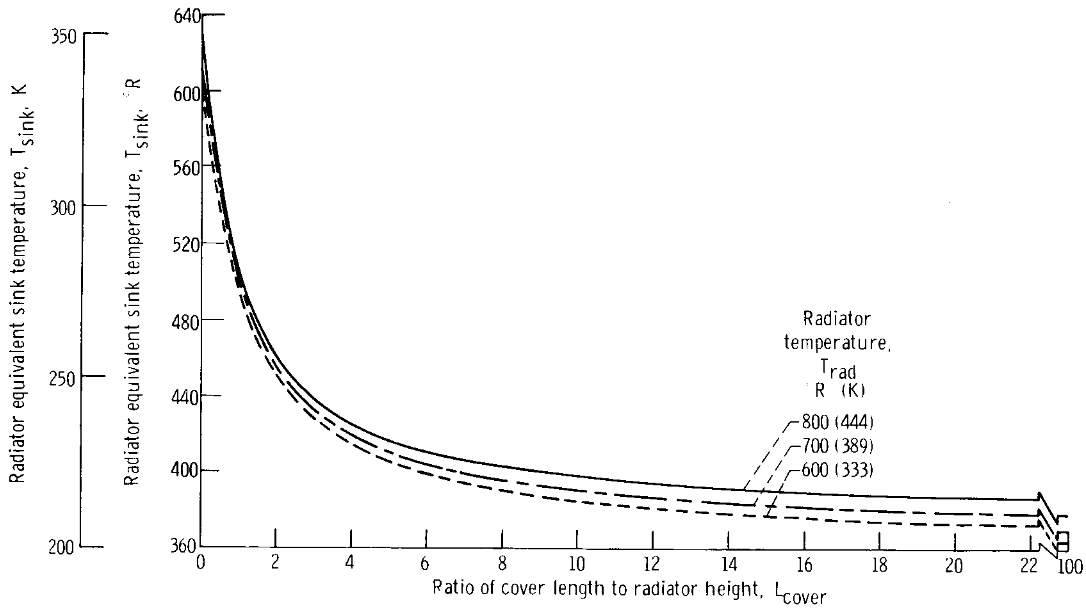


Figure 4. - Effect of cover length and radiator temperature on equivalent sink temperature of a vertical radiator on the lunar surface. Cover emissivity, 0.12.

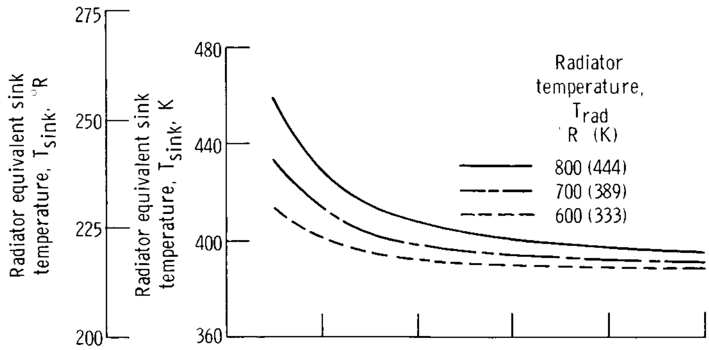
for environmental control and life support systems.

The equivalent sink temperature decreases very rapidly from values between 600° and 630° R (333 and 350 K) at L_{cover} = 0 (no cover) to values near 400° R (222 K) at a cover length L_{cover} between 6 and 8. The reduction in equivalent sink temperature is much less beyond a cover length of 8 because of the low configuration factor from the lunar surface to the radiator. At a cover length L_{cover} of 100, the equivalent sink temperature is between 360° and 380° R (200 and 210 K), depending upon radiator temperature. In terms of radiator area, this reduction in equivalent sink temperature to 400° R corresponds to a reduction in required radiator area of 34 percent at a radiator temperature of 800° R (444 K), and 54 percent at a radiator temperature of 700° R (389 K). A radiator operating at a temperature of 600° R (333 K) is impossible without the use of a cover because of the 602° R (334 K) equivalent sink temperature.

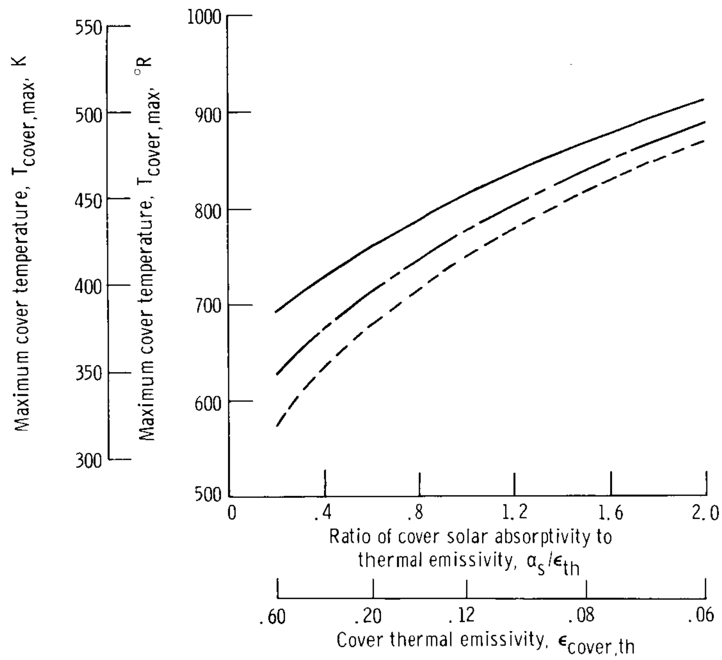
The maximum cover temperature for the assumed value of cover emissivity (ϵ_{th} = 0.12) occurs near the radiator, and ranges from 750° to 815° R (417 to 453 K) over the radiator temperature range from 600° to 800° R (333 to 444 K).

Effect of Cover Thermal Emissivity

Figure 5 shows the effect upon equivalent sink temperature and maximum cover temperature of varying the thickness of the silicon oxide coating on the aluminized plastic cover surface. Increasing coating thickness increases the cover thermal emissivity.



(a) Effect on equivalent sink temperature.



(b) Effect on maximum cover temperature.

Figure 5. - Effect of cover thermal emissivity on equivalent sink temperature and maximum cover temperature. Cover length, 8; radiator elevation, 0.

Since the solar absorptivity remains constant, this corresponds to a variation in α_s/ϵ_{th} of the cover. A radiator resting on the lunar surface $H = 0$ and a cover length $L_{cover} = 8$ are assumed.

Figure 5(a) is a plot of equivalent sink temperature as a function of the α_s/ϵ_{th} (or thermal emissivity ϵ_{th}) of the cover for three radiator temperatures. Figure 5(b) is a corresponding plot of the maximum cover temperature. It is seen that by keeping the cover α_s/ϵ_{th} in the range between 0.6 and 1.0 (ϵ_{th} between 0.2 and 0.12), the maximum cover temperature can be held to between 675° and 815° R (375 and 453 K), depending upon the radiator temperature, with little change in equivalent sink temperature.

Effect of Radiator Elevation

Figure 6 shows the effect of radiator elevation H on the equivalent sink temperature for a radiator temperature T_{rad} of 700° R (389 K) and cover thermal emissivity ϵ_{th} of 0.12 (α_s/ϵ_{th} = 1.0). Equivalent sink temperature is plotted as a function of cover length L_{cover} for elevations of 0, 0.5, and 1.0.

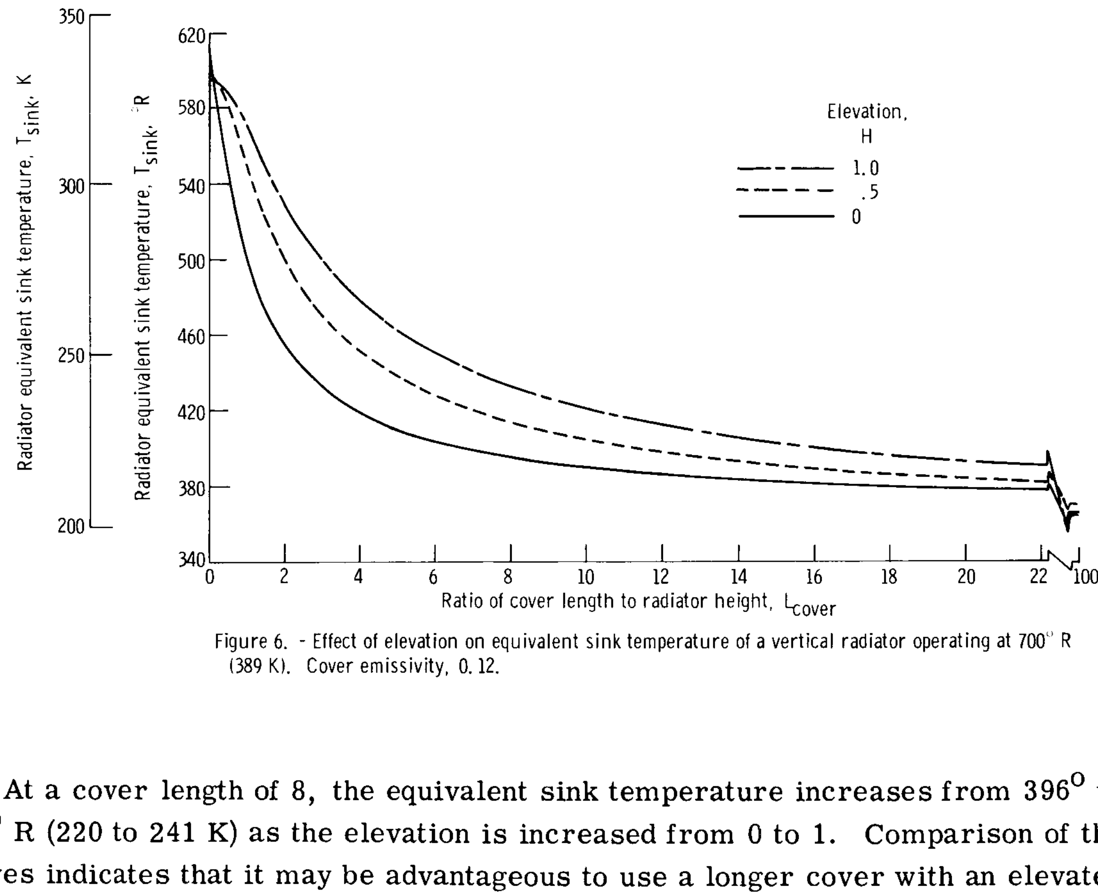


Figure 6. - Effect of elevation on equivalent sink temperature of a vertical radiator operating at 700° R (389 K). Cover emissivity, 0.12.

At a cover length of 8, the equivalent sink temperature increases from 396° to 434° R (220 to 241 K) as the elevation is increased from 0 to 1. Comparison of the curves indicates that it may be advantageous to use a longer cover with an elevated radiator.

For the case of L_{cover} = 0 (no cover), the elevated radiator has a somewhat reduced equivalent sink temperature. The reason for this can be seen by examination of equation (10) where, for no cover, the only term affected by elevation is the fourth term involving F_{rad-j}. For increments near the radiator F_{rad-j} decreases with increasing H. The result is that the sum of squares of configuration factors $\sum_{Moon} F^2_{rad-j}$ is less for an elevated case than for the unelevated case.

As cover length increases, however, the equivalent sink temperature for the elevated radiator exceeds that for the unelevated radiator. The reason for this is that the elevated radiator has a larger value of $F_{rad\text{-}Moon}$ and a smaller value of $F_{rad\text{-}cover}$ than does the radiator on the lunar surface. In other words, a given length of cover is not as effective in blocking lunar input to an elevated radiator as it is in blocking input to an unelevated radiator.

Maximum cover temperature for a radiator elevated above the surface is between 25^{o} and 70^{o} R (14 and 39 K) less than that for a radiator on the surface. The point of maximum cover temperature occurs at some distance from the intersection of the radiator and surface cover planes. The reason for this is seen in equation (8) where the increment having the largest $F_{rad\text{-}i}$ will have the highest temperature. As stated previously, for the elevated radiator the maximum value of $F_{rad\text{-}i}$ occurs at some distance from the radiator plane.

CONCLUDING REMARKS

It has been shown that substantial reductions in equivalent sink temperature can be achieved through the use of a light-weight, aluminized plastic sheet to cover the lunar surface near a vertically oriented radiator alined in a plane parallel to the lunar equatorial plane. For a radiator with an operating temperature of 700^{o} R (389 K), the reduction in equivalent sink temperature makes possible a 50 percent reduction in radiator area.

Although the analysis was made for a radiator located at the lunar equator, the same concept can be used for landing sites at latitudes up to about 30^{o}. For such locations, the orientation of the radiator in a plane parallel to the lunar equatorial plane results in a tilt of the radiator relative to the vertical of an angle equal to the latitude. To prevent solar reflection back to the radiator, the angle between the radiator and the cover must be maintained at a minimum of 90^{o}. This requires that the radiator be elevated so that the cover on the lower side of the radiator can be sloped away from the bottom of the radiator. This will result in some small input to the cover from the lunar surface. The average configuration factors for the two sides of a radiator tilted in this manner are approximately the same as the configuration factors of a vertical radiator. As a result, an estimate of the equivalent sink temperature at latitudes greater than zero can be made from the sink temperature for a radiator at the equator of equal elevation (fig. 6). Because of the reduced solar intensity, the equivalent sink temperature should be somewhat less than that of a radiator at the equator with equal elevation. For the case of a landing site at a latitude of 30^{o}, the required radiator elevation $\dot{H}$ is 0.87, measured in a vertical direction. From figure 6, the equivalent sink temperature should be somewhat less than 430^{o} R (239 K) for a radiator temperature of 700^{o} R (389 K) and a cover length of 8.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 15, 1968,
120-27-06-10-22.

APPENDIX - SYMBOLS

F	configuration factor
H	normalized elevation, elevation divided by radiator height
L	normalized length, length divided by radiator height
S	solar constant, 442 Btu/hr ft^2 (1393 w/m^2)
T	temperature, ^oR (K)
α	absorptivity
ϵ	emissivity
ρ	reflectivity
σ	Stefan-Boltzmann constant, 0.1713×10^{-8} Btu/(hr)(ft^2)($^oR^4$) (5.6697×10^{-8} $w/(m^2)(K^4)$)

Subscripts:

cover	lunar surface cover
i	increment designation, cover surface
j	increment designation, lunar surface
max	maximum
Moon	bare lunar surface
rad	radiator
s	solar
sink	sink
th	thermal

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