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ABSTRACT

Several factors are important in the development of active thermal control systems for planetary habitats. Low system mass and power usage as well as high reliability are key requirements. Ease of packaging and deployment on the planet surface are also important. In the case of a lunar base near the equator, these requirements become even more challenging because of the severe thermal environment. One technology that could be part of the thermal control system to help meet these requirements is a radiator shade. Radiator shades enhance direct radiative heat rejection to space by blocking solar or infrared radiation which lessens the performance of the radiator. Initial development work, both numerical and experimental, has been done at the Johnson Space Center (JSC) in order to prove the concept. Studies have shown that heat rejection system mass may be reduced by 50% compared to an unshaded low-absorptivity radiator.

Several different shade geometries have been evaluated using Thermal Synthesizer System (TSS) math models. These models have pointed to the most promising shade geometries by providing an estimate of their expected performance. The models have also been used to study the effects of different optical properties in order to understand how the system will perform over time. Models have been used to optimize designs by considering such factors as end-effects, height-to-length ratio and shade height. Thermal math model predictions indicate that a parabolic shade will reduce the effective environment sink temperature of the radiator by more than 100 K compared to an unshaded vertical radiator.

In order to verify numerical predictions, testing of the parabolic radiator shade concept has also been done. A proof of concept thermal vacuum test has been carried out on a small scale rigid parabolic shade test article under a variety of operating conditions. The rigid shade used a section of a cylinder to approximate a parabola and had non-ideal optical properties. Still, the shade lowered the effective sink temperature of the radiator by 70K compared to the unshaded radiator in the thermal vacuum test.

One shade design which is under study is an inflatable shade. In this design, gas pressure is used to hold the parabolic shape of the shade which is covered with a clear cover to form a long tubular enclosure. A vertical radiator is supported inside the enclosure. Analytical studies indicate that shade performance is reduced due to the transparent cover, but that overall system mass may be reduced over other flexible parabolic shade designs due to the elimination of a support structure and the use of light weight materials.

Future plans include construction of an inflatable shade test article and construction of a flexible parabolic shade deployment test article. Eventually these test articles could be used in a full scale thermal vacuum test.

INTRODUCTION

The design of aerospace systems presents many difficult requirements which must be met. Operation in vacuum, resistance to cosmic radiation, reasonable development costs, high reliability, and low mass are just a few. Equipment and crew must also be protected from thermal extremes which range from full sun with no moderating atmosphere to the near absolute zero conditions of deep space. For human missions, the thermal control system must maintain inhabited volumes in the range of 18 to 27°C using only radiation for ultimate heat rejection. For a lunar mission, there are lengthy day and night periods to contend with as well as dust from the lunar surface which may adhere to thermal control surfaces and alter optical properties.

Horizontal radiators with a low solar absorptance coating could be used to reject life support waste heat directly, but radiator performance would decrease rapidly as ultraviolet radiation and dust degraded the optical properties of the coating. There is no atmosphere on the moon and the lunar regolith is a very poor thermal conductor, making these options unattractive as heat sinks. Due to the length of the lunar day, thermal storage is not a viable option either [1].

Despite these difficulties, several different technologies exist which should be able to meet the stringent requirements of a thermal control system for the moon. The two lunar base thermal control technologies currently receiving the most attention at NASA JSC are vapor compression heat pumps powered by solar energy and parabolic shading systems which protect the radiator from the hot thermal environment of the moon [1-4]. Parabolic shading system development at JSC is the focus of this paper.

SHADE DESCRIPTION

Figure 1 shows how heat from the sun and the planet surface severely degrades radiator heat rejection on the moon near the equator. A radiator operating at 270K can reject 271 Watts per square meter of exposed area, its emissive power at that temperature. Once the incoming heat fluxes from the sun and moon are subtracted, the net heat flux in both the horizontal and vertical radiator cases is negative (see Figure 1). If the average radiator temperature is 290K, the horizontal radiator has a net positive heat rejection (alpha=0.23), but the vertical radiator still does not. At a radiator temperature of 370K, the 2-sided heat rejection of the vertical radiator has surpassed the single sided heat rejection of the horizontal radiator (see Figure 1).

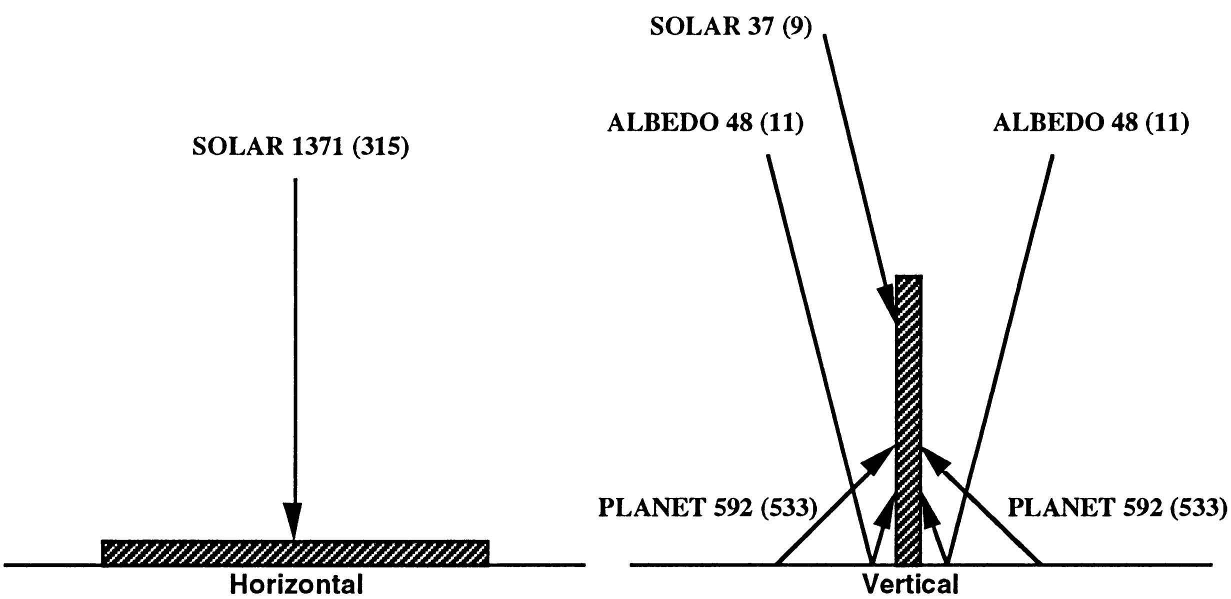
A radiator shade is any device that blocks incoming thermal radiation from striking the thermal control system radiator. If a radiator shade with appropriate optical properties is placed between the heat source and the radiator, the absorbed fluxes can be reduced. If they are reduced sufficiently, net heat rejection from a moderate temperature radiator will be enabled. Figure 2 shows two potential shade configurations. The first blocks solar radiation from a horizontal radiator. The second V-shaped shade blocks planet infrared radiation from a vertical radiator. The top surface of the V shade has a high reflectivity so that solar radiation is reflected back to space and a low emissivity to reduce the IR transmitted from the shade to the radiator. These and other shade geometries have been studied at JSC [1].

WORST CASE INCIDENT AND (ABSORBED) FLUXES (W / M^2) AT THE EQUATOR AT NOON

RADIATOR PROPERTIES ALPHA/EPSILON = 0.23/0.9

HORIZONTAL RADIATOR
SUN ANGLE = 0°

VERTICAL RADIATOR
SUN ANGLE = 1.53°



Net heat rejection = emitted - absorbed energy

Radiator temperature	Horizontal net rejection	Vertical net rejection
270K	- 44 W/m^2	- 555W/m^2
290K	46 W/m^2	- 375W/m^2
370K	641 W/m^2	815W/m^2

Figure 1: Lunar Radiator Thermal Environment

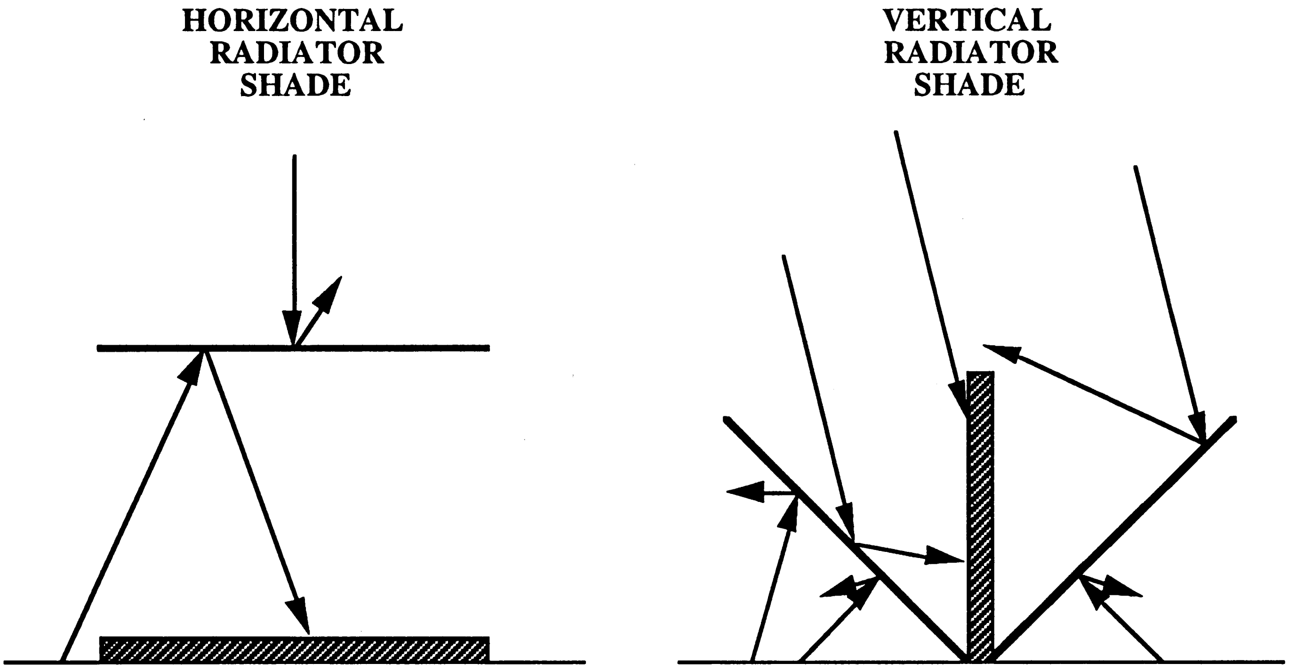


Figure 2: Potential Lunar Radiator Shade Geometries

Analytical studies have shown that heat rejection system mass using a parabolic trough shaped radiator shade may be half that of an unshaded low-absorptivity radiator. Table 1 compares a 2-sided vertical radiator shaded by a thin parabolic shade with unshaded vertical and horizontal radiators having an absorptivity (alpha) of 0.1. With this lower absorptivity than used in Figure 1, the unshaded horizontal radiator can reject heat (from 1 side) at 270K. The unshaded vertical radiator still absorbs heat. Table 1 shows the differences in absorbed heat flux for each case in terms of an effective radiator heat sink temperature. This is a convenient way of characterizing all of the radiator absorbed heat fluxes with a single number. It can be thought of as the effective temperature that the radiator "sees". In Table 1, the effect of the shade on the vertical radiator can be seen in terms of a drastic reduction in the effective sink temperature.

Table 1 compares shaded and unshaded heat rejection system masses for a 50 kW lunar base habitat. Key assumptions are given in the table and other details may be found in reference 1. The total mass of the shaded system is about half the mass of the unshaded system. This analysis shows the attraction of pursuing the development of a parabolic shade for use on the moon.

Table 1: Comparison of Shaded and Unshaded Heat Rejection System Mass

Assumptions	Shaded	Unshaded	Unshaded
Radiator type	vertical 2-sided	horizontal 1-sided	vertical 2-sided
Heat load to reject (kW)	50	50	50
Radiator operating temperature (K)	270	270	270
Radiator mass per unit area (kg/m^2)	9	9	9
Shade mass per radiator area(kg/m^2)	1.7	not applic.	not applic.
Radiator emissivity x fin efficiency	0.81	0.81	0.81
Calculations			
Effective sink temperature (K)	222	228	320
Heat rejection per unit area (W/m^2)	265	120	- 475
Required actual radiator area (m^2)	189	417	
Radiator mass (kg)	1698	3751	
Shade mass (kg)	321		
Total mass (kg)	2019	3751	not applic.

DEVELOPMENT APPROACH AT JSC

As discussed earlier, several factors are important in the development of active thermal control systems for planetary habitats. Low system mass and power usage as well as high reliability are key requirements. Ease of packaging, deployment and long term performance on the planet surface are also important. Radiator shades are passive, requiring no power other than for deployment. Their reliability should also be high once deployed. The shades, however, cover a large area, which may translate into a large mass for some designs. Good predictions of performance (both initial and end-of-life) are essential for sizing the shades and radiators. Therefore, the key issues to be investigated in the development of a lunar radiator shading system are: system mass, packaging, deployment and long term performance considering the potential impact of lunar dust.

A parabolic radiator shade concept was considered in a 1989 NASA planetary exploration study [5]. Although the shade traded well with a heat pump on a mass basis, the heat pump was preferred due to the uncertainties associated with the immaturity of the shade concept. In 1991, a concept was presented for a light-weight, deployable, flexible, hanging parabolic radiator shade [4] (see Figure 3). Numerical studies suggested that a parabolic shade with realistic optical properties could reduce the effective sink temperature of a vertical radiator at the equator from 322K to 206K at lunar noon [4]. Subsequently, several different radiator shade geometries were considered and parametric studies were performed. These results were presented in 1993 along with an updated trade study of the favored parabolic geometry versus a heat pump [1]. The shade system had a slightly lower mass than the heat pump system with the mass of a combination heat pump/ shade system in between. Later that year, a proof-of-concept test of a rigid parabolic shade was conducted in a thermal vacuum chamber at JSC. A heat sink temperature reduction of 70K was demonstrated using a small scale rigid parabolic shade test article. Results of this test are presented in more detail below.

Additional numerical studies have also been conducted to address issues such as optimum parabola height, interaction of multiple parabolas and the effect of different shade optical properties. A summary of these studies is presented below and the details are reported in reference 6.

In addition to rigid and flexible, hanging parabolic shade designs, an inflatable design is also being considered at JSC [7]. In this design, the parabolic trough would be covered with a transparent cover forming a complete enclosure. A vertical radiator would be supported inside the enclosure. The shade materials would be light-weight and flexible and would be supported by gas pressure. Preliminary feasibility of this concept was proven in the thermal vacuum test mentioned above by placing a thin Teflon® film over the parabolic shade. Numerical studies have also validated

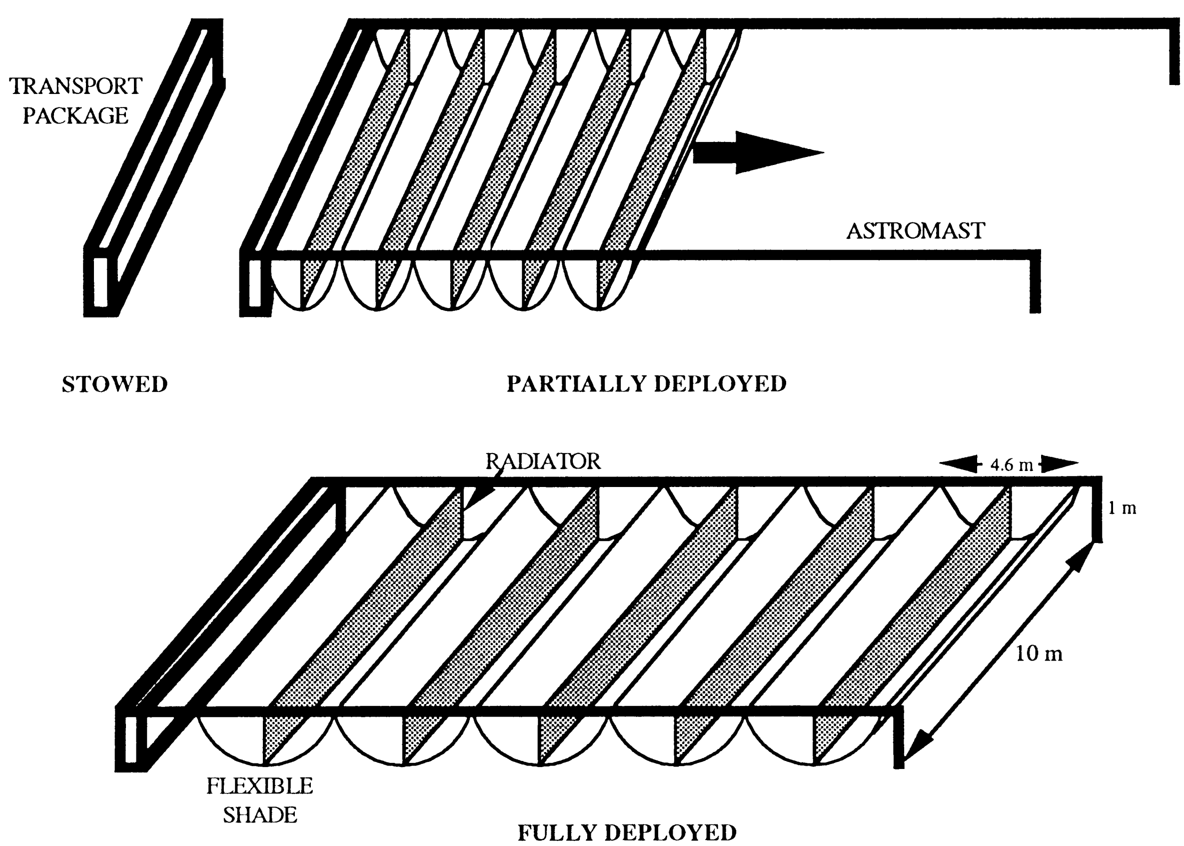


Figure 3: Flexible, Hanging Parabolic Shade Concept

the concept from a radiation standpoint; however, the effect of convection within the parabola must still be addressed. Currently, an inflatable shade test article is under construction which will be filled with a gas and tested in the thermal vacuum chamber.

Lunar dust is an important issue that must be addressed when considering a technology which depends on good optical properties [8]. The Apollo experience showed that dust was ever present and hard to clean off [9]. Numerical studies have shown the importance of maintaining a high specular reflectivity on the shade surface [10]. It may be wise, then, to focus on abatement measures. Reference 11 documents a study of the effect of dust on lunar power systems and concludes by recommending defensive measures. The methods used in reference 11 are currently being extended at JSC to the case of thermal control systems in order to quantify the impact of dust on parabolic shades and other thermal control surfaces.

As stated above, packaging and deployment are also key development issues associated with parabolic radiator shades. Plans call for the construction of a parabolic radiator shade deployment test article in order to study these issues. One concept for the test article is shown in Figure 4.

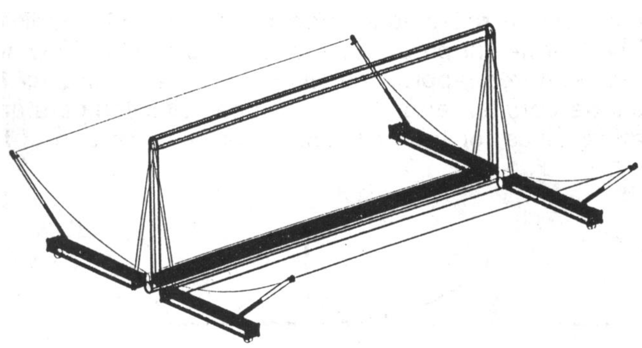


Figure 4: Concept for a Shade Deployment Test Article

A thermal vacuum test of the inflatable and flexible hanging shades described above is planned for 1995. The rigid parabolic shade will also be re-tested. Even better performance than the 1993 test is expected after the thermal control surfaces are upgraded.

Though there are many steps left in the development of a full scale lunar radiator parabolic shading system, work is in progress at JSC on each of the key issues which must be addressed. A great deal of progress has been made in the important areas of numerical simulation and small scale thermal vacuum testing. These two aspects of the development program are discussed in more detail below.

NUMERICAL PREDICTIONS OF PERFORMANCE

MODELING APPROACH - In the study of lunar shade systems, a wide variety of geometries, optical properties, orientations and environmental conditions must be examined. In lieu of an extensive thermal vacuum testing program, numerical models of the various systems can be used to determine the optimum design parameters. For the present study, the Thermal Synthesizer System (TSS) and the Systems Improved Numerical Differencing Analyzer (SINDA) thermal analysis programs were employed and a variety of cases were examined.

The Thermal Synthesizer System is a geometric math modeling program which determines infrared radiation conductors (RADKs) between surface nodes and environmental heat loads. These RADKs can then be used in a thermal resistance network to determine the temperatures and net heat rejection. TSS uses a Monte-Carlo, ray tracing scheme to determine RADKs and can evaluate diffuse, specular, and transparent surfaces. Multiple surface reflections are also included in the overall radiation conductor. To account for wavelength dependent optical properties, the user is required to input infrared (emissivity) and solar (absorptivity) optical properties. The emissivity is used to determine the infrared RADKs, while the absorptivity is used to determine solar heating.

Once the RADKs and solar heating rates are determined, a solution routine which uses the thermal resistance method determines the temperatures of the various shade components and the heat rejection capability of the radiator. For this study, SINDA was chosen to solve the thermal resistance network. This program uses the TSS generated RADKs and heating rates as input to determine the response of the system.

ANALYSIS CONDITIONS - Since dimensionless parameters cannot be used with radiative heat transfer problems, the radiator was given a height of 1.0 m and a length of 50 m. This length was chosen to eliminate any significant end effects. For all cases, the surface temperature of the radiator was held to 273 K (0 °C).

Due to the wide range of possible optical properties for the shade and radiator, a single set of optical properties was selected as a base case. The base case optical properties used in the numerical studies are listed in Table 2. They represent end-of-life conditions but do not include allowance for heavy lunar dust contamination. The properties of Teflon®, including the transmittance (τ) are used for the inflatable shade studies. The values of emissivity (ε) and absorptivity (α) were obtained from various manufacturer data. It should be noted that the solar and infrared specularities (percent of reflections that are specular) of the shade top surface were measured and found to be greater than 99%. Lunar surface properties were obtained from Reference 4.

The thermal environment of the lunar surface also affects the heat rejection performance of the radiator. Since there is no atmosphere, the lunar surface receives the maximum possible solar load and for this study was held to a nominal value of 1370 W/m^2. To account for the orbital inclination of the moon all simulations included a worst case 1.53° sun angle on the vertical radiator.

After the dimensions had been chosen, a study was conducted to determine the appropriate discretization of the radiator and shade. First, simple TSS and SINDA models were developed as outlined in their corresponding user's manuals [12,13], and the thermal response of the shade and radiator was determined over a lunar day. The number of nodes was then doubled and the thermal response of the system was then re-determined. This process of doubling the number of nodes and finding a transient solution was continued until increasing the number of nodes had little effect (<1%) on the results.

Table 2:	Component Optical Properties (End-of-Life Conditions)			
	α	ε	τ_α	τ_ε
Radiator	0.30	0.90	NA	NA
Shade Top	0.14	0.05	NA	NA
Shade Bottom	0.90	0.90	NA	NA
Lunar Surface	0.93	0.93	NA	NA
Teflon®	0.03	0.13	0.92	0.82

Note:
NA Not Applicable
Scattering through the Teflon is not considered

EVALUATION OF SEVERAL SHADE GEOMETRIES - The first step in the development of the lunar base shading system is the selection of a shade geometry that maximizes radiator heat rejection and minimizes mass. Several candidate shade shapes (shown in Figure 5) were considered: a 45° step shade, a 75° V shade, a 45° V shade, and 1.0m and 1.5m focal length parabolic shades of "full" and "half" height.

Models of the various shades geometries were run over half of a lunar day (from dawn to noon) on the equator and predicted sink temperatures are shown in Figure 6. The sink temperature is determined from a heat balance on the radiator surface and is defined as,

$$T_{sink} = \left(T_{rad}^4 - \frac{Q_{rej}}{\varepsilon A \sigma}\right)^{1/4}$$

where Q_{rej} is the heat rejected by the radiator, ε is the emissivity of the radiator, A is the surface area, σ is the Stefan Boltzmann constant, T_{rad} is the radiator surface temperature, and T_{sink} is the sink temperature. The sink temperature can be thought of as the average ambient temperature for radiator heat rejection. It is clear that the heat rejection capability of the radiator is strongly dependent upon the shade's geometric shape. The parabolic shades produce the lowest sink temperatures, since due to their shape, all the incident solar energy on the shade is reflected to a focal point above the radiator. The half height parabolic shades also produce low sink temperatures, approximately 30 K higher than their full shade counterparts. These higher sink temperatures arise, since for the half height shade, a portion of the

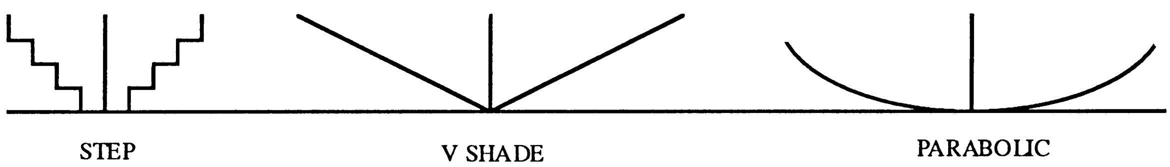


Figure 5: Candidate Shade Geometries.

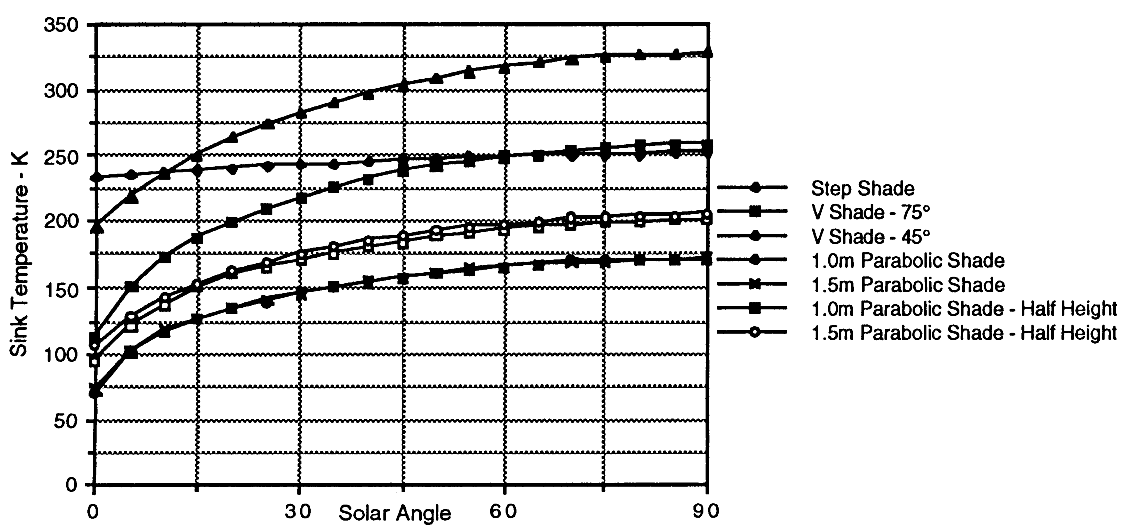


Figure 6: Predicted Sink Temperatures for Various Shade Types (end of life properties, radiator is 273 K, equator)

radiator views the hot lunar surface. The 75° V shade is also capable of producing sink temperatures which could be acceptable for lunar base operations. Here, the maximum sink temperature at noon is 259 K. For this system only a small portion of the solar energy incident on the shade is reflected onto the radiator. On the other hand, the sink temperatures for the 45° V shade are much higher and are the result of most of the solar energy falling on the shade being redirected onto the radiator. The step shade produces sink temperatures below the radiator operating temperature, but the heat rejection capability of the radiator at these sink temperatures is fairly small.

The predictions shown in Figure 6 indicate that, of the shade geometries examined, the parabolic shades produce the greatest enhancement of the radiator's heat rejection. While the heat rejected from a radiator is a good measure of the performance of a shade, the overall mass of the entire heat rejection system must also be examined. Therefore, a simple trade study of the various radiator and shade combinations was conducted. For this study, a lunar base heat load of 25 kW was selected, the sink temperature at solar noon was used, the radiator mass to area ratio was set to 9 kg/m^2 (4.5 kg/m^2 of radiating area), and the shade mass to shade area ratio was set to 0.56 kg/m^2 as in reference 1. The 45° V shape was eliminated from this study since its noon time sink temperature is above the operating temperature of 273 K.

The results of the trade study (shown in Table 3) indicate that thermal systems which employ a parabolic shade weigh substantially less than those which use other shade types. Specifically, the mass of the step and 75° V shade systems are 2.5 to 4 times greater than parabolic shades systems, respectively. The masses of the heat rejection systems which employ parabolic shades are nearly identical. As such, a trade study of optical properties, shade height and materials needs to be conducted.

Once the parabolic shade geometry was selected, several different studies were conducted to optimize the design. The first study examined the optical properties of the shade and radiator and its orientation on the lunar surface so that the heat rejection of the radiator was optimized. The results of this study can be found in Reference 6. The next study optimized the mass of the system by reducing the height of the shade. Another study considered a lightweight inflatable system (7). The most recent numerical study considered the effect of multiple, side-by-side shades on the heat rejection of the radiator.

HEIGHT OPTIMIZATION STUDY - For this study, the height of the radiator was held constant at 1.0 m, while the height of the shade was reduced. The effect of shade height reduction on the net heat rejected by the radiator was determined and the overall system mass was calculated. Figure 7 shows the predicted total radiator heat rejection rates for the two types of parabolic shades at lunar noon as their height was reduced. As the height was reduced from 1.0 m to 0.5 m, the heat rejection capability of the both radiators showed only a small decrease, because the radiator's view factor to the lunar surface only increased slightly. As the shade height was further decreased, a rapid rise in the sink temperature was noted. For these cases, the decrease in the shade height increased the view factor between the radiator and the lunar surface. Since both the radiator and the lunar surface have a high emissivity (~0.9), the amount of absorbed environmental infrared radiation by the radiator was substantial. As a result, the heat rejection was reduced. It is interesting to note that the heat rejection of the radiator first increased slightly when the height of the 1.0 m focal length shade was reduced. Here, as the shade height is decreased, the upper portion of the radiator has a greater view factor to the cold deep space sink and a smaller view factor to the hot shade (~ 425 K), and hence slightly higher overall heat rejection.

Once the numerical models had determined the radiative heat rejection rate, the shade and radiator area required to reject a 25kW lunar base heat load were calculated. Using the previous values for specific masses, each component mass was determined. The total heat rejection system mass for various shade heights is shown in Figure 8. The minimum for both focal length shades is near 0.65 m shade height and represents about a 10% decrease in the overall mass of the system compared to a full 1.0 m tall shade.

Table 3: Mass Comparison Study for Various Shade Types

Shade Type	T_{sink} (K)	Q_{rej} (W/m^2)	Radiator Area (m^2)	Shade Area (m^2)	Radiator Mass (kg)	Shade Mass (kg)	Total Mass (kg)
1.0m Parabolic	170.7	228	109.6	503.1	493.2	282	775.2
1.5m Parabolic	171.1	227	110.1	594.5	495.5	333	828.5
1.0m Parabolic-1/2	200.5	189	132.3	403.5	595.5	226	821.5
1.5m Parabolic-1/2	205.2	181	138.1	502.7	621.5	282	903.5
Step	251.7	66	376.0	752.0	1692.0	421	2113.0
75° V	259.0	46	543.5	2098.0	2446.0	1370	3816.0

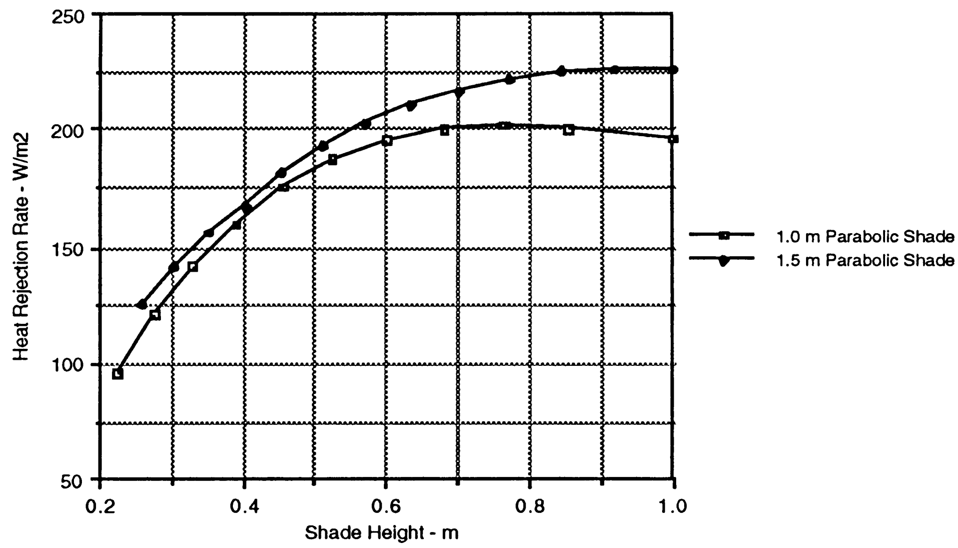


Figure 7: Predicted Radiator Heat Rejection for Two Different Shade Heights (noon, equator)

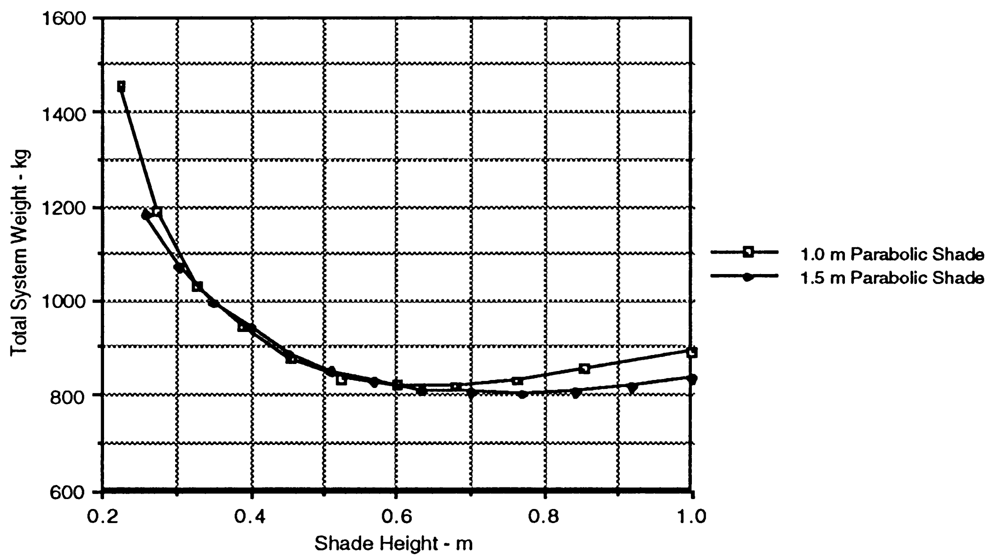


Figure 8: Predicted Heat Rejection System Mass for Different Shade Heights (noon, equator)

INFLATABLE SHADE STUDIES - An alternative approach to reducing the height of the shade is to use lightweight materials. One such system, an inflatable shade concept, is shown in Figure 9. Here, a two-sided radiator is placed within an inflated, thin walled, Teflon® "balloon" (~0.1mm thick). The sun-facing side of the lower surface of the balloon is aluminized to produce a highly reflective (specular) surface. The infrared radiation produced by the lunar surface is blocked by the shade and, since its emissivity is extremely low, the amount of infrared radiation absorbed by the radiator is small. The upper surface is nearly transparent in both the solar and infrared bands so the heat rejection capability of the radiator will only be slightly reduced compared to an open shade. The shape of the upper surface is a mirror image of the lower parabolic surface. This shape was selected after preliminary studies showed that high Teflon® temperatures resulted when a flat or slightly curved surface was used.

Figure 10 shows the predicted radiator sink temperature for an open shade and an inflatable shade over a range of solar angles. For both cases, the focal length of the shade is 1.5 m. As is evident, the heat rejection of the radiator is greater when an open shade is employed. Two factors produce the lower heat rejection for the inflatable shade. First, a portion of the incoming and reflected solar energy is absorbed by the nearly transparent upper surface, which in turn raises the

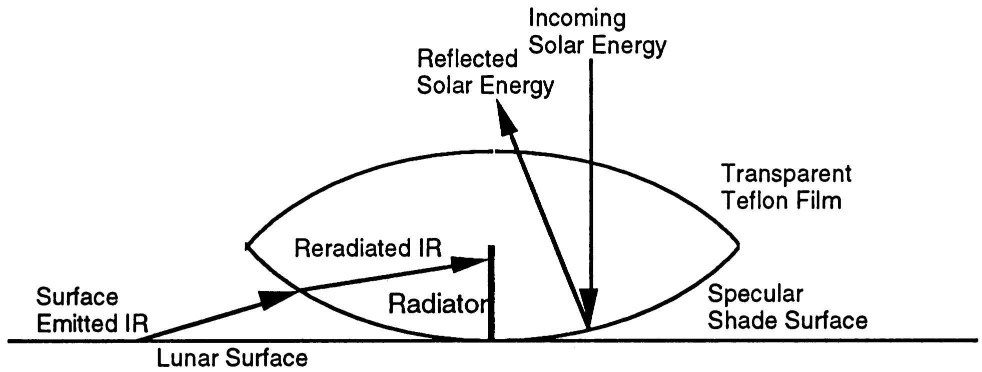


Figure 9: Schematic of the Inflatable Shade Concept (end view)

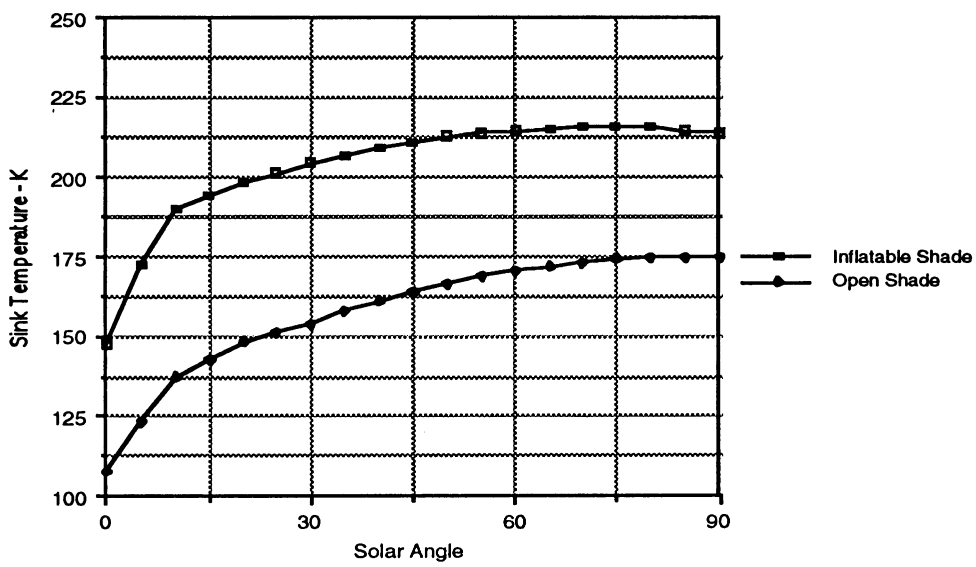


Figure 10: Calculated Radiator Sink Temperatures for Inflatable and Open Parabolic Shades

temperature of the upper surface. Since this surface has a large view factor to the radiator, it imposes an infrared load on the radiator. Second, a portion of the infrared radiation emitted by the radiator is attenuated by the upper surface, again warming this surface, but also reducing the heat rejection capability of the radiator.

Using the data from Figure 10, the overall mass of the two systems was determined. For both types of shades, the lunar base heat load was set to 25 kW, and the previously used values of specific mass were employed. The Teflon shade mass-to-area ratio from manufacturer data was 0.08 kg/m^2. Using these values, the component masses were determined, and are shown in Table 4. These results show that a larger and heavier radiator is needed for the inflatable system, while a heavier shade is needed for the open shade system. Summing the component masses shows that the inflatable shade concept has a slightly lower overall mass than the open shade concept.

Table 4: Comparison of Open and Inflatable Shades (T_{rad} = 273 K)

Shade Type	T_{sink} (K)	Q_{rej} (W/m^2)	Radiator Area (m^2)	Radiator Mass (kg)	Shade Area (m^2)	Shade Mass (kg)	Total Mass (kg)
Open	183.5	226.2	110.5	497.3	596.7	334.2	831.5
Inflatable	213.8	177.0	140.9	634.0	1521.7	121.7	755.7

MULTIPLE SHADE STUDIES - Figure 11 shows the predicted sink temperatures for a single open rigid shade, a single inflatable shade and their corresponding multiple side-by-side shade systems over half a lunar day (dawn to noon). For the multiple shade systems, values for the center and one edge are shown, since the shade is symmetric about the center and the predictions for the two edge radiators are identical. For the rigid shades, there is only a slight difference in radiator heat rejection (approximately 10%) between the single and multiple shade systems. This difference occurs in the multiple shade systems because the back sides of the inner shades do not view the deep space cold sink and become slightly hotter than those in a single shade system. As a result, these warmer shades emit more infrared radiation which is absorbed by the radiator, thereby reducing its performance. The center radiator does not reject as much heat as the two edges radiators because it views the hotter inner shade.

The heat rejection performance of the radiator is more severely degraded when multiple <u>inflatable</u> shades are examined. Again, the inner shades are hotter and the performance of the radiators is reduced. The hotter inner shades heat the upper Teflon® surface which in turn produces increased amounts of infrared radiation which are absorbed by the radiator. Since the Teflon® surfaces also have a reduced view factor to deep space in the multiple inflatable shade system, they will be hotter and emit more infrared radiation than their single shade counterparts. As a result of a combination of factors, the radiators receive significantly more infrared radiation than in a single shade system, which dramatically reduces the performance of the radiator.

Overall system mass was also examined for the single and multiple shade systems. For each, the previously defined values of heat load, specific masses and radiator set point temperature were used. Table 5 shows that there is little difference in overall system mass between single and multiple rigid shade systems (≈ 4%); however, there is a substantial increase in system mass between single and multiple inflatable shade systems. The increase occurs because the heat rejection capability of the radiators is substantially reduced in a multiple inflatable system and more radiating area is required to achieve the necessary heat rejection.

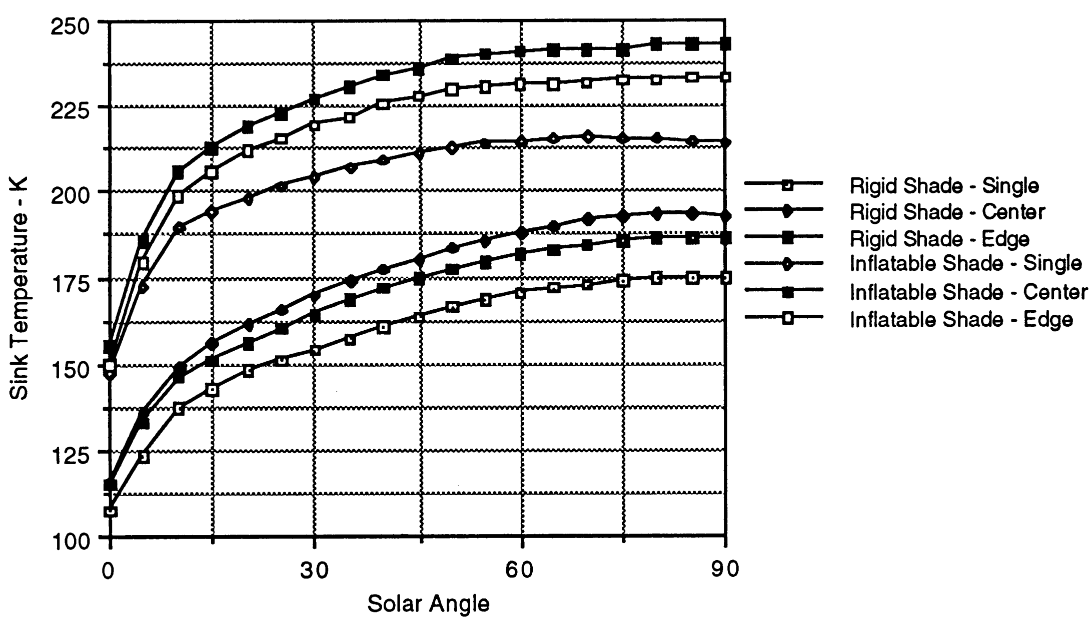


Figure 11: Calculated Sink Temperatures for Multiple Shade Systems

Table 5: Mass Comparison Between Multiple Rigid and Inflatable Shades

Shade Type	T_{sink} (K)	Q_{rej} (W/m^2)	Radiator Area (m^2)	Radiator Mass (kg)	Shade Area (m^2)	Shade Mass (kg)	Total Mass (kg)
Rigid Single	183.5	226.2	110.5	497.3	596.7	334.2	831.5
Rigid Multi	189.5	218.3	114.6	515.8	618.9	346.6	862.4
Inflatable Single	213.8	177.0	140.9	634.0	1521.7	121.7	755.7
Inflatable Multi	236.9	123.4	202.6	911.7	2188.0	175.1	1086.8

While the numerical studies have provided a wealth of data on the performance of lunar radiator shades and the factors with influence their operation, experimental testing is also required to prove the conceptual designs. As a result of these favorable numerical predictions, a thermal vacuum test of a rigid parabolic shade test article was undertaken.

EXPERIMENTAL STUDIES

In November 1993, a small scale rigid "parabolic" shade was tested in a thermal vacuum chamber at JSC [14]. An electrically heated vertical radiator with dimensions 50 cm x 5 cm was used with and without a 2.5 cm tall (ie. "half high") parabolic radiator shade as seen in Figure 12. A solar simulation lamp provided a heat flux on the shade and on a lunar surface simulator.

Two objectives of the test were to study the influence of the rigid shade on the radiator heat rejection capability and to demonstrate the initial feasibility of the inflatable shade concept. To examine the inflatable shade concept, the radiator and shade were covered, but not enclosed, by a transparent Teflon® cover as shown in Figure 13. Therefore, in the test, no convection was present as in the actual inflatable shade concept. However, the presence of the Teflon® cover provided a similar radiative environment and gave some insight into how the radiator's heat rejection performance would be affected by the transparent Teflon cover.

TEST DESCRIPTION - The radiator was constructed out of a silicone rubber heater sandwiched between two 5.0 x 50.0 cm aluminum plates coated with white Aeroglaze® paint. The post-test optical properties of the paint used on the radiator were α=0.37 and ε=0.89.

The rigid shade was made of an aluminum sheet rolled to match a circular curve of radius 16.2 cm. This produced a nearly parabolic shape. Aluminized Kapton®, with thermal properties of α=0.1, ε=0.06 and specularity greater than 99%, covered the concave portion of the shade. The lunar surface simulator was a 0.635 cm thick aluminum disk with a 1 meter diameter. The lunar surface simulator was coated with black Aeroglaze® paint with an α=0.96 and ε=0.91 to simulate the lunar surface properties. Multi-layer insulation was attached with Velcro® to the rear of the lunar surface to reduce back side thermal radiation thereby creating temperatures similar to those found on the lunar surface. A summary of optical properties is shown in Table 6.

The radiator was placed in the middle of the concave portion of the shade. Then, the shade and radiator were mounted in the center of the lunar surface simulator as shown in Figure 14. When the shade was not used, the radiator was mounted directly to the lunar surface simulator. The inflatable shade was simulated by attaching a clear Teflon® sheet to both sides of the shade as shown in Figure 13.

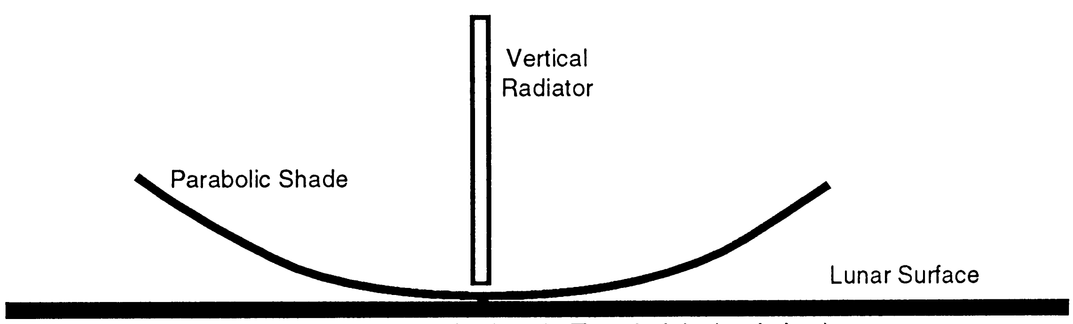


Figure 12: Parabolic Shade Test Article (end view)

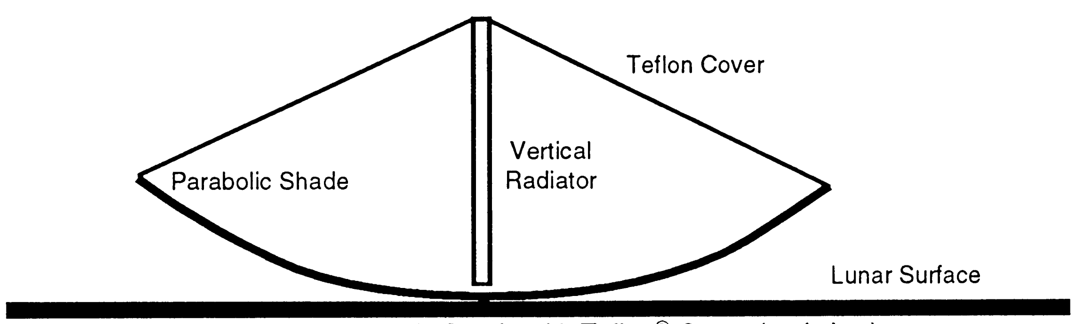


Figure 13: Parabolic Shade with Teflon® Cover (end view)

Table 6: Radiator Shade Test Article Optical Properties

Surface	Emissivity	Absorptivity
Lunar Surface	0.91	0.96
Lunar Shade	0.06	0.1
Radiator	0.89	0.37
Lunar Shade Rear	0.06	0.38

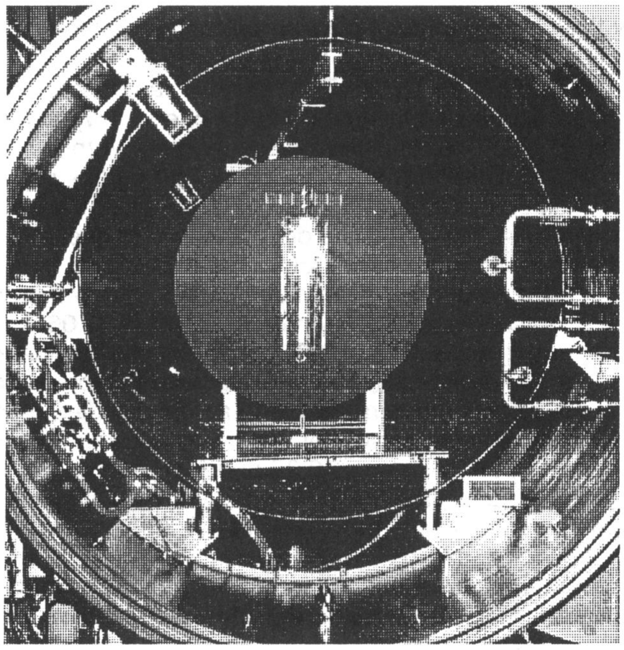


Figure 14: Shade Test Article in Vacuum Chamber

The lunar surface simulator, with radiator alone or with radiator and shade, was placed in a thermal vacuum chamber to simulate the lunar environment. The liquid nitrogen filled cold walls held the environment at 108K while vacuum pumps maintained the chamber pressure at approximately 1.3×10^{-3} N/m^2 (10^{-5} torr). The vacuum chamber solar lamp (shown in Figure 15 with test article) intensity averaged 987W/m^2 or 0.72 suns over the shade area and 1041W/m^2 or 0.76 suns average over the lunar surface. Full sun was not tested due to temperature limits on the test article.

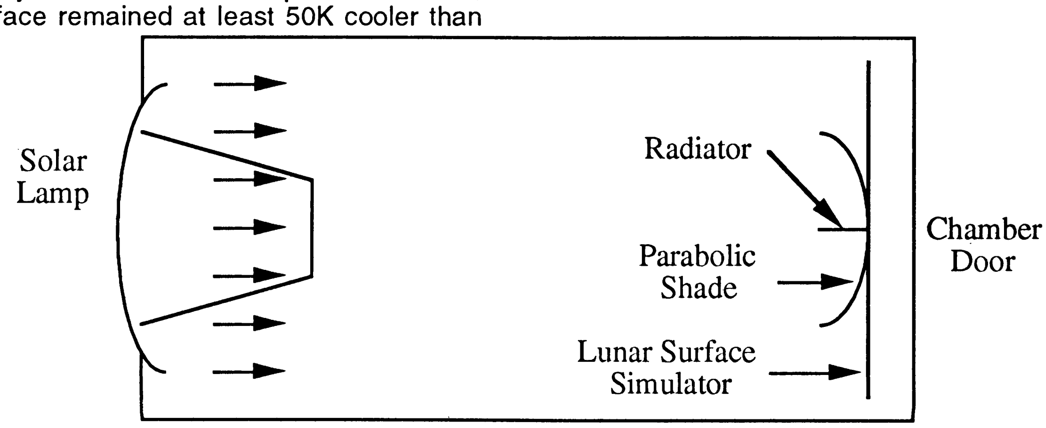
TEST RESULTS - The parabolic shade reduced the radiator surface temperature at all heater powers as expected. The radiator surface temperature was reduced by approximately 70K at the 0 W power setting as shown in Figure 16. At zero power, the radiator assumes the temperature of its environment at steady state. Therefore, the radiator temperature is equal to the effective sink temperature for the zero power case. Both the shaded and unshaded radiator surface temperature trends were nearly the same. With the parabolic shade, the radiator surface remained at least 50K cooler than without the parabolic shade. The radiator with the parabolic shade demonstrated positive heat rejection in a temperature range that is comfortable for human existence.

The addition of the Teflon cover raised the radiator surface temperature by 30K at the 0W power setting as shown in Figure 17. At high levels of heat rejection, the radiator surface temperature with the Teflon cover was as much as 40K higher than without. The Teflon cover negated some of the effect that the parabolic shade had on the radiator surface temperature. However, the sink temperature, approximately 270K, was still 40K lower than without the shade at low power levels (Figure 16).

TEST SUMMARY AND CONCLUSIONS - Optical properties of the shade and radiator measured post-test were not as good as expected due to handling prior to and during the test. Attempts to clean finger prints from the shade resulted in scratching of the surface. Nevertheless, an environment temperature reduction of 70K was demonstrated for a rigid parabolic shade test article and a 40K temperature reduction was demonstrated for a simulated inflatable radiator shade. Better materials and further care in handing can reasonably be expected to result in experimental sink temperature reductions of over 100K.

CONCLUSION

Engineering trade studies have shown that parabolic radiator shades have the potential to reduce heat rejection system mass by 50% for a lunar base. Numerical studies have shown that a parabolic trough shade has the potential to reduce the environmental heat sink temperature by over 100K. A proof-of-concept test has been carried out at JSC which achieved a sink temperature reduction of 70K. Many issues, however, must be addressed to develop a viable lunar radiator parabolic shading system. Development activities at JSC are focused on these issues which include system mass, packaging, deployment and long term performance considering the potential impact of lunar dust. Progress has been made in each of these areas and all indications are that development will continue to fruition.



Thermal Vacuum Chamber

(top view)

Figure 15: Thermal Vacuum Chamber Layout

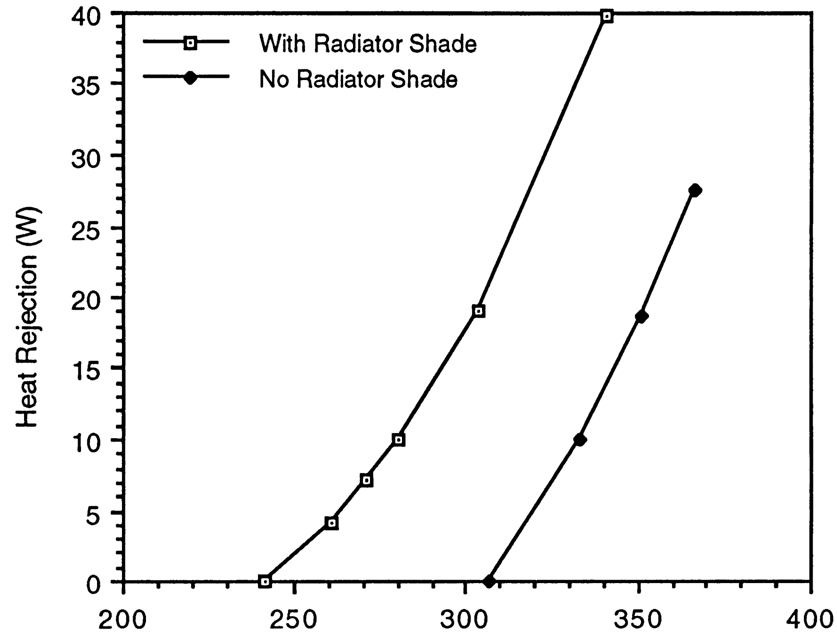


Figure 16: Radiator Temperatures with and without Parabolic Shade in Test

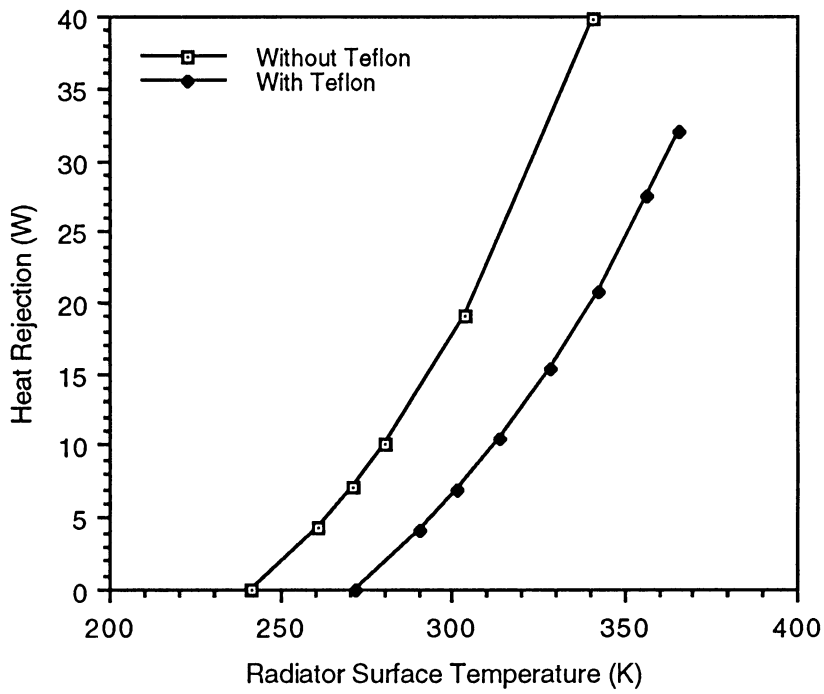


Figure 17: Inflatable Shade Test Results

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