

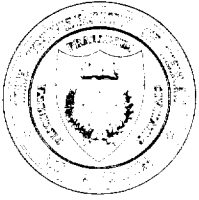
# **Preliminary Design of a Radiator Shading Device for a Lunar Outpost**

**Submitted to:**  
**Michael K. Ewert**  
**Thermal Control System Analyst**  
**Lyndon B. Johnson Space Center**  
**NATIONAL AERONAUTICS AND SPACE ADMINISTRATION**  
**Houston, Texas**

**Prepared by:**  
**Carlos Barron**  
**Norma I. Castro**  
**Brian Phillips (Team Leader)**

**Mechanical Engineering Design Projects Program**  
**THE UNIVERSITY OF TEXAS AT AUSTIN**

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MECHANICAL ENGINEERING DESIGN PROJECTS PROGRAM

THE UNIVERSITY OF TEXAS AT AUSTIN

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ETC 4.102 • Austin, Texas 78712-1063 • (512) 471-3900 • FAX (512) 471-7682

November 20, 1991

Mr. Michael K. Ewert  
Crew and Thermal Systems Division  
Lyndon B. Johnson Space Center, EC7  
Houston, TX 77058


Dear. Mr. Ewert:

Enclosed is the design report entitled Preliminary Design of a Radiator Shading Device for a Lunar Outpost. The report discusses the shading devices developed by the design team. The shading devices also include alternates for supporting and deploying and retracting the shading systems. A shading device, support structure, and deploy and retract alternates were combined and a preliminary design was developed. In addition, a thermal performance analysis of the thermal control system was conducted for the shading devices. The preliminary design includes thermal performance and mechanical stress analyses.

It has been a pleasure working with you in this design project and we look forward to seeing you at our oral presentation. The oral presentation is scheduled for Tuesday, December 3, 1991, at 1 p.m. in room 4.110 of the Engineering Teaching Center at the University of Texas at Austin. A catered luncheon starting at noon will precede the presentation.

Thank you for your assistance throughout the semester.

Sincerely,

  
\_\_\_\_\_  
Carlos Barron

  
\_\_\_\_\_  
Norma I. Castro

\_\_\_\_\_  
Brian Phillips

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## I. INTRODUCTION

The National Aeronautics and Space Administration (NASA) sponsored a project at The University of Texas at Austin to design a shading device for a radiator. The radiator is part of a thermal control system for a permanent outpost on the moon. This section presents the purpose of the project, design criteria, results required of the project, and the design methodology.

### 1.1 Sponsor Background

NASA, established by the United States government in 1958, is responsible for aeronautical and aerospace research and exploration [1]. The design project sponsor, the Lyndon B. Johnson Space Center, is one of ten NASA facilities. Several responsibilities of the Johnson Space Center are

- the selection and training of astronauts
- the design, development, and testing of spacecraft and associated systems for manned space flights
- thermal and fluid systems analysis and testing
- selection and testing of materials and structures
- planning and conducting of manned space flight missions

Currently, NASA is planning to establish manned bases on the moon and Mars. In addition, NASA is involved in the design, development, and testing of Space Station Freedom, which is to be placed in earth orbit.

## **1.2 Project Background**

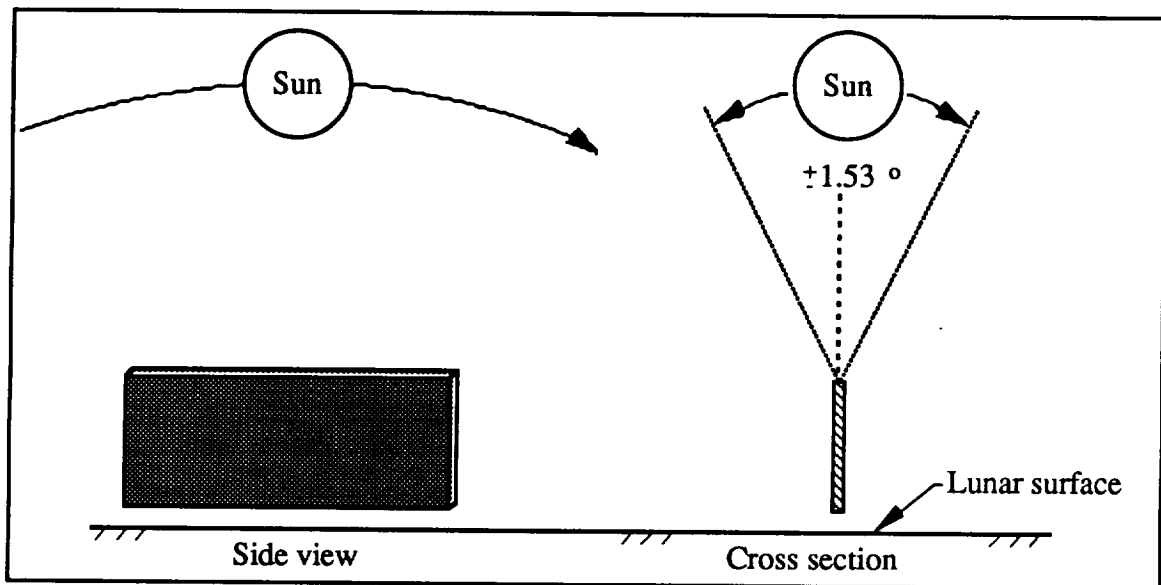
The extreme temperatures on the moon surface (102 K to 384 K) and the length of the lunar day/night cycle (29.5 earth days) make it necessary for a permanent habitat to have a thermal control system [2]. A thermal control system controls the heat transfer processes occurring between the habitat and the surroundings, making it possible to heat or cool the habitat. An example of a thermal control system is a home air conditioning system.

Due to the absence of a lunar atmosphere, the only ways to transfer heat are through radiation and/or conduction. Conduction can be accomplished through the moon's top surface material (also called regolith). The lunar regolith's thermal conductivity (0.0021 W/m K) is less than the thermal conductivity of cotton (0.06 W/m K), which is a good thermal insulator [3]. As a result, a very large lunar surface area is necessary to conduct heat through regolith. For example, to conduct 1 Watt through a 1 meter thick sample of lunar regolith that is maintained at a 1°C temperature differential, an area of 476 m<sup>2</sup> is needed (see Appendix A).

A radiator can be used to reject heat to the lunar environment. The radiator carries a working fluid that absorbs waste heat produced in the habitat. As the fluid passes through the radiators, it radiates heat to the environment.

The habitat assumed for this project will be the lunar equator. In this case, if a

vertical radiator is used, it will be aligned with the line of the equator, along the sun's path (see Figure 1). As a result, the radiator area exposed to the incident solar radiation will be negligible. The area exposed to the solar radiation will vary slightly because the sun's path varies with an angle of 1.53 degrees from the vertical.



**Figure 1. Sun's path relative to a vertical radiator**

A drawback of using a radiator at the lunar equator is that the radiator absorbs more heat than it rejects during the lunar midday, which is roughly two earth days long. The radiators can be oriented in a vertical or horizontal position (see Figure 2). The heat absorbed by a vertical radiator is due to *albedo*<sup>\*</sup>, surface infrared radiation, and direct solar radiation incident on the radiator (see Figure 3). The heat absorbed by a horizontal radiator results from direct solar radiation. During midday, the *effective heat sink temperature* is greater than the operating temperature of the radiator [4]. As a result, there is a net heat transfer into the radiator.

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<sup>\*</sup> *All italicized terms are defined in the Glossary*

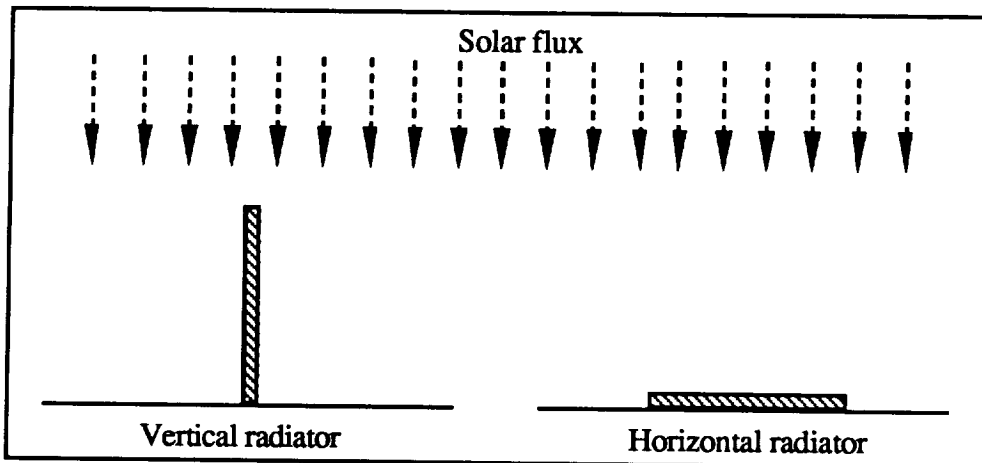


Figure 2. Radiators oriented in the vertical and horizontal positions [2]

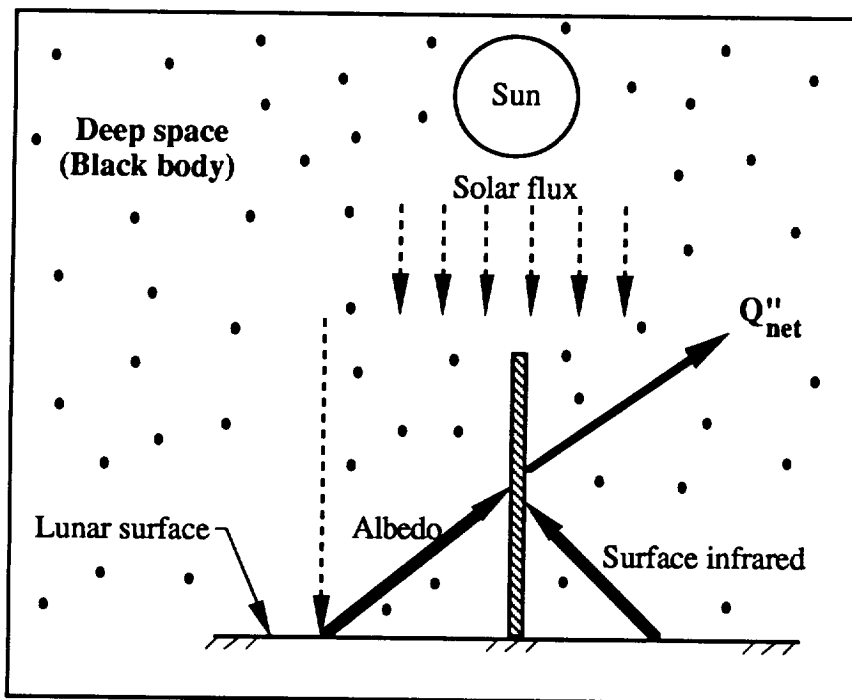


Figure 3. Radiator heat transfer processes [2]

Rejecting heat during the lunar midday can be accomplished by raising the radiator temperature or by decreasing the radiation incident on the radiator. The incident radiation can be decreased by using a shading device. NASA is considering the use of a

parabolic shading device (see Figure 4). The parabolic shade reduces the radiation incident on the radiator by blocking planetary infrared radiation. Solar radiation is reflected off the inner surface of the parabola to a focal point above the radiator. Engineers at NASA found that the effective heat sink temperature is reduced below the temperature of the radiator, thus allowing a net heat rejection from the radiator. An advantage of using a shading device is that it does not require power to operate. Raising the radiator temperature requires the use of a powered device, such as a heat pump.

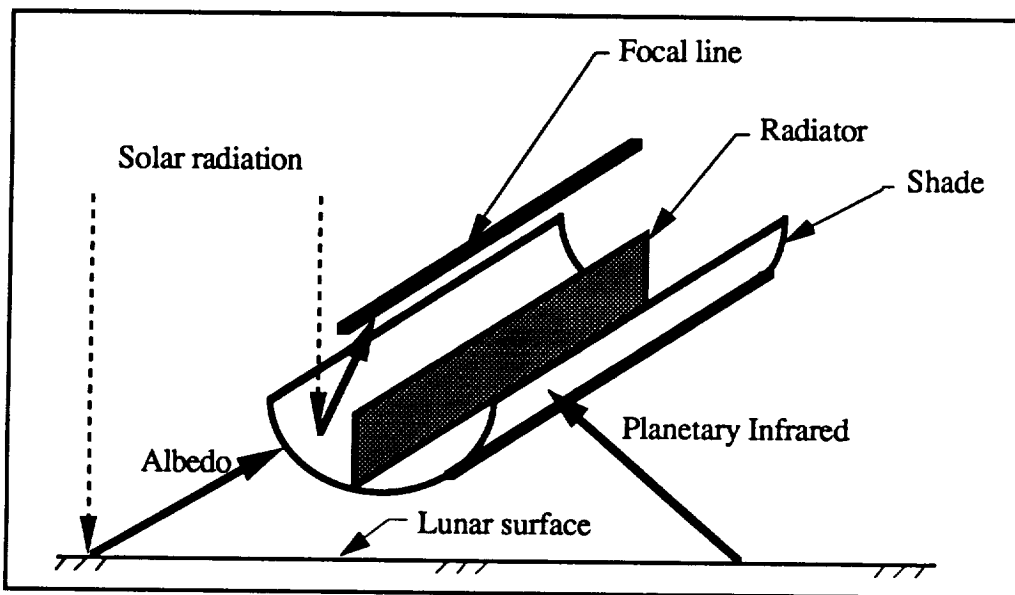


Figure 4. Parabolic shading device [4]

### 1.3 Purpose of the Project

The purpose of this project was to develop several alternates of a shading device. The alternates were evaluated and the alternate receiving the highest rating was developed into a preliminary design. The preliminary design included means of attaching

the radiator to the shading device, a support structure for the shade and radiator, and means of deploying the radiator and support structure from the lunar transport.

#### **1.4 Design Criteria**

Shading devices were developed for a thermal control system capable of rejecting 10 kW and 25 kW of waste heat. The shading device and radiator (from now on referred to as shading system) for the 10 kW thermal control system must be automatically deployable. The deploy mechanism ( support structure and device used to place the shading system in operating position) must perform its function for 200 deploy/retract cycles. Due to limited power supply on the moon, the power to deploy the shading system should be minimal. The 25 kW thermal control system is to be used for the permanent habitat. The shading system can be automatically deployable or easily assembled by two crewmen and must have a life of 20 years. Because of limited cargo space, the volume occupied by the shading system and deploying mechanism must be minimal. Because transportation costs to the moon are high, the mass of the shading system and deploy mechanism must be minimized. Other design requirements are presented in Appendix B

Other aspects considered in designing the shading system are the moon's gravity (1/6 of earth's gravity) and near perfect vacuum. It is assumed that the shading system will be deployed on a smooth surface. Several thermal and material parameters were provided by the project sponsor for the purpose of comparing the performance of the shading systems on the same basis. Other design parameters are presented in Appendix C.

## **1.5 Required Results**

A preliminary design and analysis of the chosen alternate is provided. The preliminary design includes preliminary drawings, mass breakdown, power requirement estimates, stowed and deployed volumes, and results of analyses. Preliminary analyses include mechanical stresses, and thermal performance of the shading system. In addition, the design team provided recommendations for dust removal on the shading system.

## **1.6 Design Methodology**

The design team's approach to arrive at different design solutions is based on Pahl and Beitz's design methodology [5]. One of the objectives of the project was to design a shade for a radiator. Subfunctions considered in meeting the goal are to reduce the radiation incident on the radiator, support the shading system, deploy and retract the shading system, and control lunar dust accumulation. Several alternates were developed for each subfunction and combined to fulfill the project goal.

First, the team decided to develop ideas on how to reduce the radiation incident on the radiator. Once ideas were obtained, alternates for reducing the radiation incident on the radiator were developed. At the same time, a literature and patent search was conducted to aid in the development of solutions. Research was done on methods of changing material optical properties, methods of influencing the effects of solar and planetary radiation, methods of increasing radiator thermal performance, studies done on space thermal systems, lunar environment, dust accumulation, and materials. This process resulted in several solutions for reducing the radiation incident on the radiator. The same

process was repeated for the remaining subfunctions. Combination of the subfunction alternates resulted in different solutions for shading systems.

By means of a decision matrix, ratings were assigned to each concept according to how well the concepts fulfilled the design considerations. Ratings were assigned to each alternate according to how well the alternates fulfilled the design considerations. The design considerations used were low mass, low volume, thermal performance, low power consumption, safety, reliability, ease of assembly, and ease of maintenance. The alternate receiving the highest overall rating was selected for preliminary design development. The preliminary design of the alternate having the highest rating includes preliminary drawings, mechanical and thermal stress analysis, thermal performance analysis, mass calculations, volume calculations, and power consumption estimates.

This report presents a discussion of the alternates developed by the design team for a shading device, support structure, and deploy mechanism. The report discusses the design solution and preliminary design. Finally, the report presents the conclusion and recommendations for future work.



## **II. ALTERNATE DESIGNS**

This section discusses the alternates developed by the design team for the following subfunctions:

- reducing the radiation incident on the radiator
- supporting and deploying the shading system

From the number of alternate designs that were developed for each subfunction, the alternate having the highest rating is discussed. This section begins with background information which is provided for the purpose of helping the reader understand the alternates developed. The discussion of the different alternates for reducing the radiation incident on the radiator follows the background information. The alternates for supporting and deploying and retracting the system are then discussed. Finally, this section makes recommendations on ways to prevent the accumulation of dust on the shade surfaces.

### **2.1 Background**

The primary goal of the design team was to develop several shades that will reduce the planetary infrared radiation (IR), albedo, and/or solar radiation incident on the radiator. This section identifies which type of radiation has the greatest effect on the effective heat sink temperature. Also, the surface properties that the shading device surface can have to reduce the incident radiation are discussed.

**2.1.1 Albedo, Solar, and Planetary IR.** Reducing the radiation incident on the radiator can be explained by the heat transfer processes occurring between the radiator and the environment (see Appendix D). The effective heat sink temperature ( $T_{\text{sink}}$ ) is a term that accounts for the components of the absorbed radiation (direct solar flux, albedo, and planetary infrared) in simplified form. The basic task of the shading device is to reduce  $T_{\text{sink}}$  by reducing the planetary infrared radiation, reducing the direct solar radiation and albedo, or reducing a combination of all the components incident on the radiator. For a vertical radiator, it will be necessary to reduce the planetary infrared by more than 58%. Reducing only the albedo and direct solar radiation will not result in a net radiation transfer out of the radiator. If the direct solar and albedo radiation incident on the radiator is eliminated, then the planetary infrared radiation will have to be reduced by more than 54%. For a horizontal radiator, the direct solar radiation must be reduced by more than 23% for a net transfer out of the radiator. Since the planetary infrared radiation has the greatest effect on  $T_{\text{sink}}$ , the shading device should minimize the planetary infrared radiation incident on the radiator.

**2.1.2 Reflectivity, Absorptivity, and Transmissivity.** The inner and outer surface properties of a shade, which can be different, are described by its ability to reflect, absorb, and transmit radiation. These properties will be used to reduce the heat absorbed by the radiator. Radiation can be absorbed, selectively transmitted, or reflected by the shade surface. Equation 2.1 shows how these properties are related.

$$\rho + \alpha + \tau = 1 \quad (2.1)$$

where  $\rho$  is the reflectivity,  $\alpha$  is the absorptivity, and  $\tau$  is the transmissivity. Equation 2.1 assumes that the properties are averaged over the entire spectrum. The reflectivity, absorptivity and transmissivity can be varied by applying a coating to the surface. The

material used determines which of these characteristics is dominant. A wide variety of material surfaces can be polished and coated to reflect nearly all of the incident radiation [6]. The coating is a thin layer of metal such as aluminum, silver, or gold. The outer surface of the radiator should be highly reflective to planetary IR to prevent heat absorption.

A characteristic of most polished surfaces is that they are specular. The angle of reflection for radiation reflected off a specular surface is equal to the incident angle. It is an advantage to have a specular surface instead of a diffuse surface because a diffuse surface will reflect radiation in all directions (see Figure 5). By using a specular surface, it will be possible to redirect radiation away from the radiator and predict the resulting path of the radiation.

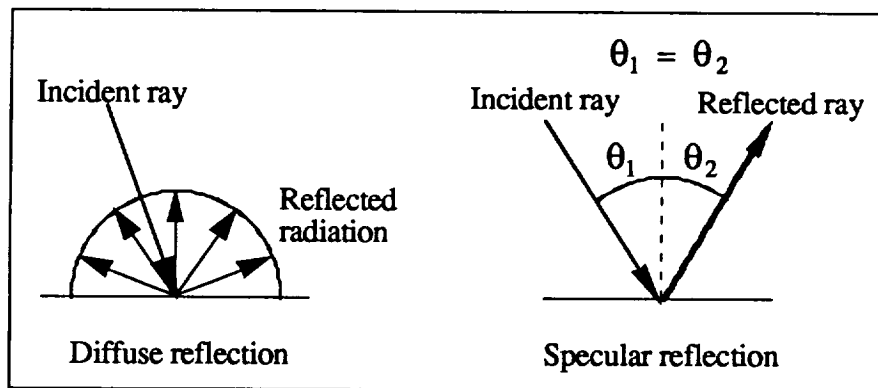


Figure 5. Modes of reflection [7]

Filtering of radiation is the selective transmission of certain radiation wavelengths. The wavelengths that are not transmitted are either reflected or absorbed. Filters are classified according to their range of transmission. Short-pass filters allow transmission of everything below a given wavelength; long-pass filters allow transmission of everything above a given wavelength; band-pass filters allow transmission in a wavelength range; and rejection filters reject radiation in a given wavelength range [8].

A shade surface cannot utilize a filter to prevent transmission of albedo, infrared and/or solar radiation into the radiator while allowing radiation from the radiator to be transmitted away from the radiator. Heat transfer by radiation results from matter being at a finite temperature. The range of wavelengths that are emitted is temperature dependent. For a blackbody (ideal surface), which emits and absorbs more radiation than any other surface, the intensity of radiation at smaller wavelengths increases with increasing temperature. The temperature of the radiator (270 K) and the lunar surface (384 K) do not differ enough to make much of a difference in their range of wavelengths. The sun, which is assumed to be a blackbody at 5800 K, emits a spectrum of radiation that encompasses the spectrum of radiation of the radiator and the lunar surface. Because the spectra of radiation overlap, it will not be possible to prevent transmission of albedo, solar, and/or planetary radiation to the radiator while allowing radiator emission to pass through the filter. Therefore, the only way to reduce the infrared and albedo radiation absorbed by the radiator is to make the surfaces of the shade highly reflective.

The outer surface of the shade should have a low absorptivity in the planetary IR spectrum. For a given surface emissivity, a decrease in absorptivity decreases the amount of heat that is emitted to the radiator. The inner surface will have a low emissivity and the absorptivity depends on the shading device used. These characteristics will reduce the amount of solar radiation incident on the radiator while minimizing the radiation emitted from the shade. For the parabolic reflector the inner surface is highly reflective and the radiation is reflected to a focal point above the radiator. This thermal energy can be converted to electricity or some other form of energy.

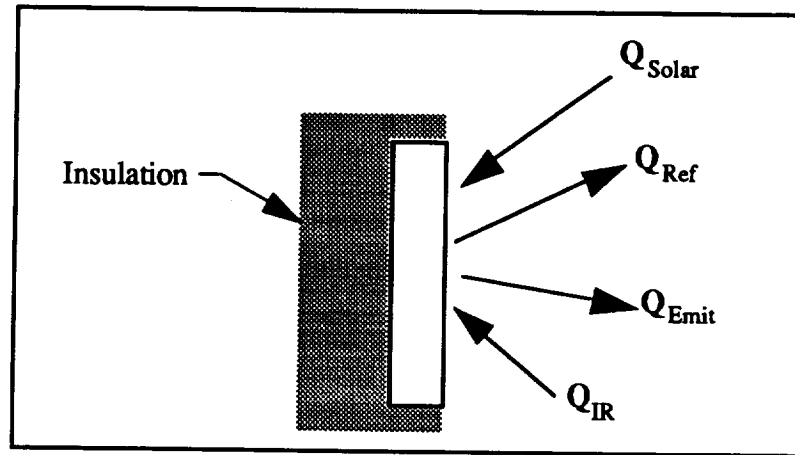
Using equation 2.1, the reflectivity of the outer surface can be maximized by making the surface opaque ( $\tau = 0$ ) and minimizing the absorptivity. For the inner surface, the appropriate reflectivity and absorptivity can be determined by performing a thermal

analysis.

**2.1.3 Serrated Surfaces.** To further reduce the radiation reflected to the radiator the shade surfaces can be serrated. Serrations are grooves of a specified angle or radius of curvature which reflect radiation in a different direction. Thermal analysis were made assuming the surfaces were not serrated. Several of the alternates incorporate serrated surfaces.

**2.1.4 Thermal Performance Using Shading Devices.** The thermal performance, using different shades, can be accomplished by performing an energy balance on a vertical radiator (see Figure 5). Doing an energy balance results in equation (2). Substituting  $T_{\text{sink}}$  into equation (3) gives the area necessary to reject a quantity of heat. From equation (3), it can be seen that reducing  $T_{\text{sink}}$  reduces the radiator area required to reject a fixed quantity of heat, and hence reduces the mass of the system. An estimated effective heat sink temperature and radiator area for each alternate is presented at the end of the descriptions to give a general idea of the relative thermal performance of each alternate (see Table 1). The calculations are made on the assumption that the system rejects 25 kW of waste heat produced in the habitat. The system is designed for the worst case, which is rejection of heat at the lunar midday. A drawback of designing the shading system for the worst case is that the thermal control system will be oversized for operation during the lunar night. An oversized thermal control system will be capable of rejecting more than the 10 kW or 25 kW of waste heat, which will cause the habitat to become too cold for the astronauts. To control the amount of heat being rejected at night, the flow rate of the heat transfer fluid can be reduced or some of the radiators can be bypassed. The project does not propose how to implement these solutions. The design team did not consider the

performance of the systems when arranged side by side, end to end, or in an array. For purposes of illustration and simplicity, the calculations represent one radiator/shade system.



**Figure 6. Heat Transfer Processes**

$$T_{sink} = [\sigma^{-1}((\alpha/\epsilon)q_{sol} + q_{IR})]^{1/4} \quad (2.2)$$

$$A = Q/\eta\epsilon\sigma(T_r^4 - T_{sink}^4) \quad (2.3)$$

Where,

$\sigma$  = Stefan-Boltzmann constant ( $5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$ )

$\alpha$  = Absorptivity of the surface

$\epsilon$  = emissivity of the surface

$q_{sol}$  = Solar radiation heat flux (approx.  $1371 \text{ W m}^{-2}$ )

$q_{IR}$  = Infrared radiation flux

$\eta$  = Efficiency of the radiating surface

$A$  = Area of radiating surface

$T_r$  = Temperature of the radiating surface

$Q$  = Quantity of heat to be rejected

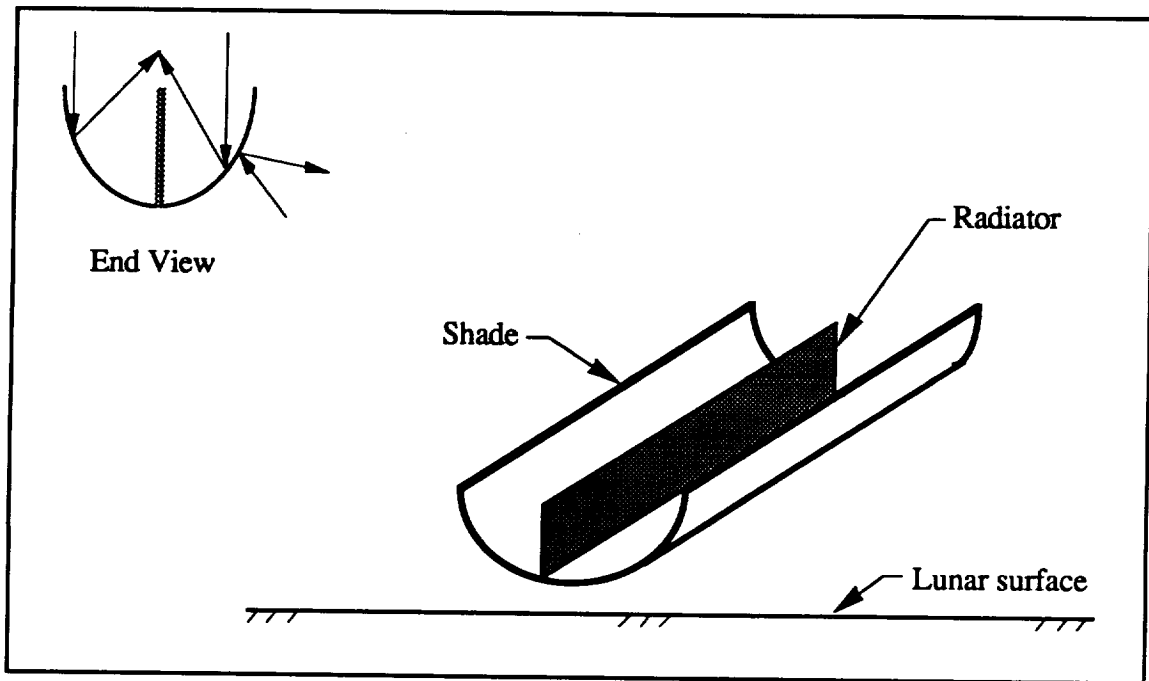
By qualitatively considering the radiator area and geometry of each shade a relative comparison of the shade masses can be made. The design team rated the alternates as having a low, moderate, or high mass.

## **2.2 Alternates for Reducing the Radiation Incident on the Radiator**

The geometries and function of the shading devices are described in the following section. The shading devices are evaluated on mass, thermal performance, and stowage volume occupied.

Unless specified, the shade and radiator length are aligned with the lunar equator. In this position, only the top of the radiator is directly exposed to the sun during the course of the day. Unless otherwise specified, the surfaces of the shades are highly reflective. The surfaces of the shades facing the radiator have a low emissivity so that radiation emitted to the radiator is minimized. The shading devices do not prevent dust from accumulating and the value of the surface properties (reflectivity, emissivity, and absorptivity) do not account for the effect of dust.

**2.2.1 Parabolic Reflector.** The shade is a parabola when viewed in transverse cross section. Its curved inner surface surrounds a vertical radiator (See Figure 6). The outer surface blocks IR radiation and albedo, and the inner surface redirects solar radiation to a focal point above the radiator. The shade can be made of either a rigid or flexible material that is coated with a thin layer of highly reflective material, such as aluminum, silver, or gold.



**Figure 7. Parabolic Reflector**

Advantages of the Parabolic Reflector are

1. Planetary IR and albedo do not strike the radiator.
2. Focussed solar radiation can be converted to useful energy.
3. If shade is made of rigid material the shade can be formed precisely into a parabolic shape.
4. If the shade is made of flexible material, it can be rolled, bent, or folded into a compact package to save space.
5. Using a Parabolic Reflector decreases the effective heat sink temperature more than the other shading devices.

Disadvantages of the Parabolic Reflector are

1. The rigid parabolic shade occupies more space than the flexible shade, since it cannot be bent, rolled, or folded into a smaller package.
2. A parabolic shade made of flexible material may not achieve a true



parabolic shape. It may assume an elliptic shape when hung from above or it may assume a hyperbolic shape when supported from below.

3. Solar radiation incident on the reflective shade at points close to the radiator will be directed into the radiator after reflection towards the focal point.
4. Moderate mass

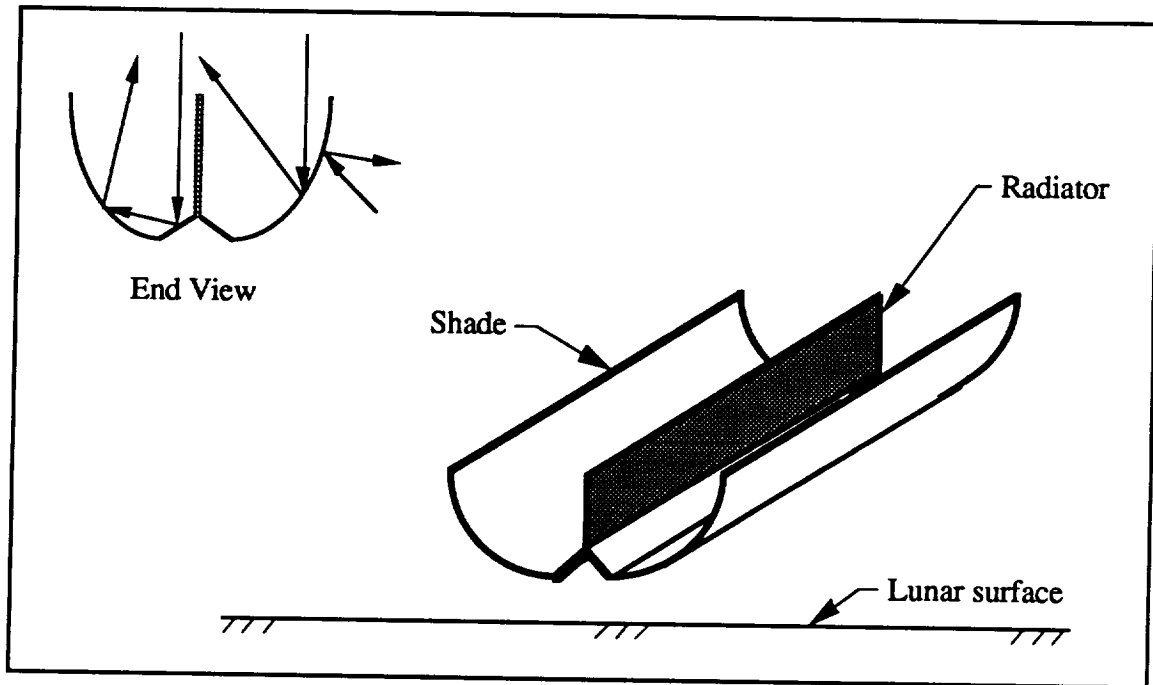
**2.2.2 Modified Parabolic Reflector.** The shade in this alternate is essentially a parabola when viewed in transverse cross section, like the parabolic reflector, but with a modified vertex. The vertical radiator is situated, as shown in Figure 7. By slanting the vertex downwards on either side of the radiator, solar radiation incident at points close to the radiator will be reflected away from the radiator instead of towards it. The rest of the shade is exactly the same as that for the Parabolic Reflector. Advantages of the Modified Parabola are

1. The planetary IR and albedo are blocked.
2. Compared to the parabolic reflector design, less solar radiation is reflected towards the radiator.
3. A shade made of flexible material can be made compact, since it can be rolled, folded or bent.
4. A shade made of rigid material can maintain a true parabolic shape.
5. The Modified Parabola significantly increases the thermal performance of the thermal control system.

Disadvantages of the Modified Parabola are

1. The slanted vertex adds a degree of complexity to manufacturing the parabolic reflector, for both rigid and flexible materials.

2. A shade of flexible material may not maintain the vertex indentation, it also may not assume a true parabolic shape.
3. A shade of rigid material cannot be easily bent, rolled, or folded into a small package.
4. Moderate mass



**Figure 8. Modified Parabolic Reflector**

**2.2.3 L-Shaped Panels.** In this design reflective panels are connected to form L-shaped shades. The shades are in a slanted position relative to the vertical radiator and are attached to the base of the radiator (See Figure 8). The downward slanted sides of the shade reflect incoming solar radiation away from the radiator. The small end pieces are turned up to prevent planetary IR and albedo from striking the radiator.

The angle and length of the side panels and end pieces that allow the to reduce

planetary IR, albedo, and the reflected radiation emitted from the radiator back to the radiator. Advantages are:

1. The shade panels are simple to manufacture.
2. The straight flat panels can be joined so they can be folded and made to lie along the vertical sides of the radiator prior to stowing.

Disadvantages of the L-Shaped Panels are.

1. Not all planetary IR and albedo will be blocked. For example, the angle of the panel from the vertical can be increased so that less reflected solar radiation strikes the radiator. The panel length can simultaneously be increased so that all planetary IR and albedo is blocked. Doing this will increase the mass of the shading device, which is a parameter to be minimized. Instead, the radiator length can be kept constant and the angle of the panel can be varied. This increases the radiator's view of deep space and allows planetary IR and albedo to strike the radiator. At a certain angle a good thermal performance is achieved. The same procedure can be performed for panels of different lengths and the results can be compared to determine the design length and angle.
2. High mass
3. Does not reduce the effective heat sink temperature below the operating temperature of the radiator

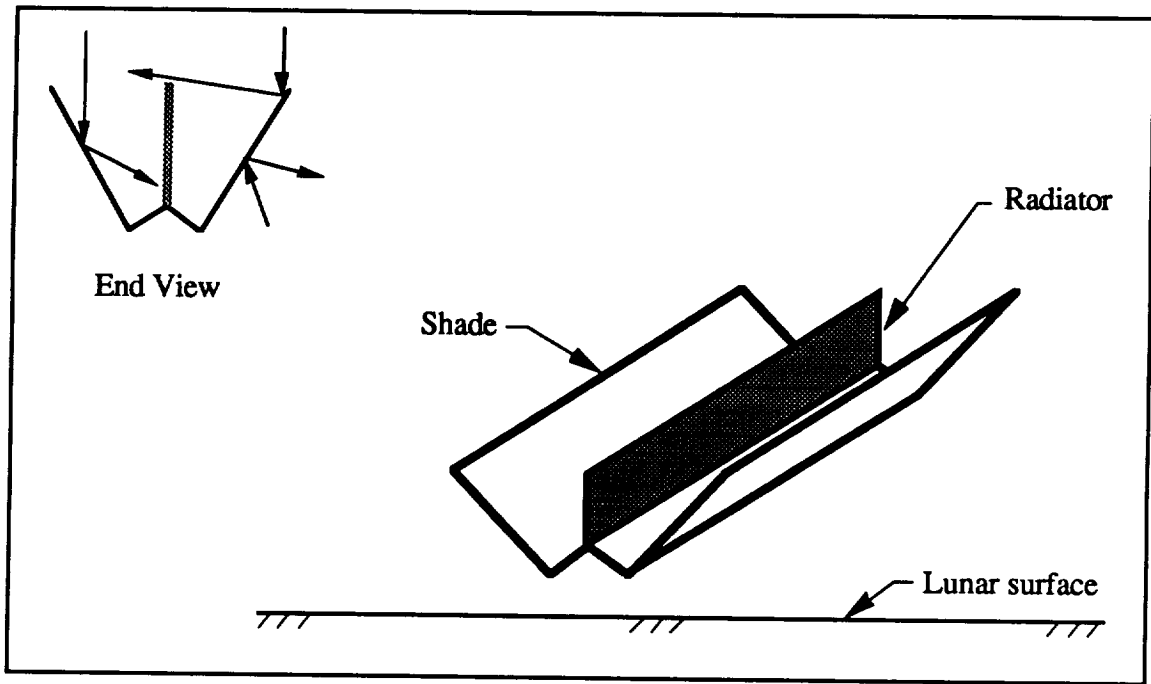
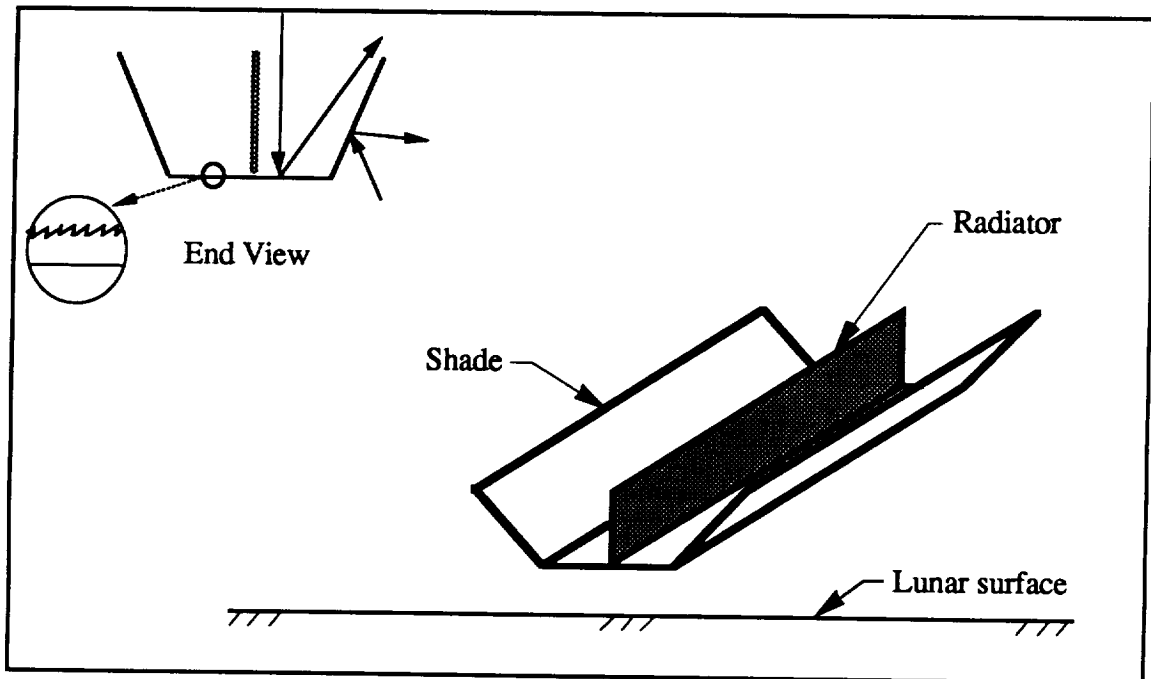


Figure 9. L-Shaped Panels

**2.2.4 Fresnel Reflector.** The shade consists of a flat panel laid horizontally with angled side panels attached to the ends of it. Both the flat and side panels are highly reflective on their upper and lower surfaces. The upper surfaces of both panels incorporate a serrated surface. The system is oriented so the path of the sun is along the top edge of the radiator (see Figure 9).



**Figure 10. Fresnel Reflector**

The side panels reduce the planetary IR and albedo incident on the radiator. The serrated surfaces have their grooves angled so that solar radiation is reflected away from the radiator. The length and angle of the side panels as well as the groove angles in the serrated surface can be optimized to obtain the maximum performance of the radiator.

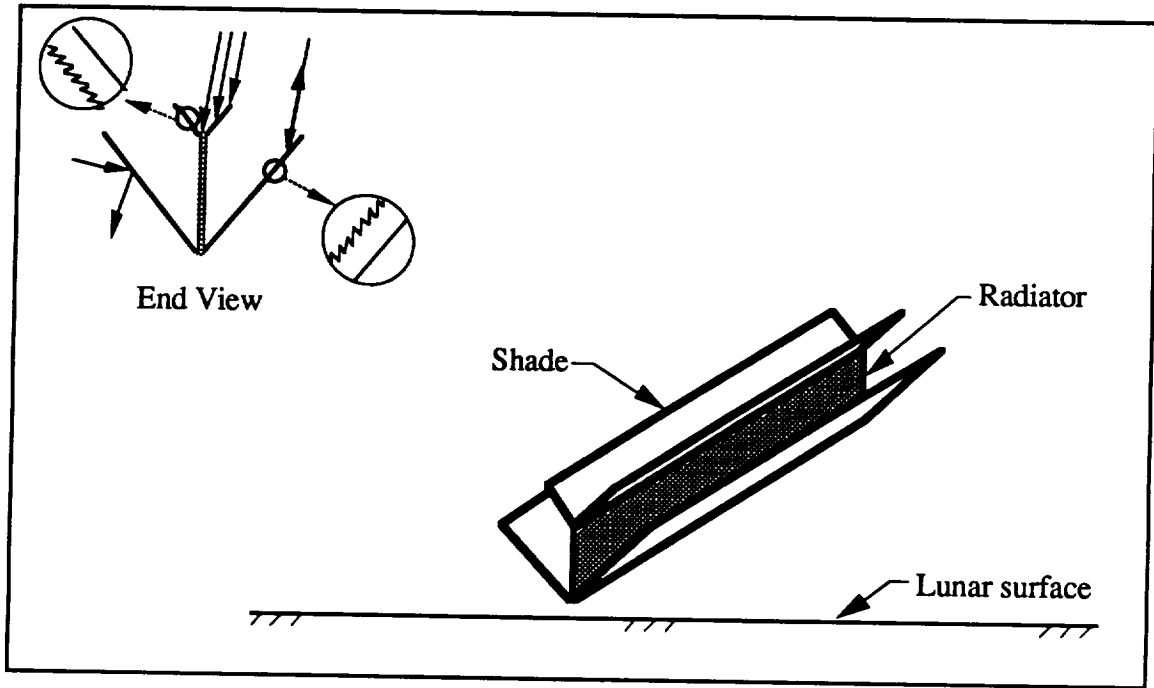
The advantages of the Fresnel Reflector are:

1. The flat panels can be folded to produce a compact package.
2. The design is simple.
3. The shade can be constructed of rigid or flexible materials.

Its disadvantages are:

1. Not all planetary IR and albedo will be blocked.
2. Moderate mass
3. Does not reduce the effective heat temperature below the operating temperature of the radiator

**2.2.5 Winged Radiator.** The shading system in this alternate consists of panels attached to the corners of the vertical radiator, as shown in Figure 10. By means of detentes in the attaching mechanism, the panels can be maintained at open or closed positions.



**Figure 11. Winged Radiator**

The top panels block direct solar radiation. Planetary IR and albedo are blocked by the bottom panels. The top panels are made shorter than the bottom panels because if the top panels were longer they would receive planetary IR radiation which would then be reflected to the radiator. Also, for a vertical radiator at the lunar equator, the effect of solar radiation is not as significant as that of planetary IR. This effect is because the the normal component of the sun's radiation on the radiator is smaller than the normal component due to planetary IR and albedo

The bottom surface of the top panel, and the top surface of the bottom panel are

serrated so that radiation that would ordinarily be reflected towards the radiator by a smooth reflective surface is instead reflected away from the radiator. Advantages are

1. The shading device is simple to manufacture.
2. The panels can be folded for compact storage.
3. The shading device can be made lightweight.
4. This is the only shading device that blocks solar radiation.
5. Decreases the effective heat sink temperature enough to allow the thermal control system to perform well

The disadvantages of the Winged Radiator are

1. Does not block all planetary IR and albedo
2. Outer surface of the top panels emit radiation to the radiator and decrease the radiator's view of the sky.

**2.2.6 Modified Winged Radiator.** This alternate is similar to the Winged Radiator, except there are no upper panels to block direct solar radiation. The assumption is that the component of direct solar radiation has little effect on the effective heat sink temperature. Blocking sufficient planetary IR and albedo will reduce the effective heat sink temperature enough to accomplish heat rejection from the radiator at lunar midday.

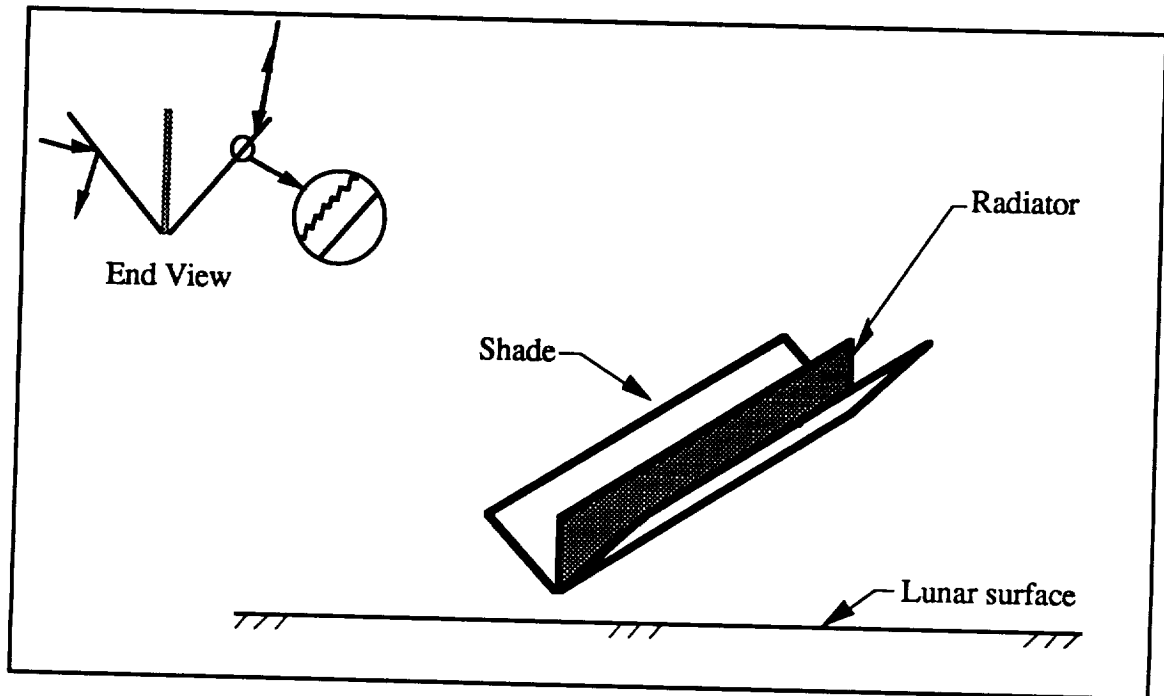
The upper surface of each panel is serrated to aid in directing solar radiation away from the radiator (see Figure 11).

Advantages of the Modified Winged Radiator are

1. This design can be folded and hence has small space requirements.
2. Manufacturing the panels is simple
3. Has the lowest mass of all shading devices

The disadvantages of the Modified Winged Radiator are

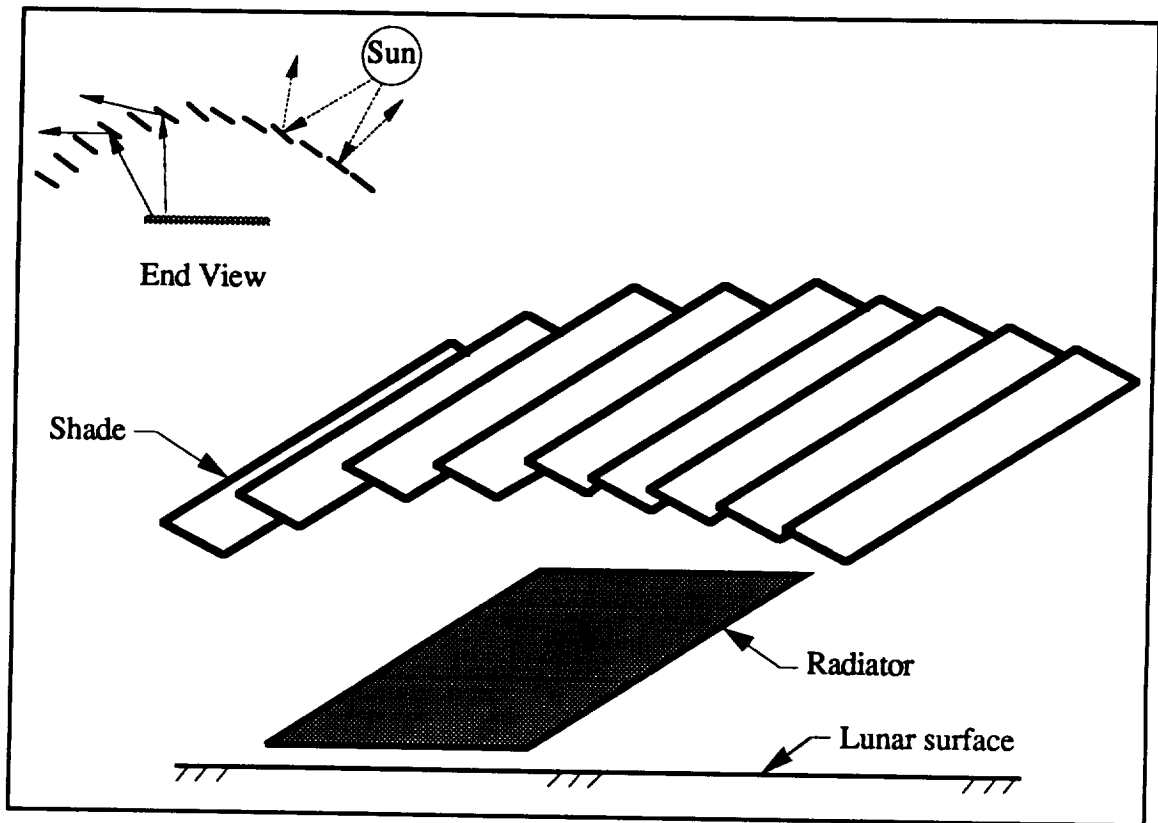
1. Does not block direct solar radiation.
2. The thermal performance is not as good as other systems.
3. Solar radiation that will normally not reach the radiator might reflect from the upper surface of the shade directly into the radiator.



**Figure 12. Modified Winged Radiator**

**2.2.7 Shading Blinds.** This alternate is similar to Venetian blinds that shade windows in buildings. It differs from the other alternates due to the fact that it is an active system. In the design, reflective panels of rectangular cross section (slats) are placed above a horizontal radiator so that their centers of mass describe an arc above the radiator (see Figure 12). The slats are positioned so that their length is perpendicular to the sun's path.





**Figure 13. Shading Blinds**

To prevent solar radiation from passing through the spaces between the slats, the system has a sun tracking device that rotates the slats with the sun's motion to ensure that they are always normal to the sun. Therefore, on the side facing the sun, the slats will be very close to one another, and some amount of radiator emission will be reflected back to the radiator from those slats. Most of the radiator's emission will pass between the slats on the side which is not exposed to the sun. The advantages of the Shading Blinds are

1. Since it is composed of parts, it will be relatively easy to store.

Disadvantages of the Shading Blinds are

1. The sun tracking device makes the system more unreliable.
2. High mass
3. This shading device does not reduce the effective heat sink temperature

below the operating temperature of the radiator.

Appendix E

**Table 1**  
**Thermal Performance Comparison for Alternates**

<b>Shade</b>	<b>Estimated Effective Heat Sink Temperature (K)</b>
Parabolic Reflector	214
Modified Parabolic Reflector	212
L-Shaped Panels	273
Fresnel Reflector	265
Winged Radiator	229
Modified Winged Radiator	250
Shading Blind	339

**2.2.6 Summary.** The thermal performance analysis conclude that the L-Shaped Panels, Fresnel Reflector, and Shading Blind Reflector do not decrease the effective heat sink temperature below the operating temperature of the radiator. Therefore, these devices will not be incorporated into the thermal control system. The Modified Winged Radiator has the lowest mass of all alternates. The thermal performance when using the Modified Parabolic Reflector or the Parabolic Reflector is better than.the other concepts.....

### **2.3 Alternates of the Deploy Mechanism**

In addition to developing different alternates for shading the radiator, the design team developed deploy mechanisms (support structure and device used to place the shading system in operating position). Since developing alternates for deploying and retracting involves developing a support structure for the shading system, alternates for both deploying and retracting and supporting the shading system were simultaneously worked on.

The shading system and support structure can be remotely operated. In other words, astronauts do not have to perform any EVA each time the shading system is to be deployed or retracted. The shading system will be placed on and deployed from the lunar surface. The shading system of the 25 kW thermal control system will be placed on the lunar surface and permanently established. Therefore, it is not as critical to have the shading system remotely deployed. Since the 10 kW and 25 kW thermal control systems differ mainly in the number of radiators available for heat rejection, the alternates developed are adaptable to both thermal control systems. For the 25 kW thermal control system, in the event that it has to be repacked and moved to another location, it will be advantageous to have it remotely activated so astronauts will be free for other important activities.

The deploy and retract devices are designed to be simple. Complex devices inherently have many more parts. Each part introduces an element of failure, and therefore, complex systems tend to be less reliable than simple ones. Alternates should minimize mass because of the enormous cost of transporting something from the earth to the moon. The volume occupied should be minimal because of the limited cargo capacity available in the lunar lander. Because of limited power supply the power required to deploy the shading system should be minimal.

Each shading device is paired with a support structure. This section describes the alternates. Also, the mass, power, and volume is calculated for each alternate. To make a comparison it is assumed that each support structure holds 5 shading devices. Appendix F contains detailed calculations of the mass, volume, and power of each alternative.

**2.3.1 Folding Support Structure and Motion System.** . The Folding Support Structure stacks shading systems in a way that they overlap. To place the shading systems in operating position, the top section of the Rail Support Structure is rotated 180° (See Figure 14). The Folding Support Structure can be used with the Rigid Parabolic Reflector and Modified Parabolic Reflector.

The top section of the support structure is made of two rails. The shading systems are attached to the rails. The bottom section is identical to the top section. Rod cross-section dimensions can be determined through stress analysis. The rails can be assumed to be loaded cantilever beams supported at one end. The motion system provides a torque in order to place the shading systems in an operating position.

Because the mass of the Rigid Parabolic Reflector and Modified Parabolic Reflector are the same, the results are the same. The total mass of this alternative, which is the heaviest of all alternatives is 270.47 kg. Because of the high torque required rotate the top section the estimated power to deploy the alternatives is 24 W. Advantages of the Folding System are

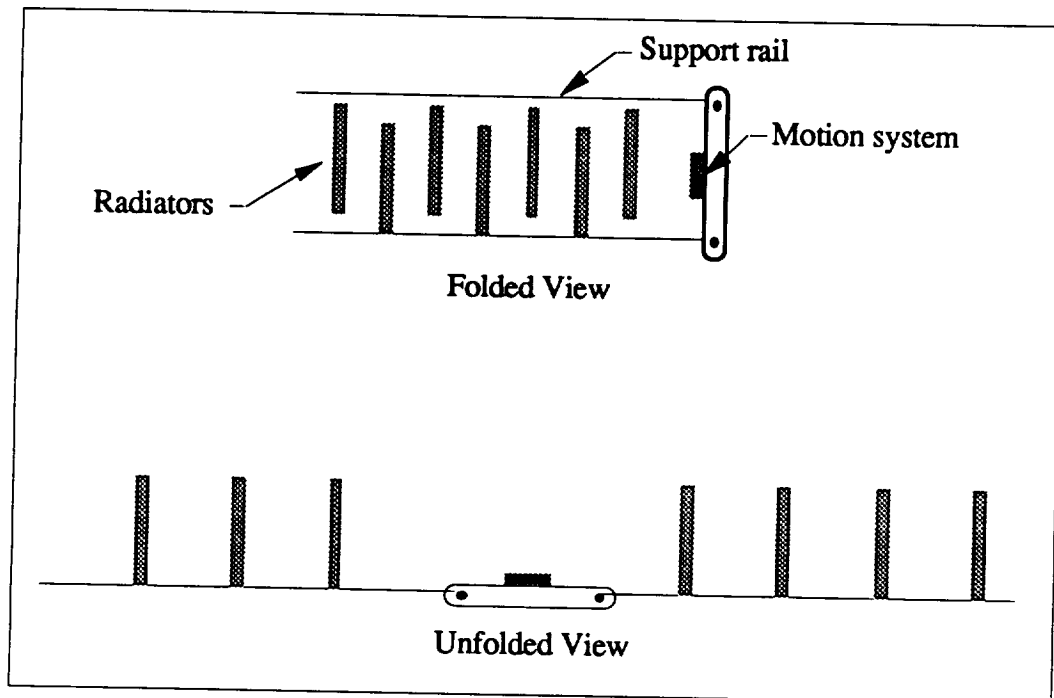
1. Compared to other support structures, twice as many shading systems can be placed in one support structure.

Disadvantages of the design are

1. Of all alternate, this alternate requires the most power to deploy
2. The rails which account for more than half of the total mass make this

system heavy.

3. The stowage volume occupied is the highest of all alternates.



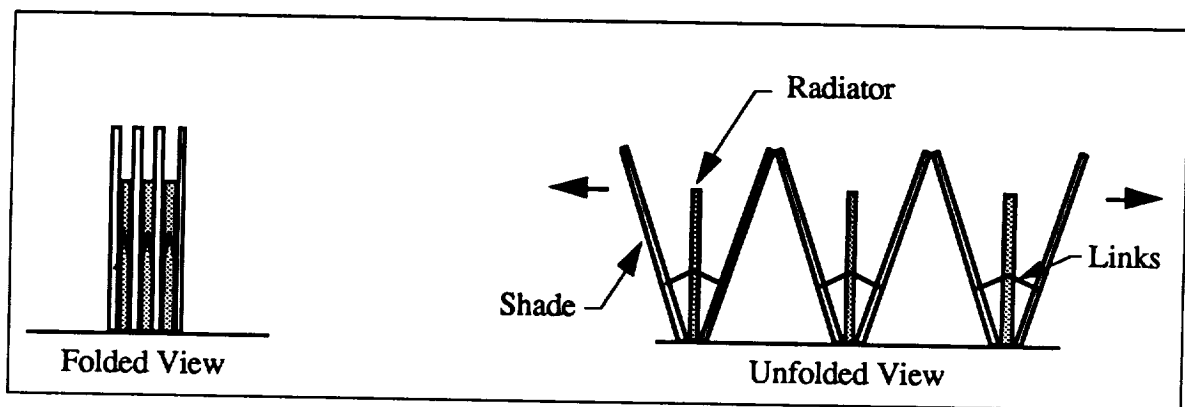
**Figure 14. Folding Support Structure and Motion System**

**2.3.2 Rail Support Structure and Scissors Mechanism.** In this alternative the shading devices lay side by side (see Figure 15). The shading devices are attached to a scissors mechanism which is used to place the shading devices in operating mode. As the scissors are extended a force is applied on the shading devices. The shading devices are separated as they slide along the rails. The shades open due to an inherent moment. To stow the shading devices the the scissors are retracted. As the scissors mechanism is retracted the shading panels come in contact and force each other to a vertical position. Shading devices that can be folded, such Winged Radiator and Modified Winged Radiator are appropriate for this system.

The support structure is a pair of rails. The rails bear the weight of shading devices

and serve as a means of moving the shading devices to the deployed position. Rollers or collars can be used. A drawback of using rollers is that grooves must be made in the rails. The grooves act as guide for the rollers. Using collars, the wear of the rail and collar occurs. If the wear is excess the structure of the rails will weaken, thus causing the rails to fail.

The total mass of the Winged Radiator and Folding Support 50.90 kg. To put it in operating position, the power required is 0.148 W. The stowed volume and deployed volume 4.2 m<sup>3</sup> and 14.8 m<sup>3</sup>, respectively. For the Modified Winged Radiator, total mass is 47.34 kg and the power is 0.147 W. The deployed volume is 3.6 m<sup>3</sup> and the stowage volume is 12.24 m<sup>3</sup>.



**Figure 15. Winged Radiator System**

The advantages of this design are

1. The rails, which constitute the support structure, can be made lightweight
2. The entire assembly can be made very compact for stowing.

Disadvantages of the design are

1. The

2. The outside surface of the shade will be scored with repeated deploying and retracting.

### **Selection of Final Design Solution**

In order to select the best alternate for preliminary design, the solutions were compared by means of a decision matrix (see Appendix G). The decision matrix contained evaluation criteria that were given weighting factors according to their relative importance as design requirements. Ratings were assigned to each alternate according to how well they fulfilled the design considerations. The rating was done in a scale from zero to ten, where zero corresponds to an absolutely useless solution and ten corresponds to an ideal solution [5]. Overall values for each alternate were calculated from the multiplication of the weighting factor and the alternate rating. The best solutions were those with the highest overall values. The evaluation criteria result from the design requirements and consist of the following factors:

1. **Safety**. The shading system should be safe during manual and automatic deployment and during operation. The design should also be safe when subjected to any vibrations during operation.

2. **Total mass**. The shading system should minimize the total mass due to the energy cost involved in transporting mass from the earth to the Moon..

3. **Stowed volume**. The shading system should also minimize the stowed volume due to the space constraints of the spacecraft.

4. **Thermal performance**. A good thermal performance is quantified with the effective heat sink temperature. The lower the effective heat sink temperature, the better the

thermal performance since a lower radiator area will be required for the required heat loads.

5. Power consumption. The deployment operation should minimize power consumption.

6. Reliability. Reliability qualitatively describes the many factors, such as the possibility of failure and the possibility of performing within design parameters.

7. Ease of maintenance. Due to the constraints that exist in the lunar environment and the limited movement of an astronaut in his spacesuit, the system should be designed for ease of maintenance by its general geometry (providing accessibility to areas that require maintenance) or by incorporating features that will help in performing the maintenance operation.

The next section will present the preliminary design of the best alternate.



### III. DESCRIPTION OF FINAL DESIGN

This section presents the a description of the final design solution, which combines the Modified Shading Device with the Rail Support Structure and Scissors Mechanism. A thermal performance analysis was performed to determine the ratio of the dimensions and angles of the shade relative to the radiator. In addition, an estimate of the power required to deploy the shading system, the volume occupied during stowage and when the system is deployed is provided. Finally, a breakdown of the total mass is provided.

#### 3.1 Thermal Performance Analysis

One disadvantage of the modified winged radiator is that, although the shades could block albedo and surface infrared radiation away from the radiator, direct solar radiation will be reflected from the shade directly into the radiator. The amount of reflected solar radiation will vary with the shade length ( $L_s$ ), the angle ( $\theta$ ) between the shade and the radiator, and the shade surface properties. The reflected radiation will decrease with decreasing shade surface reflectivity and decreasing shade length. However, the radiation from the lunar surface to the radiator will increase with decreasing shade length when the shade does not completely block the radiator view to the lunar surface. Also, for a given length and surface property, the reflected radiation will decrease with increasing  $\theta$ .

Optimum combinations of  $L_s$ ,  $\theta$ , and shade properties were obtained by performing

a thermal performance analysis on the shading system through the variation of  $\theta$  and the length of the shade (in non-dimensional terms as the ratio,  $R$ , of the length of the radiator over the length of the shade). In addition, two different cases of shade properties were varied: case 1 with a shade solar absorptivity of 0.9 and case 2 with a solar absorptivity of 0.14. Making the absorptivity high (with a corresponding decrease in reflectivity) will decrease the direct solar radiation reflected from the shade and directed to the radiator but will increase the infrared radiation emission into the radiator due to the increased shade temperature. On the other hand, making the absorptivity low (with a corresponding increase in reflectivity) will increase the reflected direct solar radiation but will decrease the infrared radiation emission from the shade.

The analysis (see Appendix H) was done by performing an energy balance on the radiator and shade. All possible radiation components (direct solar radiation and reflection and direct emission from the moon surface and shade) incident on the radiator were considered. Some of the view factors were approximated, in some cases by considering the moon surface as a finite plate of an area of 500 by 400 meters [9], in other cases by considering the shade and the radiator as infinite long plates. Other assumptions made on the analysis were,

1. All the surfaces were *diffuse* surfaces (emit and reflect diffusively). In reality, it will be preferred to make the surfaces *specular*, so that reflection and/or emission will depend on direction. A specular surface will make it possible to reduce the radiation incident on the radiator as opposed to a diffuse surface, which will emit or reflect the same in all directions. Assuming that all the surfaces are diffuse will give results for a worse case and it will be reasonable to assume that the properties of a specular surface could be varied in order to reduce the radiation incident on the radiator.

2. The radiator temperature is constant at 270K and the lunar surface is at 384K

3. The analysis does not take into account lunar dust accumulation, which will increase the absorptivity of the surfaces.

4. The shade emissivity is 0.05.

Some results obtained are presented in Table 2. The variables were varied by considering cases 1 and 2 separately and for each case R was varied for q ranging from 5 degrees to 85 degrees.

**Table 2**  
**Thermal Analysis Results for Different Parameters**

Angle	R	T <sub>sink, Case 1</sub>	T <sub>sink, Case 2</sub>
60	0.5	341 K	271 K
65	0.5	335 K	260 K
70	0.5	329 K	247 K
75	0.55	313 K	217 K

The mass of the Modified Winged Radiator and Rail Support Structure depends on the aspect ratio and radiator to shade angle. An increase in aspect ratio increases the length of the shading device panels. Increasing the radiator to shade angle increases the width of the shading device. Therefore, a longer support structure is required. An increase in these parameters increases the total mass. An aspect ratio of 0.55 and radiator to shade angle of 75° was used to do mass calculations.

Using equation X, the length of the shading device panels is calculated.

$$L_s = rL \quad (3.1)$$

$L_s$  = length of the shading panel

r= aspect ratio

L= length of radiator

The length of the shading panel is 8.25 cm.

This shading panel length is used to calculate the mass of the Modified Winged Radiator. The mass of the Modified Winged Radiator, which is dependent on the thickness of the shading device, is calculated using Equation XX.

$$m = \rho h L t p \quad (3.2)$$

m = mass per shading device

L = length of the shading device panel

$\rho$  = aspect ratio

h = height of radiator

t= thickness of the shading device material

The dimensions of the radiator selected by the design team were 6 m x 0.02 m x 0.15 m.

The length of the shading device is fixed by the dimension of the shading device. The independent parameters are the thickness of the shading device and the density.

Aluminum alloys are a common material used to make devices which are exposed to the lunar atmosphere. Aluminum alloys are easy to manufacture and are readily available. Aluminum alloys are light relative steel. Therefore, the independent variable of the equation is the thickness of the shading device material.

The thickness of the shading device can be varied to obtain different values of the shading device mass. Using a thickness of 0.635 cm yields a mass of 17.6 kg. Because transportation costs are very high, the design team decided to minimize the thickness. The design team selected Kapton, which is an Aluminum alloy, of thickness 0.0127 cm. This thickness gives a mass of 0.352 kg.

The Kapton sheets are supported by a frame, which is made of aluminum rods.

Three rods are equally spaced at a distance of 3m. The rods bear the weight of the transverse rods and Kapton sheets. The sides of the cross-section are of length 1.98 mm (See Appendix I for calculations).

The shading device support rods are inserted in the holes of the shade panel support which are slightly angled. When in the closed position, the shading panels are at a slight angle. As a result, a moment is produced. This idea is analogous to a long slender rod which is standing vertically. If the rod is tilted slightly a moment about the point where the rod is in contact with the surface is produced. As a result, the rod to fall to the surface. When the shades are separated this inherent moment causes the shade panels to open.

The radiator support attaches supports the radiator. The radiator is put in a groove which is several centimeters deep and is insulated to minimize heat conduction between the mating surfaces. The walls of the groove keep the radiator from falling over if a force is applied to the top of radiator.

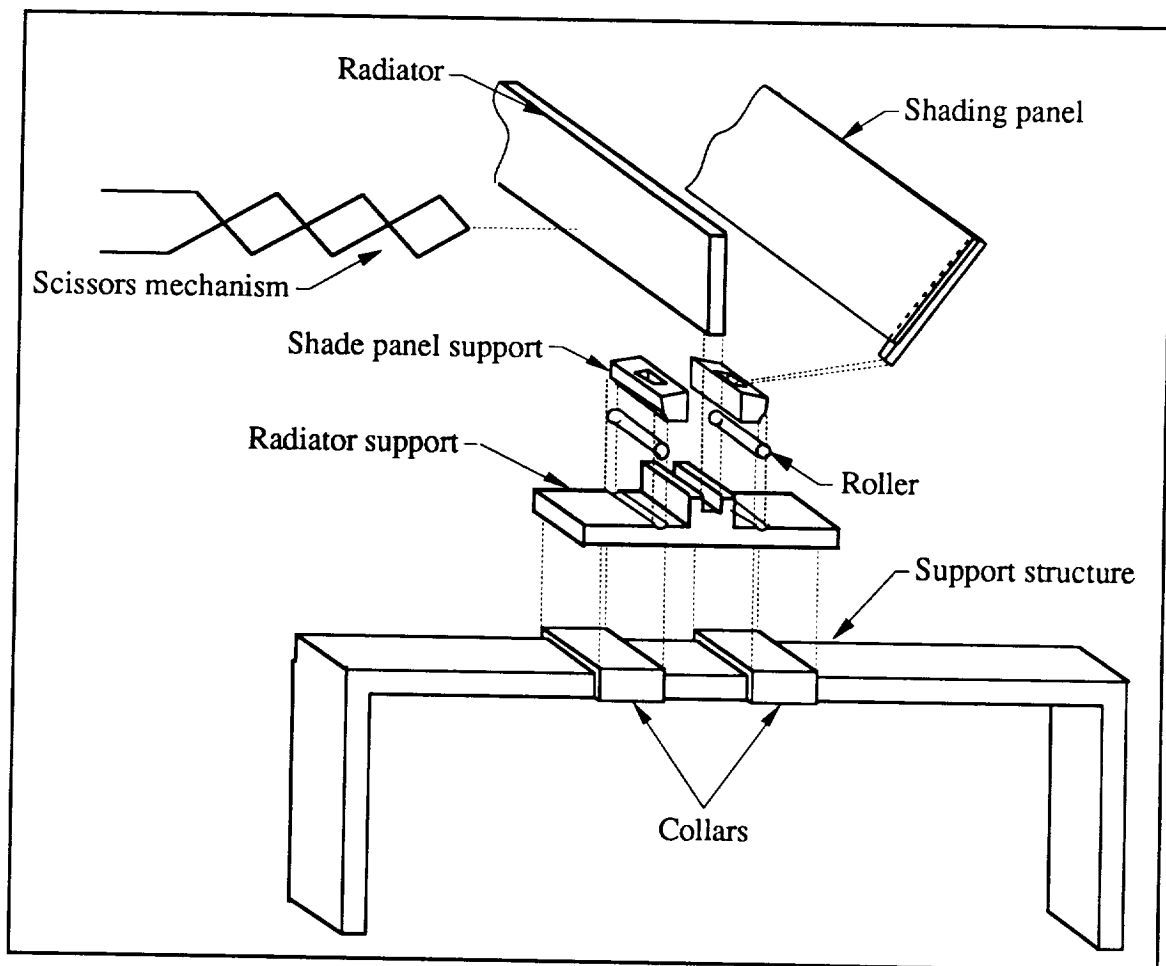
The radiator support is attached to collars which slide along the rail. To reduce the wear of the aluminum parts the collar can be coated. Most plastics can not be used in applications in the lunar extreme temperatures of 102 K to 384 K. Silicone Rubber of General Electric can be used in applications where temperatures range from 185 K to 519 K[10]. To reduce the wear of the coating a high hardness is desired. The wear percentage, in 200 deploy and retract cycles, of each collar and rail is calculated assuming no coating is used. A XX % of the collar and XX% of rail is removed.

As given in Figure 16 the rails can be folded into the transport package. The length of the rails are limited by the length of the transport package, which is 6 m. The the rails have a square cross-section of length 9.18 cm. The legs of the rail are 0.91 meters high and have a square cross-section length of 6.28 cm.

The scissors mechanism is made of links. The length of the scissors can be varied

(See Figure 16). Moving the handles towards each other will extend the mechanism, yielding the deployed position, conversely, pulling them away from each other will retract the mechanism. The radiators are attached to the scissors mechanism where the links come in contact.

The number of radiators required to reject 10 kW and 25 kW was calculated using the radiator area determined from the thermal analysis. is 389 m<sup>2</sup> for the 10 kW heat rejection system and 973 m<sup>2</sup> for the 25 kW. From the dimensions of radiator it was calculated that 433 and 1082 radiators are required for the 10 kW and 25 kW heat rejection system, respectively.



**Figure 16. Modified Shading Device with the Rail Support Structure**

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## **IV. CONCLUSIONS AND RECOMMENDATIONS**

This section presents the conclusions of the project. Also, the design team makes recommendations for removing dust from the shading system.

### **4.1 Conclusions**

The design team developed a preliminary design of the Modified Winged Radiator, Rail Support Structure, and deploy mechanism. The main objective of the design team was to develop alternates will reduce the radiation incident on the radiator. Because the planetary IR has the greatest effect on the performance of the radiator, the shading devices were designed to reduce the planetary IR incident on the radiator. The other objectives were to design a support structure for the shading system and a means of the deploying the system, and conduct a thermal performance. The device light by using sheets of Kapton attached to aluminum supports. The stowage volume of the shading device was made small by allowing the shading device panels to be closed prior to storing. Attaching the shading device panels to a support mounted on rollers will allow the panels to be closed. Finally, the power required to deploy this alternate is low.

From the thermal performance, the dimension of the shading device was calculated.

In developing the alternates for the shading device, support structure, and



deploying mechanism, the design team did not consider the problem of dust accumulation. It was assumed that the shading system had a dust control mechanism.

#### **4.1 Recommendations for Dust Control**

Most of the moon's surface is covered with regolith (small particulate matter), a large percentage of which is composed of lunar soil. Particle size of the lunar soil ranges from 45 to 100 micrometers in diameter, which is similar in size to the silty sands on earth. An example is sand along a coast. Many particles though, are much smaller than silty sand. The particles are generally angular in shape with sharp edges and have a low electrical conductivity and dielectric loss [11]. These characteristics allow lunar dust to accumulate and keep electrical charge for long periods of time. The sharp edges serve to concentrate charge at a point to create high charge densities which result in strong electrical dipoles. The electrical dipoles enable the dust particles to adhere to a variety of surfaces.

With a rarefied atmosphere and a gravity that is 1/6 the gravity of the earth's gravity, not much effort is necessary to make dust fly great distances. Dust therefore can settle on surfaces far away from where the dust was originally settled. There is evidence to show that dust can be set into motion by the passage of the boundary between day and night on the lunar surface. The proposed theory is that the steep ultraviolet flux gradient across the day night boundary may be responsible for creating electrostatically supported clouds of dust that follow the moving boundary. On the Apollo missions, dust coatings reduced visibility through helmet visors and camera lenses, and dust found its way into moving parts [11].

It is important that measures be taken to reduce dust accumulation on the shading devices. The optical performance of the shades will be reduced if dust is allowed to

accumulate on them. Also, if dust is allowed to get into joints, such as the joints on the shade deploying mechanisms, it will create a grinding powder with the dry lubricant in the joint and severely reduce the life of the joint.

The next section discusses various alternates for removing or preventing dust from adhering to critical surfaces such as the shade surfaces and joint surfaces.

**4.1.1 Shaking Mechanism.** In this alternate, a device for producing high frequency low amplitude vibration is rigidly attached to the radiator/shade support structure. The surface that will be protected must be tilted at a shallow angle. The direction of the tilt depends on the radiator/shade geometry, but must direct loosened dust towards an edge or location from which it can be removed later, or allowed to fall to the lunar surface.

With sufficiently strong vibration, the attractive force between the dust and surface can be overcome. The dust particles alternately lose contact with the surface then regain contact. Each time the particles are loose and set into motion by vibration, they will move alternately in different directions, but the resultant direction will be down the sloped surface. All shade designs but the Shading Blinds can benefit from the Shaking Mechanism because the optical surfaces are inclined. It may be advantageous to vibrate the system at its resonant frequency or at an integral multiple of that frequency so that the maximum shaking effect can be obtained from the Shaking Mechanism. It is important to ensure that the amplitude of vibration delivered by the Shaking Mechanism at the resonant frequency be small so that the radiator shading system does not vibrate hard enough to be damaged.

A suitable energy source for the system is the sun via solar cells. The intervals between between dust removal times by the device will be dictated by the rate at which dust

accumulates, and can be set by a digital timer. Advantages of the Shaking Mechanism are

1. The alternate can be adapted to a wide variety of shade designs which have a support structure capable of transmitting vibration.
2. The design does not require a replenishable source of energy, such as a battery. The sun provides enough energy to drive a small low voltage motor with an eccentric weight or to drive a transducer.

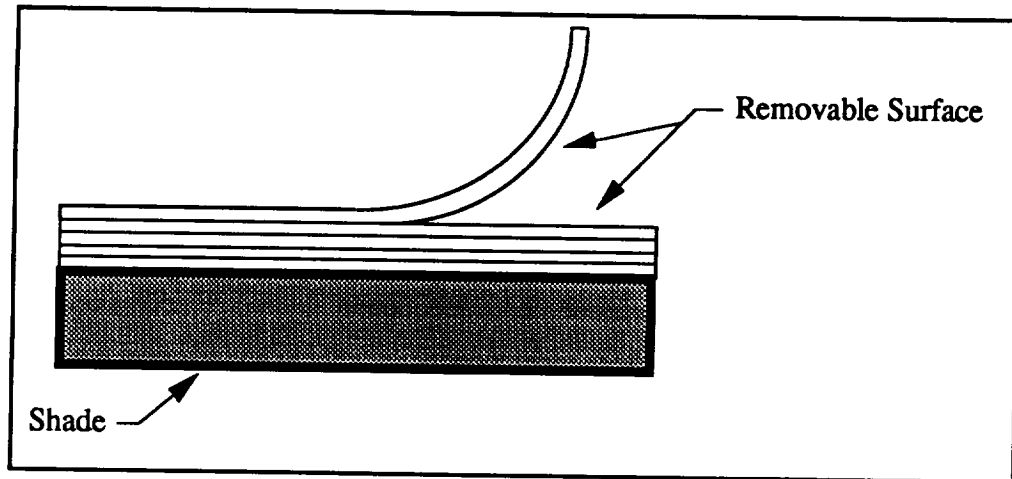
Disadvantages of the Shaking Mechanism are

1. The system will have a low reliability because of numerous mechanical parts.
2. The low amplitude vibration means that one device will have to be placed on each radiator/shading system. This will increase the mass of each radiator/shading system.

**4.1.2 Application of Removable Transparent Layers.** This alternate makes use of an idea already in worldwide use. The surface of the shade is covered with several very thin layers of material transparent to both visible and infrared radiation (see Figure 17). Dust is allowed to collect on the top layer and is intermittently wiped off. When the surface is scratched and cannot be used, the top layer is pulled off, exposing a new untouched protective layer. This idea has been in use in the Formula One racing circuit and by motorcycle dirt bike riders for some period of time. Their helmet visors have several layers of optically clear material. The driver or rider pulls off the top layer when it becomes difficult to see through it. Two advantages of the Transparent Layers are

1. Not much mass is added to the existing radiator/shading system.
2. The protective layers can be applied to a wide variety of shade geometries. Also, the pull tabs can be designed for an astronaut's

gloved hand.



**Figure 17. Removable Layers**

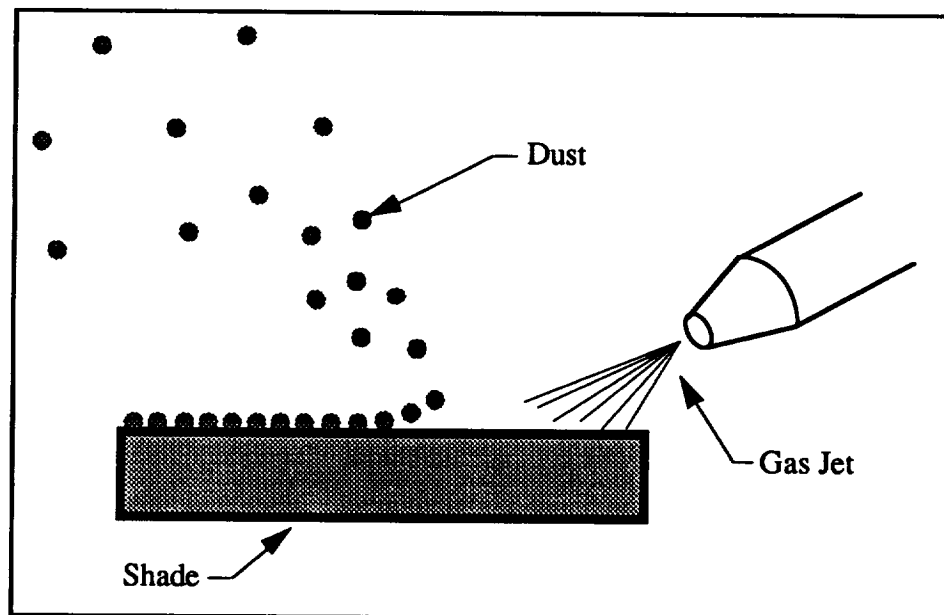
Disadvantages of the Transparent Layers found by the design team are

1. The life of the protective layers is finite. Once they are depleted, new ones cannot be applied to the surface.
2. Also, the astronaut has to wipe or remove the layers from the shade on a regular basis and at intervals determined by the rate of dust accumulation. Therefore, the layers constitute a maintenance intensive design. If the design of the thermal control system requires the use of several radiators, then a lot of unnecessary work exists for the astronauts.
3. Surface thermal properties are wavelength dependent. Depending on the material used, it will be more absorptive to one range than the other. Therefore, the material will experience a temperature rise that may affect the radiator performance.

### **3.3 Gas Jets.**

Pressurized carbon dioxide gas can be used to blow dust off the shade surface (see Figure 18). The carbon dioxide gas can be stored in a portable thermally insulated tank which is kept inside the lunar habitat to prevent the gas from solidifying during the cold lunar night and from developing dangerous pressure levels in the tank during the hot lunar day. Carbon dioxide gas may be an ideal propellant. It is produced by human beings and will have to be removed by the habitat air management system. The gas can be stored by chemical means (for example it can be absorbed by activated charcoal) and when enough gas has been stored, the chemical storing process is reversed to allow it to be captured in an appropriate container. The good points of the Gas Jets are

1. The main advantage of this design is that carbon dioxide gas is a by-product of human metabolism, and therefore it does not have to be brought from earth in large quantities for future use.
2. The device can be made portable.



**Figure 18. Gas Jets**

**Disadvantages of the Gas Jets are**

1. The rate of carbon dioxide accumulation and the process of storing and removing the gas may be so slow and inefficient that the device will be impractical.
2. Carbon dioxide released from the tank will contaminate the lunar atmosphere [6].

### **3.4 Explosive Inflation of a Balloon**

The device in this alternate is a balloon or bladder made of a material having a high tensile strength. The material can be transmissive or it can form the reflective coating for the shade. The balloon is made so that when inflated, one end rises higher than the other, about 2 or 3 millimeters. The design works by rapidly (almost explosively) filling the balloon with a suitable gas so the accumulated dust on its surface is hurled far enough away from the shade (see Figure 19).

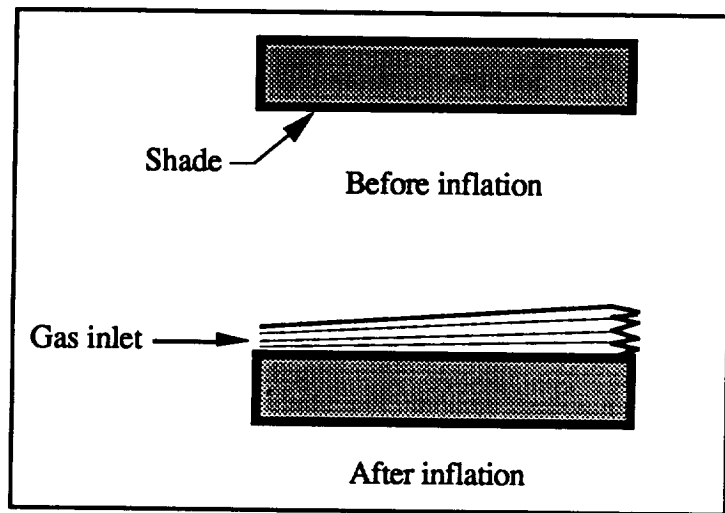
Two advantages the Explosive Inflation of a Balloon found are

1. The gas used to inflate the balloon is recoverable so it may be used repeatedly.
2. The balloon can be used once each time to remove most of the accumulated dust, and therefore is not continuously exposed to any stressful situation that may shorten its service life.

In analyzing the Explosive Inflation of a Balloon the following disadvantages were found

1. If the balloon ruptures, the shade will be rendered inoperable, and this is the most serious flaw of the design.

2. The explosive inflation may transmit damaging shocks to the rest of the radiator/shade structure
3. The balloon surface may not be smooth so it may be difficult to predict the direction of the reflected rays.



**Figure 19. Balloon Mechanism**

### **3.5 Dust Blowing Device.**

In this alternate, dust is fed into a hopper that in turn delivers the dust to a rotating impeller. The impeller accelerates the dust to a velocity which is given by:

$$V = r\omega$$

where:

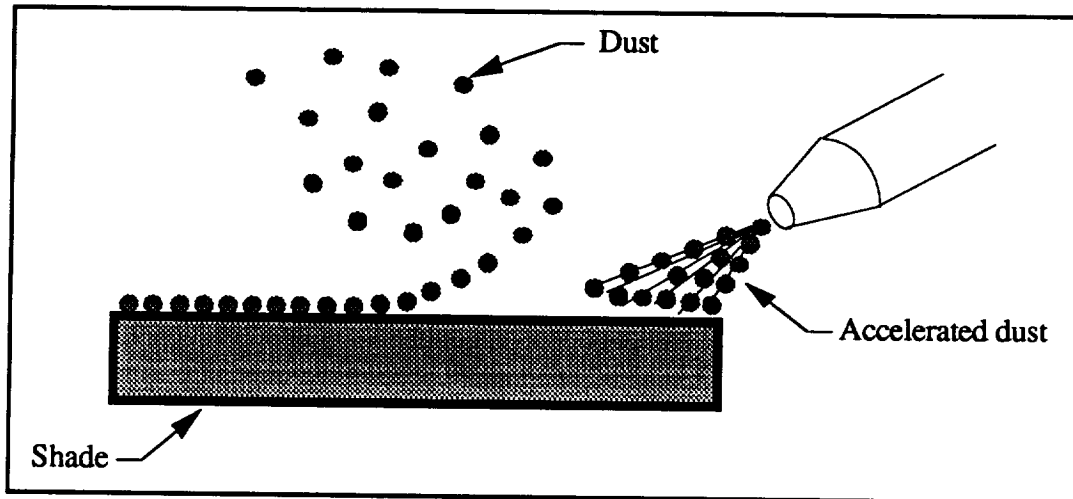
$V$  = velocity of the dust particle as it leaves the impeller

$r$  = radius of the impeller

$\omega$  = angular velocity of the impeller.

The rapidly moving dust particles can be aimed at the stationary particles on the shade to hit them off the shade(see Figure 20). Advantages of the Dust Blowing Device are

1. There is a plentiful supply of dust on the moon.
2. Operating the device is simple.
3. The device can be made very light and portable.
4. Operation for extended periods is possible by connecting it to a solar cell array.



**Figure 20. Dust Blowing Device**

Disadvantages of the Dust Blowing Device are

1. The accelerated dust particles will scratch and score the shade surface.
2. The dust particles will wear out the rotating parts in the motor/impeller system.
3. The flying dust will cover other shades or devices in the vicinity of the operating device.
4. Large particles accidentally dropped down the hopper will destroy the rapidly rotating impeller.
5. A small portable system cannot operate for long periods of time.



## **4.2 Recommendations for Future Work**

From the preliminary designs, the design team makes the following recommendations for future work. First, it is possible that the thermal performance can be improved by serrating the surfaces of the shading devices. Therefore, it is recommended that thermal analysis and testing be performed. The design team incorporated the scissors mechanism to deploy the shading devices. The rails of the support structure can be folded into the transport package. A device to deploy the rails will be necessary to deploy the rails. A stress analysis of the scissor's mechanism will determine the cross-sectional area of the links comprising the scissor's mechanism.

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## APPENDIX A

### Comparison of different conducting materials

The heat transfer rate through a material is given by:

$$Q = -KA \frac{dT}{dx}$$

for one dimensional steady state conduction in a plane wall with no heat generation and constant thermal conductivity [ ].

where  $Q$  = Heat transfer rate (W)  
 $K$  = Thermal Conductivity (W/m.K)  
 $A$  = Area of wall normal to direction of heat transfer.  
 $T$  = Absolute temperature (K)  
 $x$  = Thickness of the wall.

For a plane wall with steady state conduction;

$$Q = -KA \frac{\Delta T}{\Delta x}; \text{ Solving for } A$$
$$A = -\frac{Q \Delta x}{K \Delta T} = -\frac{Q(x_1 - x_2)}{K(T_1 - T_2)}$$

If  $Q = 1W$ ,  $\Delta T = 1K$ ,  $\Delta x = 1m$ , then

For lunar regolith with  $K = 0.0021 \text{ W/mK}$ ,

$$A = \frac{(1 \text{ W})(1 \text{ m})}{(0.0021 \text{ W/mK})(-1 \text{ K})} = \underline{476.2 \text{ m}^2}$$

For Cotton,  $K = 0.06 \text{ W/m.K}$

$$\therefore A = 16.7 \text{ m}^2$$

Similarly;

$$\left. \begin{aligned} A_{\text{copper}} &= 0.0025 \text{ m}^2 = 25 \text{ cm}^2 \\ A_{\text{silver}} &= 0.0023 \text{ m}^2 = 23 \text{ cm}^2 \\ A_{\text{diamond}} &= 0.0004 \text{ m}^2 = 4.4 \text{ cm}^2 \end{aligned} \right\} \begin{array}{l} K \text{ evaluated} \\ \text{at } 300 \text{ K.} \end{array}$$

# Appendix B

## Design Requirements

Demand/Wish	Requirements
	<b>I. Functional</b>
D	1. Reduce the heat absorbed by the radiator
D	2. Support the radiator and the shade
D	3. Deploy the system
D	4. Retract the system
D	5. Store the system
W	6. Control dust accumulation
D	7. Attach radiator to shading device
	<b>II. Geometry</b>
D	1. Minimize stowed volume
	<b>III. Forces</b>
D	1. Minimize deploying forces for manual assembly
D	2. System should withstand acceleration forces during takeoff and landing
D	3. Isolate structure from damaging vibrations
D	4. Safety factor = 1.5. Yield stresses should be 1.5 times the maximum stresses of the system
	<b>IV. Energy</b>
D	1. Two systems: 10 kW and 25 kW heat rejection capacity.
D	2. Minimize power consumption of deploying and retracting mechanism, if automatic
D	3. Shade should reduce the radiant energy incident on the radiator

### Design Requirements (Continued)

	<b>V. Materials</b>
D	1. 10 kW system should withstand 200 deploy/retract cycles
D	2. 25 kW system must have a 20 year life
D	3. Resist deterioration caused by spectrum of solar and planetary radiation
D	4. Should function in the range of temperatures on the moon: 102 K to 384 K
W	5. Minimize adhesion of lunar dust to shade material
	<b>VI. Safety</b>
D	1. Safe during remote deployment and retraction
D	2. Safe during extravehicular activity (EVA) deployment and retraction
D	3. Structure must be stable under possible impacts and vibrations
	<b>VII. Ergonomics</b>
D	1. Reasonable to operate, deploy, and retract for an astronaut (astronaut has limited mobility)
D	2. Components that need maintenance should be easily accessible
D	3. Tools (if any) should be easily handled by astronauts.
W	4. If possible, integrate tools into design of the structure
	<b>VIII. Assembly</b>
D	1. If the 25 kW system cannot be made remotely deployable, it must be constructed by 2 crew members performing a maximum of 3 hours of EVA each
D	2. The backup should require no more than 2 hours of EVA
	<b>IX. Transport</b>
D	1. Minimize mass of shade and support structure

**Design Requirements (Continued)**

	<b>X. Operation</b>
D	1. System should operate under severe thermal gradients
D	2. System should perform its function at the lunar equator during midday
D	3. Misalignment of $\pm 5^\circ$ from the equator should not affect the performance of the system
	<b>XI. Maintenance</b>
D	1. Service intervals are once every 5 years, for no more than 2 hours of EVA
	<b>XII. Reliability</b>
D	1. Incorporate redundant components or procedure where a failure will cause the system to perform at less than 50% of design capacity



# Appendix C

## Material and Thermal Parameters [5]

Parameter	Value
Radiator operating temperature	270 K
Solar flux at lunar surface	1371 W/m <sup>2</sup>
Average albedo at lunar surface	0.07
Lunar surface temperatures	102 K at night to 384 K during the day
Lunar surface absorptivity	0.93
Lunar surface emissivity	0.96
Radiator fin efficiency	0.9
Radiator emissivity	0.9
Radiator solar absorptivity	0.23
Shade material	aluminized polyimide
Shade inner surface emissivity	0.05
Shade IR reflectivity	0.95
Shade solar reflectivity	0.86
Moon's gravity	1/6 of earth's gravity
Thermal system working fluid	Freon or ammonia

## APPENDIX D

### Estimated Relative Thermal Performance Calculations.

Thermal performance calculations were done for Shades at lunar midday when the sun is at  $\pm 1.53^\circ$  from the ecliptic.

Values were calculated using estimated values for the view factors for the purpose of relative comparisons between the shade systems. They are not meant to be absolute values for each system.

#### I General Equations

A. Steady state temperature of the shade:

$$Q_{\text{absorbed}} = Q_{\text{out}}$$

$$\alpha_{\text{solar}} [F]_{\text{solar}} Q_{\text{solar}} + \alpha_{\text{IR}} [F]_{\text{solar}} Q_{\text{IR}} = \epsilon \sigma T_{\text{shade}}^4$$

Where

$\alpha_{\text{solar}}$  = absorptivity in solar spectral range.

$\alpha_{\text{IR}}$  = absorptivity in infrared spectral range

$\epsilon$  = emissivity

$[F]_x$  = View factors.

Components for  $F_{\text{solar}}$ :

- Albedo ( $F_{\text{albedo}}$ )
- Direct Solar ( $F_{\text{Direct Solar}}$ )
- Reflected from radiator ( $F_{\text{ref, rad}}$ )

Components for  $F_{\text{IR}}$ :

- From Moon surface ( $F_{\text{surface}}$ )
- From radiator ( $F_{\text{radiator}}$ )

B. Effective heat sink temperature for radiator:

$$Q_{\text{absorbed}} = Q_{\text{out}}$$

$$\alpha FQ|_{\text{solar}} + \alpha FQ|_{\text{IR}} = \epsilon \sigma T_{\text{sink}}^4$$

Components for  $F_{\text{solar}}$ :

- Albedo ( $F_{\text{albedo}}$ )
- Direct Solar ( $F_{\text{Direct Solar}}$ )
- Reflected from shade to radiator ( $F_{\text{ref, shade}}$ )

Components for  $F_{\text{IR}}$

- Moon surface ( $F_{\text{surface}}$ )
- Shade ( $F_{\text{shade}}$ )
- Radiator emission reflected from shade ( $F_{\text{shade rad}}$ )

C. Assumptions;

1. Neglect dust accumulation.
2. Specular reflectivity of shade in both IR and solar spectral ranges.
3. Diffuse emissivities.
4. Shade is at ground level.

D.  $Q''$  Values;

1.  $Q''_{\text{solar total}} = 1371 \text{ W/m}^2$
2.  $Q''_{\text{albedo}} = (0.07)(1371 \text{ W/m}^2) = 95.97 \text{ W/m}^2$
3.  $Q''_{\text{r}} @ \text{ lunar midday}$

$$\begin{aligned} &= \epsilon \sigma T_{\text{surface}}^4 \\ &= (0.9)(5.67 \times 10^{-8} \text{ W/m}^2 \text{ K}^4)(384 \text{ K})^4 \\ &= 1146.54 \text{ W/m}^2 \end{aligned}$$

$$\begin{aligned} 4. Q''_{\text{radiator}} &= \epsilon \sigma T_{\text{radiator}}^4 \\ &= (0.9)(5.67 \times 10^{-8} \text{ W/m}^2 \text{ K}^4)(270 \text{ K})^4 \\ &= 271.19 \text{ W/m}^2 \end{aligned}$$

E. Radiator properties:  $\alpha_{\text{solar}} = 0.23$  ( $\rho_{\text{solar}} = 0.77$ )

$$\alpha_{\text{IR}} = 0.9$$

$$\epsilon_{\text{IR}} = 0.9$$

Shade properties:

$$\alpha_{\text{solar}} = 0.14 \quad (\rho_{\text{solar}} = 0.86)$$

$$\alpha_{\text{IR}} = 0.05 \quad (\rho_{\text{solar}} = 0.95)$$

$$\epsilon_{\text{IR}} = 0.05$$

I

## Parabolic Shading Device

A. View factors for shade:

$$F_{\text{albedo}} = 0.8$$

$$F_{\text{direct solar}} = 0.4$$

$$F_{\text{ref. rad}} = 1$$

$$F_{\text{surface}} = 0.8$$

$$F_{\text{radiator}} = 0.6$$

$$Q''_{\text{shade}} = \alpha_{\text{solar}} [F_{\text{albedo}} Q''_{\text{albedo}} + F_{\text{direct solar}} Q''_{\text{solar}} + F_{\text{ref. rad}} Q''_{\text{solar}} \\ \text{rad}] + \alpha_{\text{IR}} [F_{\text{surface}} Q''_{\text{R}} + F_{\text{radiator}} Q''_{\text{radiator}}]$$

$$= 0.14 [(0.8)(95.97 \text{ W/m}^2) + (0.4)(1371 \text{ W/m}^2) \\ + (1)(1371 \text{ W/m}^2)(0.77 \sin 1.53^\circ)]$$

$$+ 0.05 [(0.8)(1146.54 \text{ W/m}^2) + (0.06)(271.19 \text{ W/m}^2)]$$

$$Q''_{\text{shade}} = (0.055)(475.94)^4 = 145.47 \text{ W/m}^2$$

B. View factors for radiator

$$F_{\text{albedo}} = 0$$

$$F_{\text{direct solar}} = \sin 1.53$$

$$F_{\text{ref shade}} = 0.05$$

$$F_{\text{surface}} = 0$$

$$F_{\text{shade}} = 0.7$$

$$F_{\text{shade rad}} = 0.01$$

$$\alpha_{\text{solar}} [F_{\text{albedo}} Q''_{\text{albedo}} + F_{\text{direct solar}} Q'_{\text{solar}} + F_{\text{ref. shade}} \rho_{\text{solar shade}} Q'_{\text{solar}} F_{\text{direct solar shade}}] + \alpha_{\text{IR}} [F_{\text{surface}} Q''_{\text{IR}} + F_{\text{shade}} Q''_{\text{shade}} + F_{\text{ref. rad}} Q''_{\text{radiator}} \rho_{\text{shade IR}} F_{\text{radiator}}] = \epsilon \sigma T_{\text{sink}}^4$$

$$0.23 [ \sin 153 (1371 \text{ W/m}^2) + (0.05)(0.86)(1371 \text{ W/m}^2)(0.4) ] + 0.9 [ 0.7(145.47 \text{ W/m}^2) + (0.01)(271.19 \text{ W/m}^2)(0.95)(0.6) ] = 0.9 \sigma T_{\text{sink}}^4$$

$$T_{\text{sink}} = 213.93 \text{ K}$$

### III Modified Parabolic Reflector

A. View factors for shade;

$$F_{\text{albedo}} = 0.8$$

$$F_{\text{direct solar}} = 0.4$$

$$F_{\text{ref rad}} = 1.0$$

$$F_{\text{surface}} = 0.8$$

$$F_{\text{radiator}} = 0.59$$

$$\alpha_{\text{solar}} [F_{\text{albedo}} Q''_{\text{albedo}} + F_{\text{direct solar}} Q'_{\text{solar}} + F_{\text{ref rad}} \rho_{\text{rad}} Q'_{\text{solar}} \sin 153] + \alpha_{\text{IR}} [F_{\text{surface}} Q''_{\text{surface}} + F_{\text{radiator}} Q'_{\text{radiator}}] = \epsilon \sigma T_{\text{shade}}^4$$

$$0.14 \left[ 0.8 (95.97 \text{ W/m}^2) + 0.4 (1371 \text{ W/m}^2) + 1 (0.77) (1371 \text{ W/m}^2) \right. \\ \left. \times \sin 1.53^\circ \right] \\ + 0.05 \left[ 0.8 (1146.54 \text{ W/m}^2) + (0.59) (271.19 \text{ W/m}^2) \right] \\ = \epsilon \sigma \bar{T}_{\text{shade}}^4$$

$$\bar{T}_{\text{shade}} = 475.83 \text{ K} \quad Q''_{\text{shade}} = 0.05 \sigma (475.83 \text{ K})^4 \\ = 145.33 \text{ W/m}^2$$

B. View factors for radiator

$$F_{\text{albedo}} = 0$$

$$F_{\text{direct solar}} = \sin 1.53^\circ$$

$$F_{\text{ref shade}} = 0.01$$

$$F_{\text{surface}} = 0$$

$$F_{\text{shade}} = 0.7$$

$$F_{\text{shade rad}} = 0.01$$

$$\alpha_{\text{solar}} \left[ F_{\text{direct solar}} Q''_{\text{solar}} + F_{\text{ref shade}} Q''_{\text{solar}} f_{\text{shade}} F_{\text{direct solar shade}} \right] \\ + \alpha_{\text{IR}} \left[ F_{\text{shade}} Q''_{\text{shade}} + F_{\text{shade rad}} Q''_{\text{radiator}} f_{\text{shade IR}} F_{\text{rad}} \right] \\ = \epsilon \sigma \bar{T}_{\text{sink}}^4$$

$$0.23 \left[ \sin 1.53^\circ (1371 \text{ W/m}^2) + (0.01) (1371 \text{ W/m}^2) (0.86) (0.4) \right] \\ + 0.9 \left[ 0.7 (145.33 \text{ W/m}^2) + (0.01) (271.19 \text{ W/m}^2) (0.95) (0.59) \right] \\ = 0.9 \sigma \bar{T}_{\text{sink}}^4$$

$$\bar{T}_{\text{sink}} = 211.67 \text{ K}$$

## IV L-Shaped Panels

A. View factors for shade :

$$F_{\text{albedo}} = 0.7$$

$$F_{\text{direct solar}} = 0.5$$

$$F_{\text{ref-rad}} = 1.0$$

$$F_{\text{surface}} = 0.7$$

$$F_{\text{radiator}} = 0.5$$

$$\begin{aligned} & \alpha_{\text{solar}} [F_{\text{albedo}} Q'_{\text{albedo}} + F_{\text{direct solar}} Q''_{\text{solar}} + F_{\text{ref-rad}} (\sin 1.53^\circ) \rho_{\text{rad}} Q''_{\text{solar}}] \\ & + \alpha_{\text{IR}} [F_{\text{surface}} Q''_{\text{surface}} + F_{\text{radiator}} Q''_{\text{radiator}}] \\ & = \epsilon \sigma T_{\text{shade}}^4 \end{aligned}$$

$$\begin{aligned} & 0.14 [0.7(95.97 \text{ W/m}^2) + (0.5)(1371 \text{ W/m}^2) + 1(\sin 1.53)(0.77) \\ & \quad (1371 \text{ W/m}^2)] \\ & + 0.05 [0.7(1146.54 \text{ W/m}^2) + 0.5(271.19 \text{ W/m}^2)] \\ & = 0.05(\sigma) T_{\text{shade}}^4 \end{aligned}$$

$$Q''_{\text{shade}} = 0.05 \sigma T_{\text{shade}}^4 = 150.23 \text{ W/m}^2$$

B. View factors for radiator :

$$F_{\text{albedo}} = 0$$

$$F_{\text{direct solar}} = \sin 1.53^\circ$$

$$F_{\text{ref shade}} = 0.9$$

$$F_{\text{surface}} = 0$$

$$F_{\text{shade}} = 0.75$$

$$F_{\text{shade-rad}} = 0.4$$



$$\begin{aligned}
& \alpha_{\text{solar}} [F_{\text{direct solar}} Q''_{\text{solar}} + F_{\text{ref shade}} P_{\text{shade solar}} Q''_{\text{solar}} F_{\text{direct solar shade}}] \\
& + \alpha_{\text{IR}} [F_{\text{shade}} Q''_{\text{shade}} + F_{\text{shade rad}} J_{\text{shade IR}} Q''_{\text{rad}} F_{\text{radiator}}] \\
& = \epsilon \sigma T_{\text{sink}}^4 \\
& 0.23 [\sin 1.53^\circ (1371 \text{ W/m}^2) + 0.9(0.86)(1371 \text{ W/m}^2)(0.5)] \\
& + 0.9 [0.75(Q''_{\text{shade}}) + (0.4)(0.95)(271.19 \text{ W/m}^2)(0.5)] \\
& = 0.9 \sigma T_{\text{sink}}^4
\end{aligned}$$

$$T_{\text{sink}} = 272.72 \text{ K}$$

## ∇ Fresnel Reflector

A. View factors for shade

$$F_{\text{albedo}} = 0.8$$

$$F_{\text{direct solar}} = 0.6$$

$$F_{\text{refrad}} = 0.6$$

$$F_{\text{surface}} = 0.8$$

$$F_{\text{radiator}} = 0.6$$

$$\begin{aligned}
& \alpha_{\text{solar}} [F_{\text{albedo}} Q''_{\text{albedo}} + F_{\text{direct solar}} Q''_{\text{solar}} + F_{\text{refrad}} (\sin 1.53^\circ) \\
& \quad P_{\text{radiator solar}} Q''_{\text{solar}}] \\
& + \alpha_{\text{IR}} [F_{\text{surface}} Q''_{\text{surface}} + F_{\text{radiator}} Q''_{\text{radiator}}] \\
& = \epsilon \sigma T_{\text{shade}}^4 = Q''_{\text{shade}} \\
& Q''_{\text{shade}} = 182.28 \text{ W/m}^2
\end{aligned}$$

B. View factors for radiator.

$$F_{\text{albedo}} = 0$$

$$F_{\text{direct solar}} = \sin 1.53^\circ$$

$$F_{\text{ref. shade}} = 0.4$$

$$F_{\text{surface}} = 0$$

$$F_{\text{shade}} = 0.75$$

$$F_{\text{shade rad}} = 0.5$$

$$\alpha_{\text{solar}} [F_{\text{direct solar}} Q''_{\text{solar}} + F_{\text{ref. shade}} \rho_{\text{shade solar}} F_{\text{direct solar shade}} Q''_{\text{solar}}]$$

$$+ \alpha_{\text{IR}} [F_{\text{shade}} Q''_{\text{shade}} + F_{\text{shade rad}} Q''_{\text{rad}} \rho_{\text{shade IR}} F_{\text{rad}}]$$
$$= \epsilon \sigma T_{\text{sink}}^4$$

$$0.23 [\sin 1.53^\circ (1371 \text{ W/m}^2) + (0.4)(0.8)(0.6)(1371 \text{ W/m}^2)]$$
$$+ 0.9 [0.75(182.28 \text{ W/m}^2) + (0.5)(271.19 \text{ W/m}^2)(0.95)(0.5)]$$
$$= 0.9 \sigma T_{\text{sink}}^4$$

$$T_{\text{sink}} = 264.55 \text{ K}$$

## VI Winged Radiator

A. View factors for shade.

$$F_{\text{albedo}} = 0.85$$

$$F_{\text{direct solar}} = 0.4$$

$$F_{\text{ret rad}} = 1.0$$

$$F_{\text{surface}} = 0.85$$

$$F_{\text{radiator}} = 0.5$$

$$\alpha_{\text{solar}} [F_{\text{albedo}} Q''_{\text{albedo}} + F_{\text{direct solar}} Q''_{\text{solar}} + F_{\text{ret rad}} (\sin 1.53^\circ) \int_{\text{rad}} Q''_{\text{solar}}$$

$$+ \alpha_{\text{IR}} [F_{\text{surface}} Q''_{\text{surface}} + F_{\text{radiator}} Q''_{\text{radiator}}]$$

$$= \epsilon \sigma T_{\text{shade}}^4 = Q''_{\text{shade}}$$

$$0.14 [0.85(95.97 \text{ W/m}^2) + 0.4(1371 \text{ W/m}^2) + 1(\sin 1.53^\circ) (0.77)(1371 \text{ W/m}^2)]$$

$$+ 0.05 [0.85(1146.54 \text{ W/m}^2) + (0.5)(271.19 \text{ W/m}^2)] = Q''_{\text{shade}}$$

$$Q''_{\text{shade}} = 147.65 \text{ W/m}^2$$

B. View factors for radiator:

$$F_{\text{albedo}} = 0$$

$$F_{\text{direct solar}} = 0$$

$$F_{\text{ref shade}} = 0.3$$

\* Assumption: Serrated surface reduces total reflected incident radiation by 70%

$$F_{\text{surface}} = 0$$

$$F_{\text{shade}} = 0.79$$

$$F_{\text{shade rad}} = 0.5$$

$$\alpha_{\text{solar}} [F_{\text{ref shade}} Q''_{\text{solar}} (0.4) (p_{\text{shade solar}})]$$

$$+ \alpha_{\text{IR}} [F_{\text{shade}} Q''_{\text{shade}} + F_{\text{shade rad}} Q''_{\text{rad}} (p_{\text{shade IR}} F_{\text{radiator}})]$$

$$= \epsilon \sigma T_{\text{sink}}^4$$

$$0.23 [0.3 (1371 \text{ W/m}^2) (0.4) (0.86)]$$

$$+ 0.9 [0.79 (147.65 \text{ W/m}^2) + 0.5 (271.19 \text{ W/m}^2) (0.05)]$$

$$= 0.9 \sigma T_{\text{sink}}^4$$

$$T_{\text{sink}} = 229.10 \text{ K}$$

VII

## Modified Winged Radiator

A. View factors for shade:

$$F_{\text{albedo}} = 0.85$$

$$F_{\text{direct solar}} = 0.4$$

$$F_{\text{ret rad}} = 1$$

$$F_{\text{surface}} = 0.85$$

$$F_{\text{radiator}} = 0.5$$

$$\begin{aligned} & \alpha_{\text{solar}} \left[ F_{\text{albedo}} Q'_{\text{albedo}} + F_{\text{direct solar}} Q''_{\text{solar}} + F_{\text{ret rad}} (\sin 1.53^\circ) \right. \\ & \quad \left. \int_{\text{solar}} Q''_{\text{solar}} \right] \\ & + \alpha_{\text{R}} \left[ F_{\text{surface}} Q'_{\text{surface}} + F_{\text{radiator}} Q''_{\text{radiator}} \right] \\ & = \epsilon \sigma T_{\text{shade}}^4 = Q''_{\text{shade}} \end{aligned}$$

$$\begin{aligned} & 0.14 \left[ 0.85 (95.97 \text{ W/m}^2) + 0.4 (1371 \text{ W/m}^2) + 1 (\sin 1.53^\circ) (0.77) \right. \\ & \quad \left. (1371 \text{ W/m}^2) \right] \\ & + 0.05 \left[ 0.85 (1146.54 \text{ W/m}^2) + (0.5) (271.19 \text{ W/m}^2) \right] \\ & = Q''_{\text{shade}} \end{aligned}$$

$$Q''_{\text{shade}} = 147.65 \text{ W/m}^2$$

B. View factors for radiator:

$$F_{\text{albedo}} = 0$$

$$F_{\text{direct solar}} = \sin 1.53^\circ$$

$$F_{\text{ret shade}} = 0.3$$

$$F_{\text{surface}} = 0$$

$$F_{\text{shade}} = 0.75$$

$$F_{\text{shade rad}} = 0.5$$

$$\alpha_{\text{solar}} [\sin 1.53^\circ (1371 \text{ W/m}^2) + F_{\text{ref. rad}} F_{\text{direct solar}} \rho_{\text{shade}} Q''_{\text{solar}}] + \alpha_{\text{IR}} [F_{\text{shade}} Q''_{\text{shade}} + F_{\text{shade rad}} Q''_{\text{rad}} F_{\text{radiator}} \rho_{\text{shade IR}}] = \epsilon \sigma T_{\text{sink}}^4$$

$$0.23 [\sin 1.53^\circ (1371 \text{ W/m}^2) + 0.3(0.4)(0.86)(1371 \text{ W/m}^2)] + 0.9 [0.75 (147.65 \text{ W/m}^2) + 0.5(271.19 \text{ W/m}^2)(0.5)(0.95)] = 0.9 \sigma T_{\text{sink}}^4$$

$$T_{\text{sink}} = 249.77 \text{ K}$$

VIII Shading Blinds

$$\alpha_{\text{solar}} F Q''_{\text{solar}} + \alpha_{\text{IR}} F Q''_{\text{IR}} = \epsilon \sigma T_{\text{sink}}^4$$

$$\alpha_{\text{solar}} F_{\text{solar}} Q''_{\text{solar}} + \alpha_{\text{IR}} F_{\text{surface}} Q''_{\text{surface}} + \alpha_{\text{IR}} F_{\text{radiator}} Q''_{\text{radiator}} = Q''_{\text{shade}}$$

$$F_{\text{solar}} = 1$$

$$F_{\text{surface to shade}} = 0.7$$

$$F_{\text{radiator}} = 0.5$$

$$Q''_{\text{shade}} = 0.14(1)(1371 \text{ W/m}^2) + (0.05)(0.7)(1146.54 \text{ W/m}^2) + (0.5)(0.05)(271.19 \text{ W/m}^2) = 238.85 \text{ W/m}^2$$

For radiator:

$$F_{\text{direct solar}} = 0$$

$$F_{\text{albedo surface}} = 0$$

$$F_{\text{surface IR}} = 0$$

$$F_{\text{reflected shade}} = 0.6$$

$$F_{\text{emitted shade}} = 0.6$$

$$\alpha_{\text{IR}} [F_{\text{reflected shade}} [Q''_{\text{radiator}} F_{\text{radiator}} \rho_{\text{shade}}^{\text{IR}} + Q''_{\text{surface}} F_{\text{surface}} \rho_{\text{shade}}^{\text{IR}}] + F_{\text{emitted shade}} Q''_{\text{shade}}]$$

$$= \epsilon \sigma T_{\text{sink}}^4$$

$$0.9 [0.6 [271.19 \text{ W/m}^2 (0.1)(0.95) + (1146.54 \text{ W/m}^2) (0.9)(0.95)] + (0.6)(238.85 \text{ W/m}^2)]$$

$$= 0.9 \sigma T_{\text{sink}}^4$$

$$T_{\text{sink}} = 338.79 \text{ K}$$

# Appendix E

## Heat Transfer Calculations

Figure C-1 presents the components of the radiation incident on the radiator.

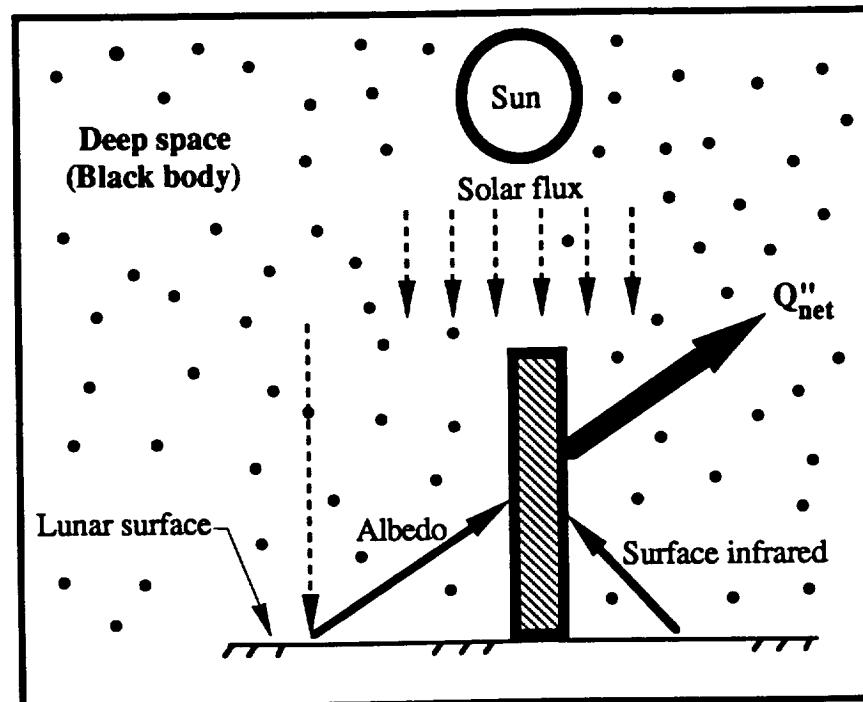


Figure C-1. Radiator heat transfer processes

The heat transfer processes are described by the following equations,

$$Q''_{net} = Q''_{out} - Q''_{absorbed}$$

$$Q''_{out} = \eta \sigma \epsilon T_r^4$$

$$Q''_{absorbed} = \alpha F Q''_{solar} + \alpha F(\text{albedo}) Q''_{solar} + \alpha_{IR} F(\text{infrared})$$

$$Q''_{net} = \eta \sigma \epsilon (T_r^4 - T_{sink}^4)$$

where,

$$Q''_{net} = \text{net radiation transfer}$$



$Q''_{\text{out}}$  = radiation out of the radiator

$Q''_{\text{absorbed}}$  = radiation into the radiator

$T_r$  = radiator temperature

$T_{\text{sink}}^4$  = effective heat sink temperature (270K)

$\eta$  = radiator fin efficiency (0.9)

$\sigma$  = Steffan Boltzman's constant ( $5.67 * 10^{-8}$ )

$\epsilon$  = radiator emissivity (0.9)

$F$  = view factor

$\alpha$  = solar absorptivity (0.23)

$\alpha_{\text{IR}}$  = radiator absorptivity in the infrared (long wavelength) range (0.9)

albedo = .07

### I. Vertical Radiator

Considering the view factors for a vertical radiator, the fluxes incident on the radiator are [5]:

Solar flux =  $37 \text{ W/m}^2$

Albedo radiation =  $48 \text{ W/m}^2$

Surface infrared radiation =  $592 \text{ W/m}^2$

A. Percentage (x) by which the infrared radiation has to be reduced to produce a net radiation transfer out of the radiator,

$$Q''_{\text{out}} = Q''_{\text{absorbed}}$$

$$\eta \sigma \epsilon T_r^4 = \alpha F Q''_{\text{solar}} + \alpha F(\text{albedo}) Q''_{\text{solar}} + \alpha_{\text{IR}} F(\text{infrared}) (1 - x)$$

$$244.07 \text{ W/m}^2 = 19.55 \text{ W/m}^2 + 532.8 (1 - x) \text{ W/m}^2$$

$$x = 57.9\%$$

B. Percentage (x) by which the solar radiation (albedo & direct solar radiation) has to be reduced to produce a net radiation transfer out of the radiator,

$$Q''_{\text{out}} = Q''_{\text{absorbed}}$$

$$\eta \sigma \epsilon T_r^4 = \alpha F Q''_{\text{solar}} (1 - x) + \alpha F(\text{albedo}) Q''_{\text{solar}} (1 - x) + \alpha \text{IR} F(\text{infrared})$$

$$244.07 \text{ W/m}^2 = 19.55 (1 - x) \text{ W/m}^2 + 532.8 \text{ W/m}^2$$

$$-288.73 \text{ W/m}^2 = 19.55 (1 - x)$$

$$x = 1,577\%$$

$$x > 100\%$$

Therefore, reducing only the albedo and direct solar radiation will not result in a net radiation transfer out of the radiator.

C. Percentage (x) by which the infrared radiation has to be reduced if there is no albedo or direct solar radiation incident on the radiator.

$$Q''_{\text{out}} = Q''_{\text{absorbed}}$$

$$\eta \sigma \epsilon T_r^4 = \alpha \text{IR} F(\text{infrared}) (1 - x)$$

$$244.07 \text{ W/m}^2 = 532.8 (1 - x) \text{ W/m}^2$$

$$x = 54\%$$

## II. Horizontal Radiator

The view factors for the albedo and infrared radiation are almost zero for a horizontal radiator. The only incident radiation to be considered is the solar flux ( $1371 \text{ W/m}^2$ ) [2].

Percentage (x) by which the solar radiation has to be reduced so that there is a net radiation transfer out of the radiator,

$$Q''_{\text{out}} = Q''_{\text{absorbed}}$$

$$\eta \sigma \epsilon T_r^4 = \alpha F Q''_{\text{solar}} (1 - x)$$

$$244.07 \text{ W/m}^2 = 315.33 (1 - x) \text{ W/m}^2$$

$$x = 22.6\%$$

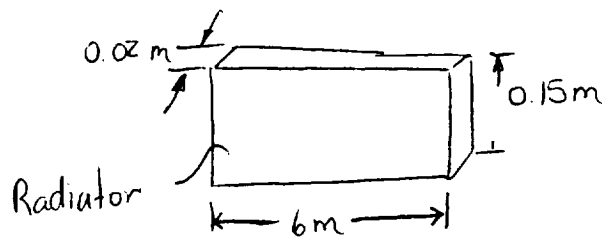
## Appendix F

### Mass, Volume, and Power Calculations

This Appendix presents detailed calculations of the mass of each shading device and support structure. Also, the stowage volume, deployed volume, and power required to deploy each system is provided.

Assumptions common to all alternates:

1. The shading device is fitted to a radiator of dimensions:  $6\text{ m} \times 0.02\text{ m} \times 0.15\text{ m}$



The density of the radiator per unit width is

$$\rho_r = 5 \frac{\text{kg}}{\text{m}}$$

2. A safety factor of 1.5

3. The shading devices are made of Kapton sheets supported by Aluminum rods. Unless specified, the cross-section of the Aluminum rods are square. The thickness of Kapton used is 0.0127cm. The density per unit width is

$$\rho_k = 0.1814 \frac{\text{kg}}{\text{m}^2}$$

The properties used for Aluminum are

$$\rho_{Al} = 2800 \frac{\text{kg}}{\text{m}^3}$$

$$E_{Al} = 72 \times 10^9 \frac{\text{N}}{\text{m}^2}$$

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Fundamentals of Machine  
Component Design

4. The time to deploy the shading system and support structure is 60 seconds.

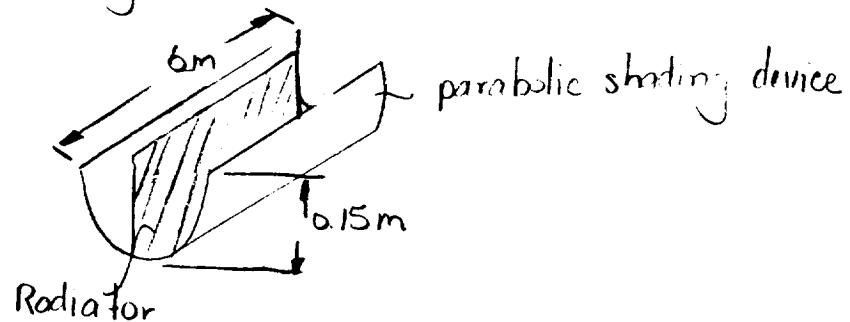
5. Each support structure contains 5 shading systems

6. Deploying and Retracting occur on the moon surface. Therefore, the power calculations are done using the moon's gravity.

$$g_{\text{moon}} = \frac{1}{6} g_{\text{earth}} = 1.635 \text{ m/s}^2$$

# Mass Calculations of Rigid Parabola Shading System and Folding Support Structure

## Parabolic Shading Device



- mass of 5 radiators

$$m_r = \rho_r A = \frac{5 \text{ kg}}{\text{m}^2} \times 6 \text{ m} \times 0.15 \text{ m}$$

$$m_r = 4.5 \text{ kg}$$

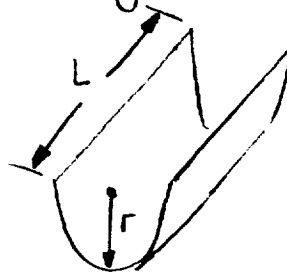
$$m_{r_r} = 5 \times 4.5 \text{ kg} = \underline{\underline{22.5 \text{ kg}}}$$

- total mass of Kapton in 5 shades:

Assume: shade geometry is a semicircle

$$r = 0.35 \text{ m}$$

$$L = 6 \text{ m}$$



$$m_s = \rho_k P L$$

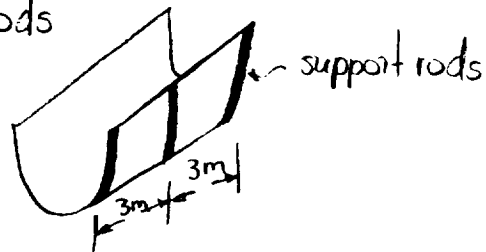
$$P = \pi r$$

$$m_s = 0.1814 \frac{\text{kg}}{\text{m}^2} \times \pi \times 0.35 \text{ m} \times 6 \text{ m}$$

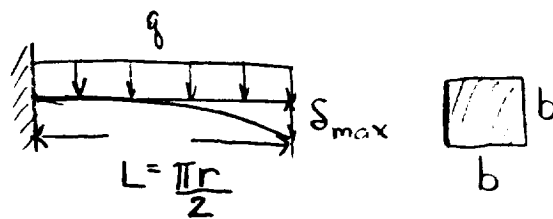
$$m_s = 1.197 \text{ kg}$$

$$m_{\text{ST}} = 5 \times 1.197 = 5.98 \text{ kg}$$

- total mass of support rods



Assume: - support rods are loaded cantilever beams



$$\text{let } \delta_{\text{max}} \leq 1 \text{ mm}$$

$$\delta_{\text{max}} = \frac{1.5 \times q \times L^4}{8 \times E_{\text{AI}} \times I}$$

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$$q = \frac{m_s \times g}{L}$$

$$I = \frac{1}{12} b^4$$

$$b = \left[ \frac{12 \times 1.5 \times L^3 \times m_s \times g}{8 \times E_{al} \times \delta_{max}} \right]^{1/4}$$

$$b = \left[ \frac{12 \times 1.5 \times (0.550)^3 \text{ m}^3 \times 1.197 \text{ kg} \times 9.81 \frac{\text{m}}{\text{s}^2}}{8 \times 72 \times 10^9 \frac{\text{N}}{\text{m}^2} \times 0.001 \text{ m}} \right]^{1/4}$$

$$b = 0.0157 \text{ m}$$

$$b = 1.57 \text{ cm}$$

$$m_{SR} = b^2 \times L \times \rho_{al} = (0.0157)^2 \text{ m}^2 \times 6 \text{ m} \times 2800 \frac{\text{kg}}{\text{m}^3}$$

$$m_{SR} = 0.379$$

each shade has 6 support rods and there are 5 shades

$$m_{SRT} = 6 \times 5 \times 0.379 \text{ kg}$$

$$m_{SRT} = \underline{\underline{11.38 \text{ kg}}}$$

total mass of the shading system:

$$11.38 \text{ kg} + 22.5 \text{ kg} + 5.98 \text{ kg}$$

$$= \underline{\underline{39.86 \text{ kg}}}$$

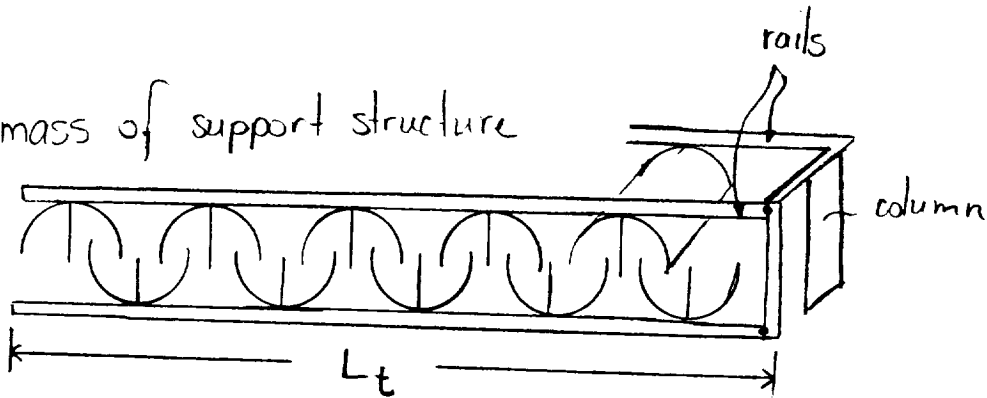
$$\approx \underline{\underline{40 \text{ kg}}}$$



Discontinuous Masses:

joints - 1 kg  
 motion system - 4 kg

- mass of support structure



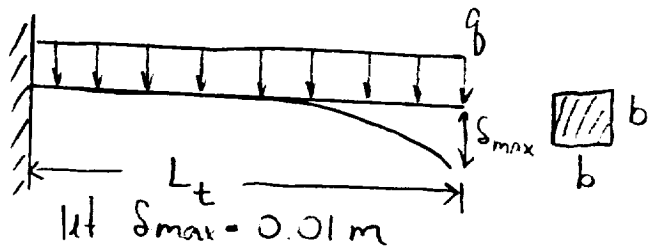
The top parabolas are attached to rails of length  $L_t$ , which depends on the length of the 5 parabolic shading devices.

the total length:

$$L_t = 5 \times [0.70 \text{ m} + 2(0.000127 + 0.0157) \text{ m}]$$

$$L_t = 3.67 \text{ m}$$

Assume: - each rail is a cantilever beam  
 - weight of shading system is evenly distributed along each rail.



$$q = \frac{39.86}{2} \times \frac{q}{L_t}$$

$$b = \left[ \frac{12 \times 1.5 \times (3.67)^3 \text{ m}^3 \times 19.932 \text{ kg} \times 9.81 \text{ m/s}^2}{8 \times 72 \times 10^9 \frac{\text{N}}{\text{m}^2} \times 0.01} \right]^{1/4}$$

$$b = .0739 \text{ m}$$

$$b = 7.40 \text{ cm}$$

$$m_{\text{rail}} = \rho_{\text{rail}} V = 2800 \frac{\text{kg}}{\text{m}^3} \times (.074)^2 \text{ m}^2 \times 3.67 \text{ m}$$

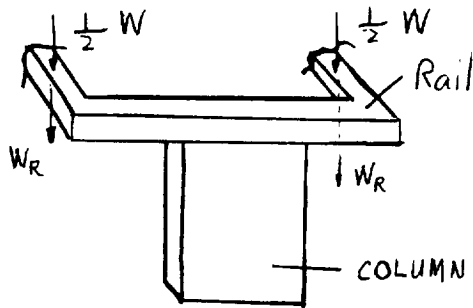
$$= 56.27 \text{ kg}$$

mass for 4 rails:

$$4 \times 56.27 = \underline{\underline{224 \text{ kg}}}$$

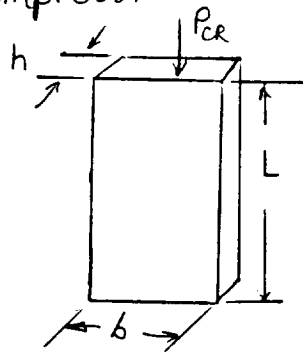
- mass of column

The column joins the top section and bottom section of the support structure. It is assumed the weight of the shading systems is concentrated.



$W_R$  = weight of the rail  
 $W$  = weight of the shading systems

Because each rail supports half of the weight of the shading system the moment caused by the weight on the left rail is equal and opposite to the moment caused by the other rail. As a result, the column is under compression.



$$L = 0.40 \text{ m}$$

$$b = 0.61 \text{ m}$$

To determine the minimum value of  $h$  which will prevent the column from buckling, Euler's equation is used

$$P_{CR} = \frac{\pi^2 EI}{L_e^2}$$

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Fundamentals of Machine  
Component Design ]

$P_{CR}$   $\equiv$  load which causes buckling

$I$   $\equiv$  moment of inertia of the section with respect to the buckling-bending axis. This is the smallest  $I$  about any axis.

$L_e$   $\equiv$  equivalent length of the column

Assumptions:

1. perfectly straight column
2. load precisely axial
3. stress in linear range

Analysis:

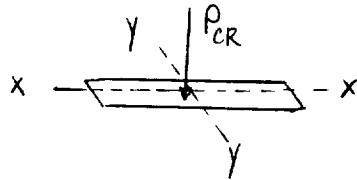
$$P_{CR} = s.f. \times m \times g$$

$$= 1.5 \times (40 \text{ kg} + 112 \text{ kg}) \times 9.81 \text{ m/s}^2$$

$$P_{CR} = 2236.7 \text{ N}$$

$$L_e = L$$

The smallest value of  $\Gamma$  occurs about the x-x axis.



Rewriting Euler's Equation

$$\Gamma = \frac{P_{CR} L_e^2}{\pi^2 E_{Al}} = \frac{1}{12} b h^3$$

$$h = \left[ \frac{12}{b} \times P_{CR} \times L_e^2 \right]^{1/3} = \left[ \frac{12}{0.61} \times 2236.7 \times (0.40)^2 \frac{\text{m}^2}{\pi^2 \times 72 \times 10^9 \text{ N/m}^2} \right]^{1/3}$$

$$h = 2.15 \text{ mm}$$

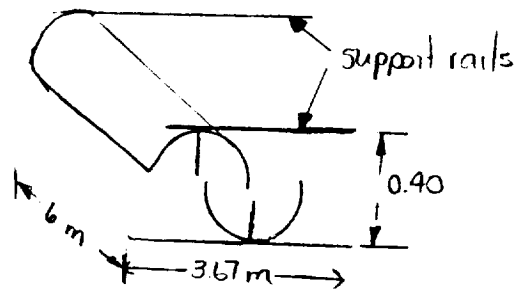
$$m_{\text{column}} = \rho_{Al} V = 2800 \frac{\text{kg}}{\text{m}^3} \times 0.00215 \text{ m} \times 0.61 \text{ m} \times 0.40 \text{ m}$$

$$m_{\text{column}} = \underline{\underline{1.47 \text{ kg}}}$$

Total Mass of the Rigid Parabola Shading System and  
Folding Support  $40 \text{ kg} + 1 \text{ kg} + 4 \text{ kg} + 224 \text{ kg} + 1.47 \text{ kg}$   
 $= \underline{\underline{270.47 \text{ kg}}}$

## Estimated Stowed and Deployed Volume of the Rigid Parabola and Folding Support

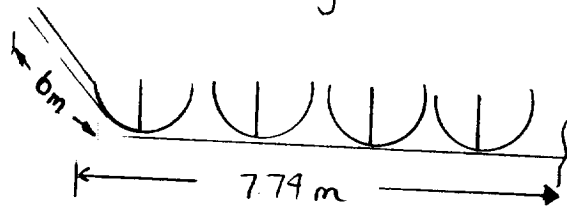
The estimated stowed volume is :



$$V = 6 \text{ m} \times 3.67 \times 0.40 \text{ m}$$

$$V = \underline{\underline{8.81 \text{ m}^3}}$$

Estimated deployed volume :

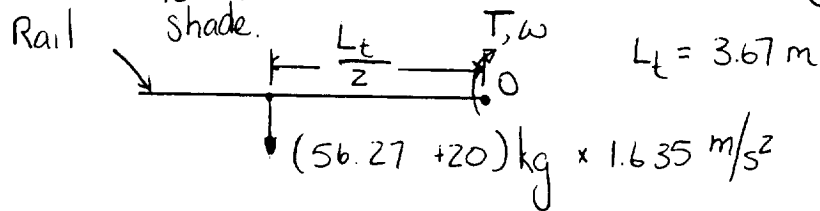


$$V = 0.15 \text{ m} \times 6 \text{ m} \times 7.34 \text{ m}$$

$$V = \underline{\underline{6.61 \text{ m}^3}}$$

## Estimated Power Required to Deploy the Rigid Parabola Shading System and Folding Support

Assume: - weight of the shade system is a concentrated load. Each rail carries half of the weight of the shade.



$T$  = torque that must be provided to rotate the rail

$\omega$  = angular speed

$$\sum M_o = 76.27 \text{ kg} \times 1.635 \frac{\text{m}}{\text{s}^2} \times 1.84 \text{ m} \times 2$$

$$T = 458.90 \text{ N}\cdot\text{m}$$

$$\omega = \frac{\pi}{60 \text{ SECS}} = 0.0523$$

$\therefore$  the power is

$$P = T\omega = 458.90 \text{ N}\cdot\text{m} \times 0.0523 \text{ rad/s}$$

$$\underline{\underline{P = 24.0 \text{ W}}}$$

The perimeter of the Modified Parabolic Reflector is assumed to be a semicircle. The radius is 0.35 m, which is equal to the radius of the Parabolic Reflector. Therefore, the mass, volume, and power calculations of Parabolic Shading System apply to the Modified Parabolic Reflector.

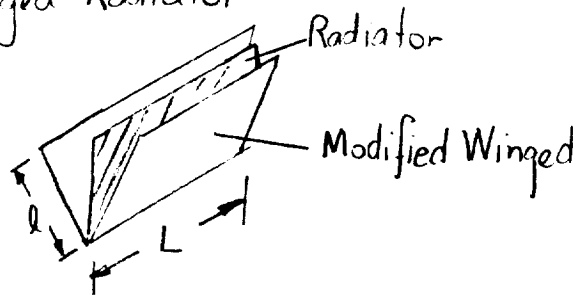


## Mass Calculations of Modified Winged Radiator Shading System and Rail Support

Modified Winged Radiator

$$l = 0.2121 \text{ m}$$

$$L = 6 \text{ m}$$



- mass of 5 radiators

$$m_r = 5 \times \rho_r \times A = 5 \frac{\text{kg}}{\text{m}^2} \times 6 \text{ m} \times 0.15 \text{ m}$$

$$m_r = \underline{\underline{22.5 \text{ kg}}}$$

- total mass of Kapton in 5 shades

$$m_s = \rho_k \times A$$

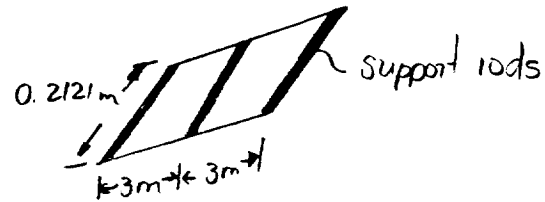
$$A = 2 \times l \times L$$

$$m_s = 2 \times 0.1314 \frac{\text{kg}}{\text{m}^2} \times 6 \text{ m} \times 0.2121 \text{ m}$$

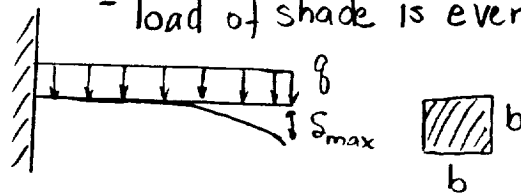
$$m_s = 0.4618$$

$$m_{st} = 5 \times 0.4618 = \underline{\underline{2.31 \text{ kg}}}$$

- mass of support rods



Assume: - support rods are cantilever beams  
- load of shade is evenly distributed



$$\text{let } \delta_{\max} \leq 1 \text{ mm}$$

$$\delta_{\max} = \frac{1.5 \times q \times L^4}{8 \times E_{AL} \times I}$$

$$q = \frac{m_s \times g}{2L}$$

$$I = \frac{1}{12} b^4$$

$$b = \left[ \frac{12 \times 1.5 \times L^3 \times m_s \times g}{8 \times E_{AL} \times \delta_{\max}} \right]^{1/4}$$

$$b = \left[ \frac{12 \times 1.5 \times (0.2121)^3 \text{ m}^3 \times 0.4613 \text{ kg} \times 9.81 \text{ m/s}^2}{8 \times 72 \times 10^9 \frac{\text{N}}{\text{m}^2} \times 0.001 \text{ m}} \right]^{1/4}$$

$$b = 0.0051 \text{ m}$$

$$b = 5.1 \text{ mm}$$

mass for 1 rod:

$$m_r = \rho_r V = 2800 \frac{\text{kg}}{\text{m}^3} (0.051\text{m})^2 (0.2121\text{m})$$

$$m_r = 0.0154 \text{ kg}$$

there are a total of 30 support rods

$$m_{rT} = 30 \times 0.0154 \text{ kg}$$

$$m_{rT} = \underline{\underline{0.462 \text{ kg}}}$$

total mass of the shading device and radiator.

$$2.31 \text{ kg} + 22.5 \text{ kg} + 0.462 \text{ kg}$$

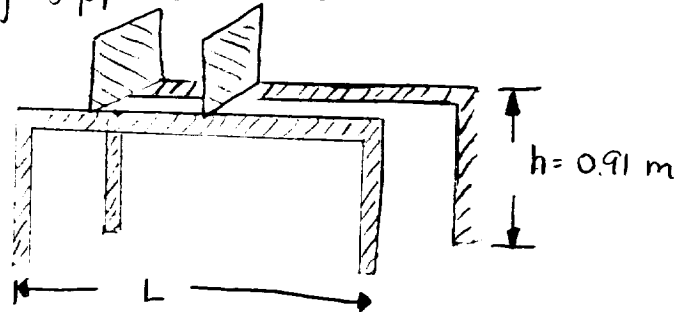
$$= \underline{\underline{25.27 \text{ kg}}}$$

Miscellaneous Masses:

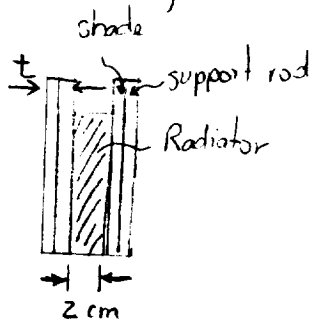
rollers : 4 kg

joints : 1 kg

- mass of support structure



- width of shades when stored -  $W_t$



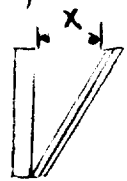
$$t = (1.000127 + 0.01) \text{ m}$$

$$W_t = 5 \times [(2 \times 0.010127) \text{ m} + 0.02]$$

$$W_t = 0.20 \text{ m}$$

$$W_t = 20 \text{ cm}$$

width of shades when deployed



$$x = 0.15 \text{ m}$$

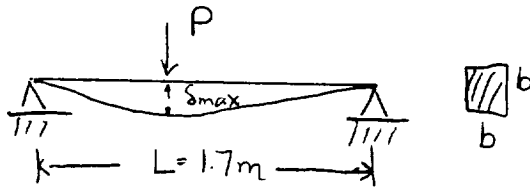
$$W_d = [0.02 \text{ m} + 2 \times (.15 + 0.000127 + 0.02)] \times 5$$

$$W_d = 1.7 \text{ m}$$

$\therefore$  the total length of the support rail is

$$L = 1.7 \text{ m}$$

- Assume:
- rails are simple beams
  - weight of shading system is concentrated and acts at the center of the beam



$$P = 12.64 \text{ kg} \times 9.81 \text{ m/s}^2 = 123.95 \text{ N}$$

$$\text{let } \delta_{\text{max}} \leq 1 \text{ cm}$$

$$\delta_{\text{max}} = \frac{1.5 \times P \times L^3}{48 \times I \times E_{\text{Al}}}$$

[Timoshenko and Gere  
Mechanics of Materials]

$$b = \left[ \frac{1.5 \times 12 \times P \times L^3}{48 \times \delta_{\text{max}} \times E_{\text{Al}}} \right]^{1/4} = \left[ \frac{1.5 \times 12 \times 123.95 \text{ N} \times (1.7)^3 \text{ m}^3}{0.01 \text{ m} \times 48 \times 70 \times 10^9 \frac{\text{N}}{\text{m}^2}} \right]^{1/4}$$

$$b = 0.0237 \text{ m}$$

$$b = 2.37 \text{ cm}$$

$$m_{\text{rail}} = \rho_{\text{Al}} V = 2800 \frac{\text{kg}}{\text{m}^3} \times (0.0237)^2 \text{ m}^2 \times 1.7 = 2.67 \text{ kg}$$

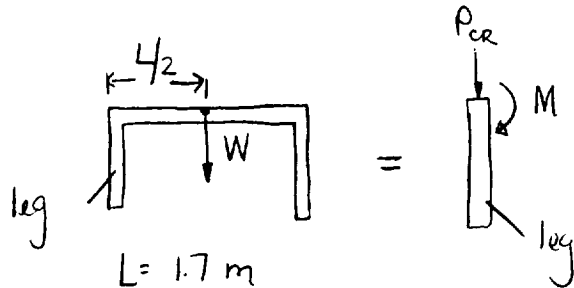
- total rail mass

$$\begin{aligned} m_{\text{rail}_T} &= 2 \times 2.67 \text{ kg} \\ &= \underline{\underline{5.35 \text{ kg}}} \end{aligned}$$

- mass of the legs

Assume

- effect of shading system and rail weight can be replaced by an equivalent load and moment.
- load of shade system is concentrated.



$$L = 1.7 \text{ m}$$

$W =$  weight of shading system and rail

$$= \frac{(12.64 + 5.35/2) \text{ kg} \times 9.81 \text{ m/s}^2}{2}$$

$$W = 75.12 \text{ N}$$

$$P_{cr} = \left( \frac{25.27 + 5.35}{3} \right) \text{ kg} \times 9.81 \text{ m/s}^2$$

$$P_{cr} = 37.55 \text{ N}$$

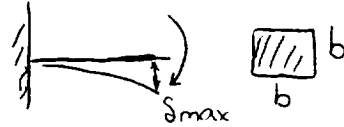
$$M = W \cdot \frac{L}{2} = 127.66 \text{ Nm}$$

$$b = \left[ \frac{1.5 \times 37.55 \text{ N} \times (0.91)^2 \text{ m}^2 \times 12}{\pi^2 \times 72 \times 10^9 \text{ N/m}^2} \right]^{1/4}$$

$$\left. \begin{array}{l} b = 0.00529 \text{ m} \\ b = 5.30 \text{ mm} \end{array} \right\} \text{ minimum length due to compression}$$

cross-section due to bending

Assume: - leg is supported at one end



$$\text{let } \delta_{\max} \leq 1 \text{ cm}$$

$$\delta_{\max} = \frac{ML^2 \times 1.5}{2E_{Al} I}$$

$$I = \frac{1}{12} b^4$$

[ Robert C. Juvinall  
Fundamentals of Machine  
Component Design ]

$$b = \left[ \frac{12 \times 1.5 \times L^2 \times M}{2 \times E_{Al} \times \delta_{\max}} \right]^{1/4} = \left[ \frac{12 \times 1.5 \times (0.91)^2 \text{ m}^2 \times 127.66 \text{ N}\cdot\text{m}}{2 \times 72 \times 10^9 \frac{\text{N}}{\text{m}^2} \times 0.01 \text{ m}} \right]^{1/4}$$

$$b = 0.0339 \text{ m}$$

$$b = 3.39 \text{ cm}$$

The cross section dimensions of the legs are 3.39 cm x 3.39 cm. These dimensions will keep the legs from buckling.

- mass of each leg

$$m_{\text{leg}} = \rho_{Al} V = 2800 \frac{\text{kg}}{\text{m}^3} \times (0.0339)^2 \text{ m}^2 \times 0.91 \text{ m}$$

$$m_{\text{leg}} = 2.93 \text{ kg}$$

- total mass :  $m_{\text{legs}} = 4 \times 2.93 \text{ kg} = \underline{\underline{11.72 \text{ kg}}}$

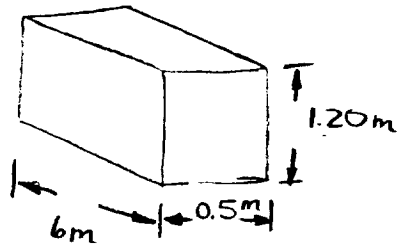
Total mass of the Modified Winged Radiator Shading System and Rail Support :

$$25.27 \text{ kg} + 4 \text{ kg} + 1 \text{ kg} + 5.35 \text{ kg} + 11.72 \text{ kg} = \underline{\underline{47.39 \text{ kg}}}$$



## Estimated Stowed and Deployed Volume of the Modified Winged-System and Rail Support

When the system is being transported the rails can be folded. The estimated stowed volume is:



$$V = 6\text{ m} \times 0.5\text{ m} \times 1.20\text{ m}$$

$$V = \underline{\underline{3.6\text{ m}^3}}$$

The estimated deployed volume is:

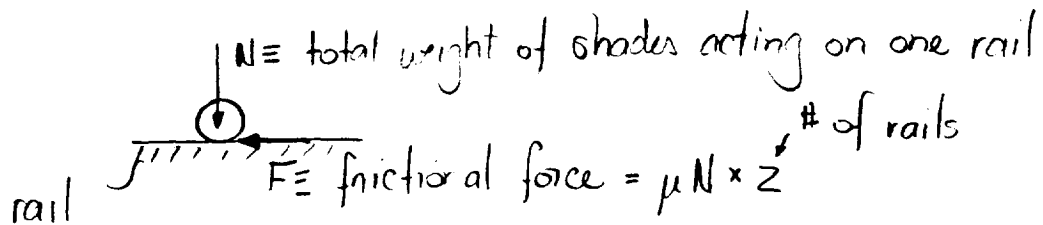
$$V = L_t \times 1.20\text{ m} \times 6\text{ m} = 1.7\text{ m} \times 1.20\text{ m} \times 6\text{ m}$$

$$V = \underline{\underline{12.24\text{ m}^3}}$$

## Estimated Power Required to Deploy the Modified Winged-System and Rail Support

The shades are attached to plastic rollers

Assume: - each rail carries half of the shade system weight.



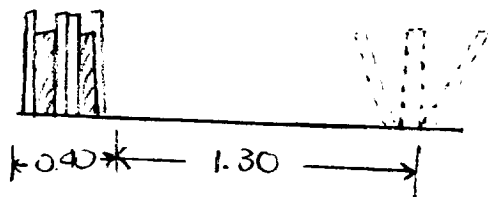
for Alum num to nonmetal assume  $\mu \approx 0.2$

$$N = 13.5 \text{ kg} \times \frac{9.81 \text{ m/s}^2}{6}$$

$$N = 22.1 \text{ N}$$

$$F = 2 \times 0.2 \times 22.1 \text{ N}$$

$$F = 8.84 \text{ N}$$



Assume each shading system moves an average of 1m

The energy to deploy the system is:

$$E = F \cdot d = 4.42 \text{ N} \times 2 \text{ m} = 8.84 \text{ J}$$

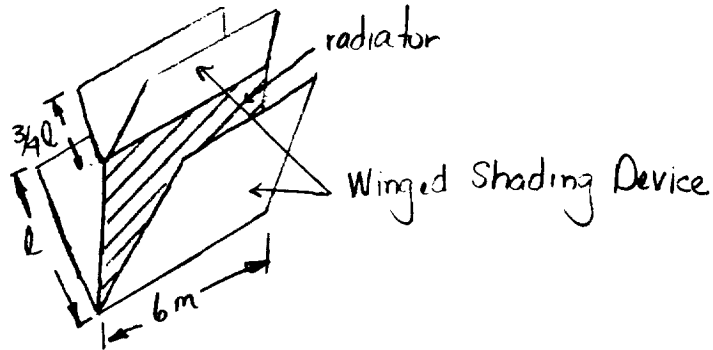
Assume it is performed in 60 seconds:

$$P = \frac{E}{t} = \frac{8.84 \text{ J}}{60 \text{ sec}} = \underline{\underline{0.1473 \text{ W}}}$$

# Mass Calculations of Winged Radiator Shading System

Winged Radiator Shading Device and Rail Support

$$l = 0.2121 \text{ m}$$



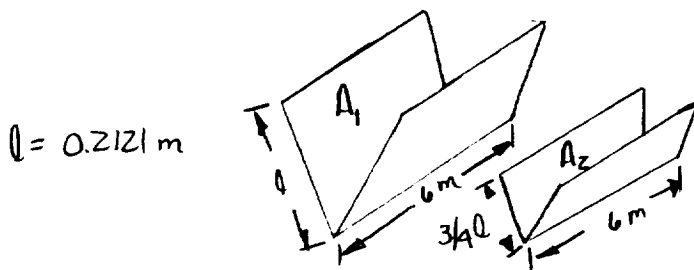
- mass of 5 radiators

$$m_r = \rho_r A = 5 \frac{\text{kg}}{\text{m}^2} \times 6 \text{ m} \times 0.15 \text{ m}$$

$$= 4.5 \text{ kg}$$

$$m_{rT} = 5 \times 4.5 \text{ kg} = 22.5 \text{ kg}$$

- total mass of Kapton in 5 shades:



$$l = 0.2121 \text{ m}$$

$$m_{A_i} = \rho_K A = 0.1814 \frac{\text{kg}}{\text{m}^2} \times 0.2121 \text{ m} \times 6 \text{ m} \times 2$$

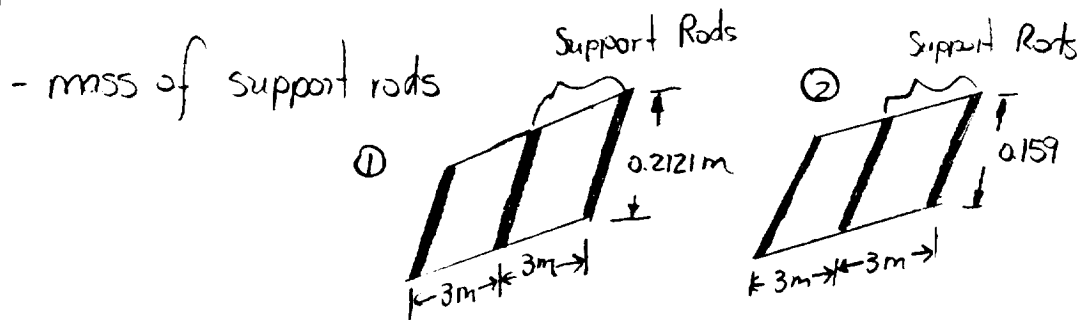
$$m_{A_i} = 0.4618 \text{ kg}$$

$$m_{AZ} = \rho_k A = 0.1814 \frac{\text{kg}}{\text{m}^2} \times \frac{3}{4} \times 0.2121 \text{ m} \times 6 \text{ m} \times 2 \text{ m}$$

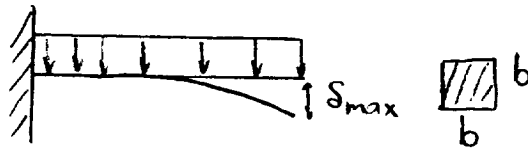
$$m_{AZ} = 0.3463 \text{ kg}$$

$$m_{sT} = 5 \times (0.4618 + 0.3463 \text{ kg})$$

$$m_{sT} = 4.041 \text{ kg}$$



Assume: - support rods are loaded cantilever beams  
 - support rods are made of Aluminum



for both ① and ② let  $\delta_{max} \leq 1 \text{ mm}$

$$\textcircled{1} \quad \delta_{max} = \frac{1.5 \times q \times L^4}{8 \times E_{AL} \times I}$$

$$q = \frac{m_s}{z} \times \frac{q}{L}$$

$$I = \frac{1}{12} b^4$$

$$b = \left[ \frac{12 \times 1.5 \times L^3 \times m_s \times g}{8 \times E_{AL} \times \Delta_{max}} \right]^{1/4}$$

$$b = \left[ \frac{12 \times 1.5 \times (0.2121)^3 \text{ m}^3 \times 0.4618/2 \times 9.81 \text{ m/s}^2}{8 \times 72 \times 10^9 \text{ N/m}^2 \times 0.001 \text{ m}} \right]^{1/4}$$

$$b = 0.0051 \text{ m}$$

$$b = 5.1 \text{ mm}$$

mass of rods for 5 shares :

$$m_{r1} = \rho_m V = 2800 \frac{\text{kg}}{\text{m}^3} \times (0.0051)^2 \text{ m}^2 \times 30$$

$$m_{r1} = \underline{\underline{0.462 \text{ kg}}}$$

②

- Use same assumptions as in case ①

$$b = \left[ \frac{12 \times 1.5 \times (0.159)^3 \text{ m}^3 \times \frac{0.3463}{2} \text{ kg} \times 9.81 \text{ m/s}^2}{8 \times 72 \times 10^9 \text{ N/m}^2 \times 0.001 \text{ m}} \right]^{1/4}$$

$$b = 0.0038 \text{ m}$$

$$b = 3.8 \text{ mm}$$

mass per 121 :

$$m_{r2} = \rho_{AL} V = 2800 \frac{\text{kg}}{\text{m}^3} \times (0.0038 \text{ m})^2 \times (0.159 \text{ m}) = 0.00643 \text{ kg}$$

$$m_{r\text{②}} = 30 \times 0.00643 \text{ kg}$$

$$m_{r\text{②}} = \underline{\underline{0.1923 \text{ kg}}}$$

$$m_{\text{SRT}} = (0.462 + 0.1923) \text{ kg}$$

$$m_{\text{SRT}} = \underline{\underline{0.654 \text{ kg}}}$$

total mass of the shading device and radiator:

$$4.041 \text{ kg} + 22.5 \text{ kg} + 0.654 \text{ kg} = \underline{\underline{27.20 \text{ kg}}}$$

Miscellaneous Masses:

rollers: 4 kg

joints: 2 kg

- mass of support structure

The width of this shading device when stowed and deployed is the equal to the Winged Shading Device.

width when being transported:

$$W_t = .20 \text{ m}$$

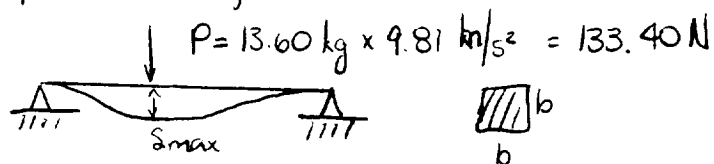
width when deployed:

$$W_d = 1.7 \text{ m}$$

Therefore the length of the rails are 1.7 m

- Assumptions in the remaining calculations are the same as for the Modified Winged Radiator

- total mass of the rails



$$\text{let } S_{\text{max}} \leq 1 \text{ cm}$$

$$b = \left[ \frac{1.5 \times 12 \times 133.40 \text{ N} \times (1.7)^3 \text{ m}^3}{0.01 \text{ m} \times 48 \times 72 \times 10^9 \text{ N/m}^2} \right]^{1/4}$$

$$b = 0.0242 \text{ m}$$

$$b = 2.42 \text{ cm}$$



mass per rail

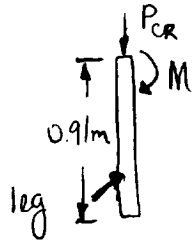
$$m_{\text{rail}} = \rho_{\text{Al}} V = 2800 \frac{\text{kg}}{\text{m}^3} \times (0.0242)^2 \text{m}^2 \times 1.7 = 2.79 \text{ kg}$$

- total rail mass

$$m_{\text{rail}_T} = 2 \times 2.79 = \underline{\underline{5.58 \text{ kg}}}$$

- mass of the legs

dimensions of the legs are determined by the moment.



$$P_{\text{CR}} = \left[ \frac{5.58}{8} + \frac{27.196}{8} \right] \text{kg} \times 9.81 \text{ m/s}^2$$

$$P_{\text{CR}} = 40.19 \text{ N}$$

$$M = \left[ \frac{5.58}{2} + \frac{27.196}{2} \right] \times 9.81 \text{ m/s}^2 \times 0.85 \text{ m}$$

$$M = 136.65 \text{ N}\cdot\text{m}$$

Under compression the minimum dimensions of the cross-section is calculated using Euler's equation.

$$b = \left[ \frac{1.5 \times 40.19 \text{ N} \times (0.91)^2 \text{m}^2 \times 12}{\pi^2 \times 72 \times 10^9 \text{ N/m}^2} \right]^{1/4}$$

$$b = 5.38 \text{ mm}$$

- the minimum cross section due to bending

$$b = \left[ \frac{12 \times 1.5 \times L^2 \times M}{2 \times E_{Al} \times S_{max}} \right] = \left[ \frac{12 \times 1.5 \times (0.91)^2 \times 137 \text{ N}\cdot\text{m}}{2 \times (72 \times 10^9) \frac{\text{N}}{\text{m}^2} \times 0.01 \text{ m}^3} \right]$$

$$b = 3.45 \text{ cm}$$

- mass per leg

$$m_{leg} = \rho_{Al} V = 2800 \frac{\text{kg}}{\text{m}^3} \times (0.035)^2 \text{ m}^2 \times (0.91 \text{ m})$$

$$m_{leg} = 3.03 \text{ kg}$$

- total mass of legs:

$$m_{legT} = 4 \times 3.03 = \underline{\underline{12.12 \text{ kg}}}$$

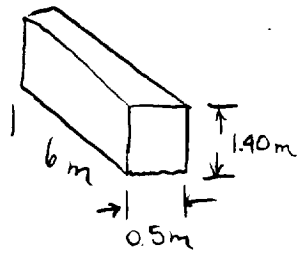
Total Mass of the ~~Modified~~ Winged Radiator and Rail Support:

$$27.196 \text{ kg} + 5.58 \text{ kg} + 12.12 \text{ kg} + 4 \text{ kg} + 2 \text{ kg}$$

$$= \underline{\underline{50.90 \text{ kg}}}$$

## Estimated Stowed and Deployed Volume of the Winged Radiator and Rail Support

Estimated Stowed Volume



$$V = 6 \text{ m} \times 0.5 \text{ m} \times 1.40 \text{ m}$$

$$V = \underline{\underline{4.2 \text{ m}^3}}$$

Estimated Deployed Volume:

$$V = 1.7 \text{ m} \times 1.40 \text{ m} \times 6 \text{ m}$$

$$V = \underline{\underline{14.28 \text{ m}^3}}$$

## Estimated Power to Deploy the Winged Radiator and Rail Support

$$E = F \cdot d \times 5$$

$E$   $\equiv$  energy required to deploy the shading systems  
and support rails

$F$   $\equiv$  force that must be overcome to slide the  
shades along the rails  $= \mu W$

$\mu$   $\equiv$  coefficient of friction  $\approx 0.20$

$W$   $\equiv$  weight of shade system acting on one rail

$d$   $\equiv$  avg. distance that each shade system moves.

$$E = (\mu W) \times d \times 5$$

$$E = 0.20 \times \frac{27.196 \text{ kg}}{10} \times 1.635 \text{ m/s}^2$$

$$E = 8.89 \text{ J}$$

Assume deploying processes occur in 60 seconds

$$P = \frac{E}{t} = \frac{8.89 \text{ J}}{60 \text{ sec}} = 0.148 \text{ W}$$

# Appendix G

## Decision Matrix

CONCEPTS	DESIGN PARAMETERS								SUM OF PRODUCTS
	Safety	Low Mass	Ease of Manual Deployment	Low Slowed Volume	Low Effective Heat Sink Temp.	Low Power Consumption	Reliability	Ease of Maintenance	
<b>WEIGHTING FACTORS</b>	0.11	0.20	0.10	0.15	0.20	0.04	0.13	0.07	<b>1.00</b>
Modified Winged Radiator With Linked System	6 0.66	7 1.40	7 0.70	8 1.20	7 1.40	8 0.32	6 0.78	5 0.35	<b>6.81</b>
Winged Radiator With Linked System	6 0.66	7 1.4	6 0.60	8 1.20	7 1.40	8 0.32	6 0.78	5 0.35	<b>6.71</b>
Flexible Parabolic Reflector With Scissors Mechanism	3 0.33	5 1.00	5 0.50	8 1.20	8 1.60	6 0.24	5 0.65	4 0.28	<b>5.80</b>
L-Shaped Panels With Linked System	6 0.66	7 1.40	6 0.60	8 1.20	2 0.40	8 0.32	6 0.78	5 0.35	<b>5.71</b>
Rigid Parabolic Reflector With Folding System	4 0.44	5 1.00	3 0.30	3 0.45	8 1.60	4 0.16	4 0.52	7 0.49	<b>4.96</b>
Modified Parabolic Reflector With Folding System	4 0.44	5 1.00	3 0.30	3 0.45	8 1.60	4 0.16	4 0.52	7 0.49	<b>4.96</b>
Fresnel Reflector With Scissors Mechanism	4 0.44	5 1.00	5 0.50	5 0.75	3 0.60	5 0.20	5 0.65	4 0.28	<b>4.42</b>

# APPENDIX I/H

## THERMAL PERFORMANCE CALCULATIONS

For radiator:

$$Q''_{\text{NET}} = Q''_{\text{out}} - Q''_{\text{absorbed}}$$

$$Q''_{\text{out}} = \eta \sigma \epsilon T_r^4$$

where,  $T_r = 270\text{K}$

$\eta = 0.9 = \text{fin efficiency of radiator}$

$\epsilon = 0.9 = \text{radiator emissivity}$

$$Q''_{\text{absorbed}} = \alpha_{\text{solar}} (Q''_{\text{solar}} \sin 1.53^\circ)$$

$$+ \alpha_{\text{radiator}} F_{\text{shade to radiator}} Q''_{\text{shade}} + \alpha_{\text{radiator}} F_{\text{surface to radiator}} Q''_{\text{surface}}$$

$$+ \alpha_{\text{radiator}} \times Q''_{\text{solar}} \rho_{\text{shade}} \cos(90 - 2\theta)$$

$$+ \alpha_{\text{radiator}} F_{\text{shade to radiator}} Q''_{\text{radiator emission reflected from shade}}$$

$$R = \text{aspect ratio} = \frac{L_{\text{shade}}}{L_{\text{radiator}}}$$

where,  $X = 1$  for  $R \geq 1$

$X = R$  for  $R < 1$

$$Q''_{\text{shade}} = \alpha_{\text{solar}} Q''_{\text{solar}} \sin \theta + \alpha_{\text{solar}} F_{\text{surface to shade}} Q''_{\text{absorbed shade}}$$

$$+ \alpha_{\text{shade}} F_{\text{surface to shade}} Q''_{\text{surface}}$$

$$+ \alpha_{\text{shade}} F_{\text{radiator to shade}} Q''_{\text{radiator}}$$

$$+ F_{\text{radiator to shade}} (Q''_{\text{solar}} \sin 1.53^\circ) \rho_{\text{radiator solar}}$$

$$+ F_{\text{radiator to shade}} \alpha_{\text{shade}} Q''_{\text{shade emission reflected from radiator}}$$

Assumptions:

- 1) Diffuse surfaces
  - 2) No dust accumulation
  - 3) Moon surface is a rectangular plate 600 m by 500 m
  - 4) Reflector dimensions are 1 m high by 100 m long.
- Therefore, end effects are neglected and both shade and reflector can be considered to be infinitely long.

$$Q''_{\text{shade}} = 1371 \text{ W/m}^2$$

$$Q''_{\text{albedo}} = (0.07)(1371 \text{ W/m}^2) = 95.97 \text{ W/m}^2$$

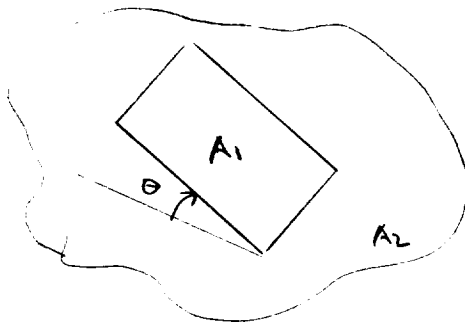
$$Q''_{\text{surface}} = \epsilon \sigma T_{\text{surface}}^4 = (0.93)(5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4)(284 \text{ K})^4 \\ = 1,146.54 \text{ W/m}^2$$

$$Q''_{\text{reflector}} = \epsilon \sigma T_{\text{reflector}}^4 \\ = (0.9)(5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4)(270 \text{ K})^4 \\ = 271.19 \text{ W/m}^2$$

Finding the view factors:

①  $F_{\text{surface to shade}}$

use following configuration:



$$F_{1-2} = \frac{1 - \cos \theta}{2}$$

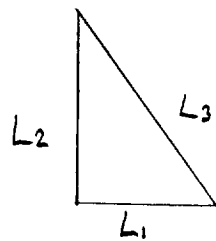
$$A_{\text{surface}} F_{\text{surface to shade}} = A_{\text{shade}} F_{\text{shade to surface}}$$

$$F_{\text{surface to shade}} = \frac{A_{\text{surface}}}{A_{\text{shade}}} F_{\text{shade to surface}}$$

$$= (0.0005) \left( \frac{1 - \cos(90 + \theta)}{2} \right)$$

② Fraction to shade

Use following configuration:



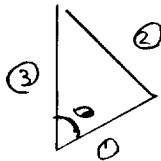
Infinitely long enclosure formed by three plane areas

$$F_{12} = \frac{L_1 + L_2 - L_3}{2L_1}$$

$L_3$  is the longest side.

Two cases:

CASE 1



①: shade

③: radiation

②: space

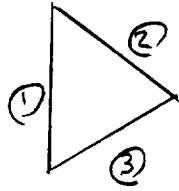
$$F_{1-2} + F_{13} = 1$$

$$F_{13} = 1 - F_{12} = 1 - \frac{L_1 + L_2 - L_3}{2L_1}$$

$$= 1 - \frac{L_1 + L_2 - L_3}{2L_1}$$



CASE 2



$$F_{1-2} + F_{2-1} = 1$$

$$F_{3-1} = 1 - F_{12} = 1 - \frac{L_1 + L_2 - L_3}{2L_1} = 1 - \frac{L_1 + L_2 - L_3}{2L_1}$$

$$R = \frac{L_1}{L_2}$$

Law of sines:  $L_1^2 = R^2 L_2^2 + L_2^2 + 2R L_2^2 \cos \theta$

$$\therefore F_{\text{shade to radiator}} = 1 - \frac{\sqrt{R + R^2 + 1 + 2R \cos \theta} - 1}{2R}$$

CASE 1

$$F_{\text{shade to radiator}} = 1 - \frac{1 + \sqrt{R^2 + 1 + 2R \cos \theta} - R}{2}$$

CASE 2

$$F_{\text{radiator to shade}} = R \left( 1 - \frac{\sqrt{R + R^2 + 1 + 2R \cos \theta} - 1}{2R} \right)$$

CASE 1

$$F_{\text{radiator to shade}} = R - \frac{\sqrt{R + R^2 + 1 + 2R \cos \theta} - R^2}{2}$$

CASE 2

View factor of strip of radiator to lunar surface if shade does not block all the lunar surface.

Have: infinite plane and a surface strip

Want:  $F_{\text{surface to strip}} = F_{\text{surface to strip}} - F_{\text{shade to strip}}$   
all

$$F_{\text{surface to strip}} = \frac{(L_r - R \cos \theta)(100)}{(500)(400)}$$

$$\times \frac{1}{2\pi} \left[ \tan^{-1} \left( \frac{400}{R \cos \theta} \right) - \frac{R \cos \theta}{400} \right]$$

$$\frac{1}{\sqrt{(1.25)^2 + \left( \frac{R \cos \theta}{400} \right)^2}}$$

$$\times \tan^{-1} \frac{1}{\sqrt{(1.25)^2 + \left( \frac{R \cos \theta}{400} \right)^2}}$$

$$F_{\text{shade to strip}} = \frac{R}{1 - R \cos \theta} \left[ \frac{R \sin \theta + 1 - \sqrt{(1 - R \cos \theta)^2 + (R \sin \theta)^2}}{2(1 - R \cos \theta)} \right]$$

$$\left. + \frac{R \cos \theta}{2(1 - R \cos \theta)} \right]$$

$\therefore F_{\text{surface to strip}} =$

$$\frac{(1 - R \cos \theta)(100)}{(500)(400)} \frac{1}{2\pi} \left[ \tan^{-1} \left( \frac{400}{R \cos \theta} \right) \right]$$

$$- \frac{R \cos \theta}{400 \sqrt{(1.25)^2 + \left( \frac{R \cos \theta}{400} \right)^2}} \tan^{-1} \frac{1}{\sqrt{(1.25)^2 + \left( \frac{R \cos \theta}{400} \right)^2}} \left. \right]$$

$$- \frac{R}{1 - R \cos \theta} \left[ \frac{(R \sin \theta + 1) - \sqrt{(1 - R \cos \theta)^2 + (R \sin \theta)^2} + R \cos \theta}{2(1 - R \cos \theta)} \right]$$

Surface properties:

shade, case 1

$$\alpha_{\text{solair}} = 0.9$$

$$\rho_{\text{solair}} = 0.1$$

shade, CASE 2

$$\alpha_{\text{solair}} = 0.14$$

$$\rho_{\text{solair}} = 0.86$$

## Appendix I

### Analysis of Final Design Solution

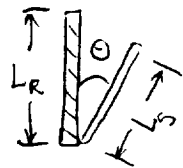
#### Modified Winged Radiator and Rail Support

A detailed calculation of the mass of the Modified Winged Radiator and Rail Support Alternate is provided. Also provided are estimates of the deployed and stowage volume and power consumed during deployment.

Using data from thermal performance analysis the length of the shading device panel and the radiator area required to reject 10 kW and 25 kW of waste heat were determined.

Data gathered from thermal performance:

$$R = \frac{L_s}{L_R} \equiv \text{aspect ratio} = 0.55$$



$\theta \equiv$  angle between the radiator and shade panel =  $75^\circ$

radiator area required to reject 10 kW and 25 kW of waste heat:

$$A_{10\text{ kW}} = 389 \text{ m}^2$$

$$A_{25\text{ kW}} = 973 \text{ m}^2$$

- Shading device panel length

Assume: radiator dimensions:  $6\text{ m} \times 0.02\text{ m} \times 0.15\text{ m}$

$$L_s = RL_R = 0.55 \times (0.15\text{ m})$$

$$L_s = 0.0825\text{ m}$$

- the width of each shading device when deployed

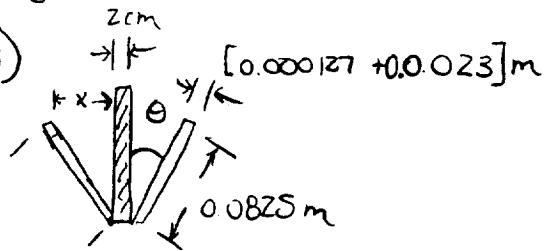
$$L_d = [0.02 + 2(0.00243 + x)]$$

$$x = L_s \sin \theta$$

$$x = 0.0825\text{ m} (\sin 75^\circ)$$

$$x = 0.0797$$

$$L_d = 0.2279\text{ m}$$



- The rails can be folded into the transport package. Therefore, the length of the rails is limited by the length of the radiator.

$$L_{\text{rails}} = \text{length of rails} = 6\text{ m}$$

- the number of shading systems in each transport package:

$$n_{ss} = \frac{6\text{ m}}{0.2279\text{ m}} = 26 \text{ shading systems}$$

- the number of radiators required to reject 10 kW and 25 kW

$$A = \text{Radiator Area} = 6\text{ m} \times 0.15\text{ m}$$

$$n_{10\text{ kW}} = \frac{A_{10\text{ kW}}}{A} = \frac{389\text{ m}^2}{6\text{ m} \times 0.15\text{ m}} = 432.2 \approx 433 \text{ radiators}$$

$$n_{25\text{ kW}} = \frac{A_{25\text{ kW}}}{A} = \frac{473\text{ m}^2}{6\text{ m} \times 0.15\text{ m}} = 1081.1 \approx 1082 \text{ radiators}$$

- number of packages needed

$$N_{10} = \frac{n_{10\text{ kW}}}{n_{ss}} = \frac{433}{26} = 16.65 \approx 17$$

$$N_{25} = \frac{n_{25\text{ kW}}}{n_{ss}} = \frac{1082}{26} = 41.61 \approx 42$$

- Mass of 26 radiators

$$m_{rT} = 26 \times \rho_r \times A = 5 \frac{\text{kg}}{\text{m}^2} \times 6\text{ m} \times 0.15\text{ m} \times 26$$

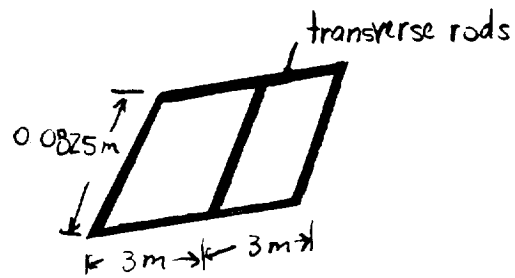
$$m_{rT} = \underline{\underline{117\text{ kg}}}$$

- Mass of Kapton in 26 shades

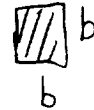
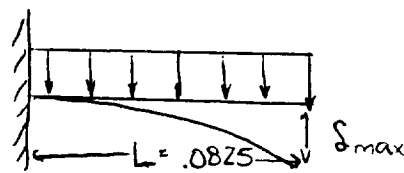
$$m_{sT} = \rho_k \times A \times 26 = 2 \times 0.1814 \frac{\text{kg}}{\text{m}^2} \times 26 \times 0.0825\text{ m} \times 6\text{ m} \times 26$$

$$m_{sT} = \underline{\underline{4.66}}$$

- mass of support rods



Assume: - support rods are cantilever beams  
- load of shade is evenly distributed



Timoshenko & Gere  
Mechanics of  
Materials

$$\text{let } \delta_{\max} \leq 1 \text{ mm}$$

$$\delta_{\max} = \frac{1.5 \times q \times L^4}{8 \times E_{Al} \times I}$$

$$q = \frac{m_s}{z} \times \frac{g}{L} = \left(\frac{4.66}{26}\right) \text{ kg} \times \frac{9.81 \text{ m/s}^2}{2L} = \frac{0.879 \text{ N}}{L}$$

$$I = \frac{1}{12} b h^3$$

$$b = \left[ \frac{12 \times 1.5 \times (0.0825)^4 \text{ m}^4 \times 0.879 \frac{\text{N}}{0.0825 \text{ m}}}{8 \times 72 \times 10^9 \frac{\text{N}}{\text{m}^2} \times 0.001 \text{ m}} \right]^{1/4}$$

$$b = 1.98 \text{ mm}$$

- mass for 1 rod

$$m_r = \rho_{Al} V = 2800 \frac{\text{kg}}{\text{m}^3} \times (0.00198)^2 \text{m}^2 (0.0825) \text{m}$$


$$m_r = 0.00091 \text{ kg}$$

- there are a total of 156 rods

$$m_{rT} = 156 \times (0.00091) \text{ kg} = 0.141 \text{ kg}$$

- mass of transverse rods

$$26 \text{ shades} \times \frac{4 \text{ rods}}{\text{shade}} = 104$$

Assume dimensions of  b

$$b = 2 \text{ mm}$$

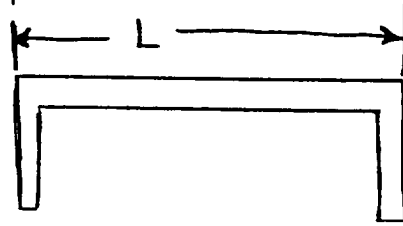
$$m_{\text{TRANS RODS}} = (0.002)^2 \text{m} \times 6 \text{m} \times 2800 \frac{\text{kg}}{\text{m}^3} \times 104 = 7 \text{ kg}$$

- total mass of shading device and radiator

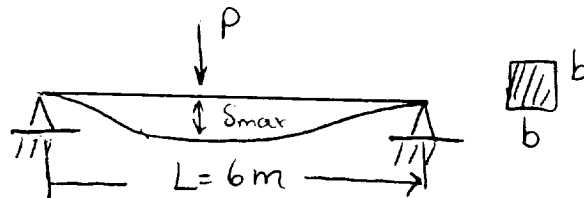
$$117 \text{ kg} + 4.66 \text{ kg} + 0.146 \text{ kg} + 7 \text{ kg} = \underline{\underline{128.81 \text{ kg}}}$$



Mass of support structure



- Assume : - rails are simple beams  
 - weight of shading system is concentrated and acts at the center of the beam



$$P = \frac{m_s}{2} \times 9.81 \text{ m/s}^2 = \frac{128.81 \text{ kg}}{2} \times 9.81 \text{ m/s}^2$$

$$P = 631.8 \text{ N}$$

$$\text{let } s_{\max} \leq 1 \text{ cm}$$

$$s_{\max} = \frac{1.5 \times P \times L^3}{48 \times I \times E_{Al}}$$

[Timoshenko and Gere  
 Mechanics of Materials]

$$I = \frac{1}{12} b^4$$

$$b = \left[ \frac{1.5 \times 12 \times L^3 \times P}{48 \times E_{Al} \times s_{\max}} \right]^{1/4} = \left[ \frac{1.5 \times 12 \times (6 \text{ m})^3 \times 631.8 \text{ N}}{48 \times 72 \times 10^9 \frac{\text{N}}{\text{m}^2} \times 0.01 \text{ m}} \right]^{1/4}$$

$$b = 9.18 \text{ cm}$$

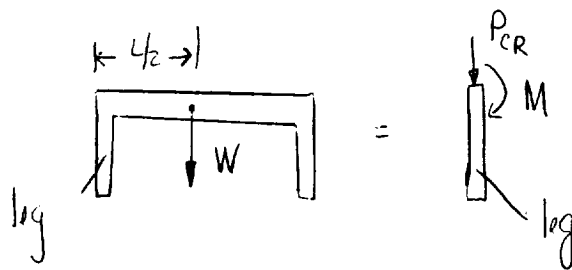
$$m_{\text{rail}} = \rho_{\text{Al}} V = 2800 \frac{\text{kg}}{\text{m}^3} \times (0.0918)^2 \text{m}^2 \times 6 \text{m} = 141.64 \text{ kg}$$

$$m_{\text{rail}_T} = 283.27 \text{ kg}$$

- mass of the legs

Assume: - equivalent load and moment represent the weight of the rail and shading system

- load of shade system is concentrated



$$L = 6 \text{ m}$$

$W$  = weight of shading system acting on one rail and weight of the rail.

$$P_{\text{cr}} = \left( \frac{128}{8} + \frac{283.27}{8} \right) \text{ kg} \times 9.81 \frac{\text{m}}{\text{s}^2}$$

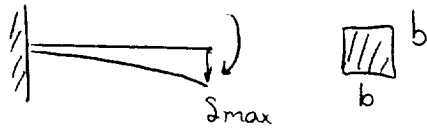
$$P_{\text{cr}} = 504 \text{ N}$$

$$M = P_{\text{cr}} \times L/2$$

$$M = 3 \text{ m} \times 504 \text{ N} = 1512 \text{ N} \cdot \text{m}$$

- dimension of leg are determined by  $M$

Assume: - leg is supported at one end



$$\text{let } \delta_{\max} \leq l_{\text{em}}$$

$$\delta_{\max} = \frac{ML^2 \times 1.5}{2E_{Al} I}$$

$$I = \frac{1}{12} b^4$$

[Robert C. Juvinoll  
Fundamentals of Machine  
Component Design]

$$b = \left[ \frac{12 \times 1.5 \times L^2 \times M}{2 \times E_{Al} \times \delta_{\max}} \right]^{\frac{1}{4}} = \left[ \frac{12 \times 1.5 \times (0.91)^2 \times 1512 \text{ N}\cdot\text{m}}{2 \times 72 \times 10^9 \times 0.01} \right]^{\frac{1}{4}}$$

$$b = 6.28 \text{ cm}$$

$$m_{\text{legs}} = 4 \times (0.0628)^2 \text{ m}^2 (0.91 \text{ m}) \times 2800 \frac{\text{kg}}{\text{m}^3}$$

$$m_{\text{legs}} = \underline{\underline{40.147 \text{ kg}}}$$

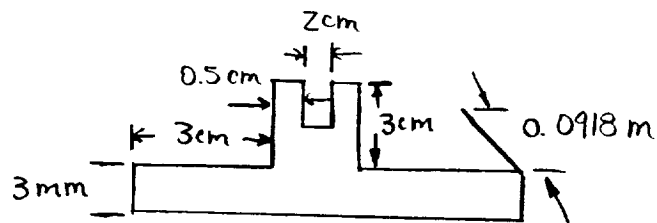
### Miscellaneous Masses:

joints : 5 kg

collars : 25.48 kg

rollers : 6 kg

radiator support :  $m = \rho V$



$$m = \rho V$$

$$m = 2800 \frac{\text{kg}}{\text{m}^3} \left[ 0.03 \text{ m} \times 0.03 \text{ m} \times 0.0918 \text{ m} + 0.003 \text{ m} \times (0.0918)^2 \text{ m}^2 \right]$$

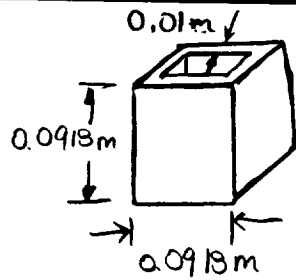
$$m = 0.3012 \text{ kg}$$

there are 52 radiator supports

$$m_{\text{TOT}} = 0.3012 \text{ kg} \times 52 = \underline{\underline{15.66 \text{ kg}}}$$

$$m_{\text{radiator support}} = \underline{\underline{15.66 \text{ kg}}}$$

- mass collars :



$$V = (0.0918 \text{ m})^2 \times 0.01 \text{ m}$$

$$V = 8.427 \times 10^{-5} \text{ m}^3$$

$$m = \rho V = 8.427 \times 10^{-5} \text{ m}^3 \times 2800 \frac{\text{kg}}{\text{m}^3}$$

$$m_{\text{collar}} = 0.236 \text{ kg}$$

- there are 108 collars

$$m_{\text{collar}}_{\text{TOT}} = 108 \times 0.236 \text{ kg} = \underline{\underline{25.48 \text{ kg}}}$$

Total mass per package:

radiator support	15.66 kg
shading system	128.81 kg
rail support	323.42 kg
collars	25.48 kg
rollers	8 kg
	<hr/>
	501.37 kg

For the 10 kW heat rejection system the total mass:

$$501.37 \text{ kg} \times 17 = 8523.29 \text{ kg}$$

For the 25 kW heat rejection system the total mass:

$$501.37 \times 42 = 21,057 \text{ kg}$$

## Estimated deployed and stowage volume:

When the system is being transported the rails can be folded. The estimated stowed volume is determined by the width of the panels when the panels are closed

$$\rightarrow \leftarrow (0.000127 + 0.0198) \text{ m}$$



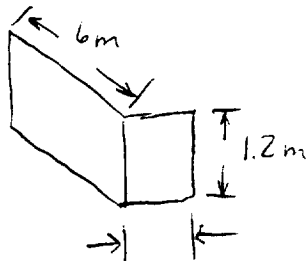
$$L_t = 2 \text{ cm} + 2 \times (0.000127 + 0.0198) \text{ m}$$

$$L_t = 0.0598 \text{ m}$$

for 26 shade systems, the total length is

$$L_t = 26 \times 0.05985 = 1.556 \text{ m}$$

stowage volume:  
per package



$$V = L_t \times 6 \text{ m} \times 1.2 \text{ m}$$

$$V = (1.56 \text{ m}) \times (6 \text{ m}) \times (1.2 \text{ m}) \quad L_t$$

$$V = 11.232 \frac{\text{m}^3}{\text{package}}$$

for 10 kW heat rejection the total occupied volume

$$V = 11.232 \frac{\text{m}^3}{\text{package}} \times 17 \text{ packages} = 190.94 \text{ m}^3$$

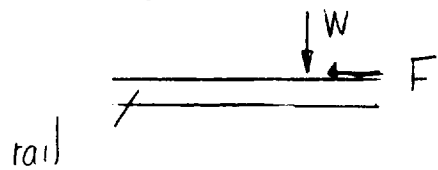
for the 25 kW rejection system the total occupied volume is:

$$V = 42 \times 11.232 \frac{\text{m}^3}{\text{package}} = 471.74 \text{ m}^3$$



## Estimated Power to Deploy the Modified Winged-System and Rail Support

- Assume:
- each rail carries half of the total shade system weight.
  - collar and rail material is aluminum, collar is coated



$F$   $\equiv$  frictional force that must be overcome to deploy the shading systems

$W$   $\equiv$  total weight of shades acting on one rail.

$$F = \mu W$$
$$\mu \approx 0.2$$

$$W = \frac{128.81 \text{ kg}}{2} \times 9.81 \text{ m/s}^2 = 631.81 \text{ N}$$

$$F = 0.20 (631.81 \text{ N}) = 126.36 \text{ N}$$

Assume each shading system moves an average of 4m.

- the energy required to deploy the system

$$E = Fd = 126.36 \text{ N} \times 4 \text{ m} = 505.45 \text{ N}\cdot\text{m}$$

- Assume the deploying and retracting process occurs in 120 secs; the power is

$$P = \frac{E}{t} = \frac{505.45 \text{ N}\cdot\text{m}}{120} = 4.21 \text{ W}$$

for the 10 kW system the total power required is:

$$P_{\text{TOT}} = 4.21 \text{ W} \times 17 \text{ packages} = 71.6 \text{ W}$$

for the 25 kW system the total power required is:

$$P_{\text{TOT}} = 4.21 \times 42 = 176.82 \text{ W}$$

## Appendix

### Wear of the collars and rail

In this appendix, the wear percentage of the collar and rail is calculated. The total amount of material removed from the surfaces after 200 deploy and retract cycles is provided.

Assumptions

- the collar is not coated
- collar and rail material is aluminium

$$W = \left( \frac{K}{H} \right) FS$$

[Juvinall, Robert C.  
Fundamentals of Machine Component  
Design]

$W \equiv$  volume of material worn away,  $\text{mm}^3$

$F \equiv$  compressive force between the surfaces, N

$S \equiv$  total rubbing distance, mm

$K \equiv$  wear coefficient

$H \equiv$  surface hardness

F, the compressive force is the weight of the shading system and radiator support carried by one rail

$$F = 5.44 \frac{\text{kg}}{\text{m}} \times 1.63 \text{ m/s}^2 = 887 \text{ N}$$

S, the total rubbing distance will be different for the collar and rail

$$S_{\text{rail}} = 200 \frac{\text{cycles}}{\text{collar}} \times 8000 \frac{\text{mm}}{\text{cycle}} \times 54 \text{ collar} = 8.64 \times 10^7 \text{ mm}$$

↑ each shading system

K, is approximately  $5 \times 10^{-2}$ , from figure 9-12, for identical metals

$$H_b = 95 \text{ for Al}$$

$$W = \left( \frac{5 \times 10^{-2} \times 887 \text{ N}}{(95 \times 9.81) \text{ MPa}} \right) \times 8.64 \times 10^7 \text{ mm} \times \frac{1 \times 10^6 \text{ mm}^2}{1 \text{ m}^2}$$

$W = 41116 \text{ mm}^3$  material removed from the rail after 200 cycles

$$\text{Volume of the rail: } 6 \text{ m} \times (0.09 \text{ m})^2 \text{ m}^2 = 0.0501 \text{ m}^3 \left( 50 \times 10^6 \frac{\text{mm}^3}{\text{m}^3} \right)$$

$$\% \text{ of volume removed: } \frac{41116 \text{ mm}^3}{50.1 \times 10^6 \text{ mm}^3} = \underline{0.082\%}$$

The amount of material removed from each collar:

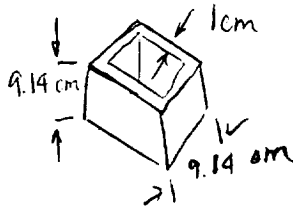
$$S_{\text{collar}} = \frac{200 \text{ cycles}}{1} \times \frac{8000 \text{ mm}}{\text{cycle}} = 1.6 \times 10^6 \text{ mm}$$

$$W = \left( \frac{5 \times 10^{-2} \times 8.87 \text{ N}}{(95 \times 9.81) \text{ MPa}} \right) \times 1.6 \times 10^6 \text{ mm} \times \frac{1 \times 10^6 \text{ mm}^2}{1 \text{ m}^2}$$

$$W = 716 \text{ mm}^3$$

Volume of collar:

$$V = (0.0914)^2 \text{ m}^2 \times 0.01 \text{ m}$$



$$V = 83539 \text{ mm}^3$$

$$\% \text{ Volume remove} : \frac{716 \text{ mm}^3}{85.34 \times 10^3 \text{ mm}^3} = 0.86\%$$