RADIATOR STUDY FOR STATIONARY LUNAR LANDERS

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ABSTRACT

This paper provides an overview of a study to identify, select and evaluate potential heat rejection radiators for application to small, low power, stationary lunar landers. While this study supported risk mitigation activities related to the International Lunar Network project, the radiator concepts and performance assessments are applicable to a wide range of lunar lander applications. The radiator concepts identified and evaluated in this study were aimed at providing reliable heat rejection for landers that might be subjected to hot lunar noon conditions at the equator. As a part of the study, a literature search of lunar radiators was performed from which many radiator designs were developed. These designs were compared in a trade study and two of the most promising were used to develop six concepts. These six radiator concepts went through a more detailed thermal analysis using Thermal Desktop. The analysis considered heat rejection capability, and sensitivity to many factors such as dust deposition, latitude, life, and topographical features like landing on a hill, on a rock, or in a hole/crater. From the result of the analysis, two radiator concepts were selected for recommendation: a flat horizontal plate with a dust cover and a stacked vertical radiator with parabolic reflectors and a one degree tilting mechanism.

OVERVIEW

Mission and Lander

The International Lunar Network initiative intends to place a number of small autonomous landers equipped with diverse instrument suites on the lunar surface to gather simultaneous, global scientific data about the moon. Consequently, the landers to support these instruments need to have the capability to operate continuously anywhere on the moon for an extended time. The current study was initiated as a part of a risk mitigation activity to identify and assess potential risks to the thermal control subsystem for potential small, general latitude, lunar landers which could satisfy the ILN type mission. While each type of location on the lunar surface poses challenges to the thermal design of these landers, operating at the lunar equator, exposes the lander to unique, diverse and extreme thermal environments: during the lunar night, extreme cold conditions persist for up to 14 days imposing challenges on the power and thermal control subsystems, and during the lunar day, hot conditions can persist that impact heat rejection capabilities and limit operational scenarios. From a heat rejection standpoint, the near-subsolar equatorial location is the driving scenario for the current effort.

Notional Lander Thermal Control Subsystem

Figure 1 shows a picture of a notional general latitude lander equipped with a radioisotope power source (RPS). Other landers equipped with solar arrays and batteries are also under investigation to support this type of mission. Most of the lander components are located between the top and lower decks. These include the liquid propulsion tanks, an electronics enclosure, and the radiator. The scientific experiments that are supported by the landers are still under development, although a notional suite was selected to formulate initial lander concepts.

Because of the extreme temperature variation associated with the lunar surface the electronics (and batteries) required for lunar surface operation will be thermally isolated from the surrounding environment as much as possible, inside the warm enclosure. This enclosure must be kept cool during the day and warm during the night. To achieve this, a thermal transport switching device was chosen early in the design cycle. During the day it will switch on allowing for the heat to transport efficiently from the electronics enclosure to the radiator. At night it will switch off allowing the enclosure to keep itself warm using the heat dissipation of the electronics.

For the spacecraft to operate during mission life it is necessary to keep the electronics safe and functioning. This means components and batteries must not be exposed to temperatures outside their operating temperature range, which generally is from 0°C to 50°C. While thermal switching device addresses the cold end, the radiator must contribute to meet the high end temperature requirement. However, this is difficult because of the Moon's complex thermal environment. The lunar surface at the subsolar point and near the spacecraft can reach temperatures as high as 116°C, In addition, adjacent rocks, holes/craters, and hills can contribute addition thermal loads on the radiator. The Sun above moves very slowly through the sky where sunrise to sunset last roughly 14 Earth days and has a high heat flux. The design of the radiator must mitigate these problems in order to provide a thermal sink cold enough to reject the heat dissipated within the electronics enclosure.

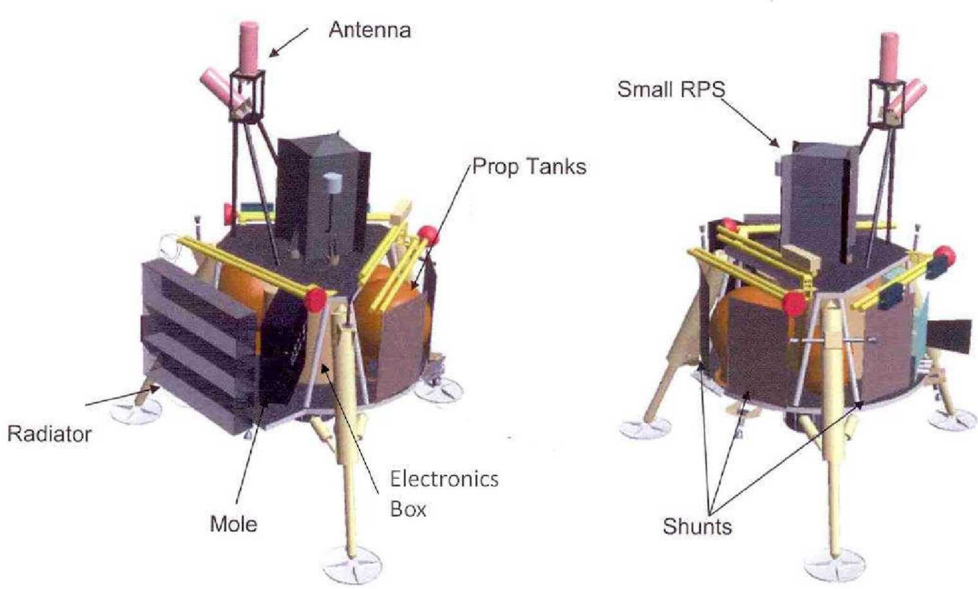


Figure 1: Nuclear Powered Lander

Radiator Literature Review

Three sources proved to be influential to the radiator study. These were the Apollo Lunar Scientific Experiments Package (ALSEP), Surveyor, and James Webb Space Telescope (JWST). ALSEP was a collection of scientific experiments that each Apollo mission carried and placed on the Moon. Most of the experiments performed for a number of years.(1)(2) Three interestingly designed components were the Main Station, the Lunar Surface Magnetometer (LSM), and the Solar Wind Spectrometer (SWS). All are shown in the left side of Figure 2. The Main Station contained most of the higher dissipating electronics. Its radiator was parallel to the lunar surface and had a specular reflective foil in the shape of a V.(3) The LSR and SWS's radiator consisted of a stack of emissive fins with specular reflective parabolic surfaces. The specular reflective surfaces were used to direct away from the radiator the infrared radiation emitted from the hot lunar surface. Also, both were designed so the heat rejecting surfaces would be shaded from the Sun when placed on the ground by astronauts. By limiting the exposure to the high solar flux above and the hot lunar surface below, this type of design solves two thermal rejection problems associated with a lunar surface mission.

The Surveyor spacecraft is shown in the right side of Figure 2. These were a series of lunar landers that preceded the Apollo landings. They used a mechanical thermal switching device between the electronics and the radiator. Unfortunately some of the switches failed and most of the landers did not survive through the first lunar night.(4) Surveyor used a flat plate radiator that faced skyward and was uncovered. This design limited the view to the surface, but exposed the radiators to the Sun. By selecting a thermal coating with a low solar absorptivity and turning off components during extreme temperatures of lunar noon the lander was able to survive the hot day. The radiator was also aided by partial shadowing provided by the solar arrays when the sun was directly overhead.

The JWST baffled radiator assembly is shown in Figure 3. This design was inspired by Winston trough type solar concentrators which were developed in the 1970's. By using two parabolic reflectors the assembly controlled the radiator emission in two directions which was of concern for the JWST project. The design is advantageous for the lunar surface because, like the ALSEP radiators, the parabolic reflectors can control where the energy that is being reflected onto the radiator is coming from. By having two reflectors, the baffle design has two acceptance angle ranges which can be tailored for expected hills and tilts.

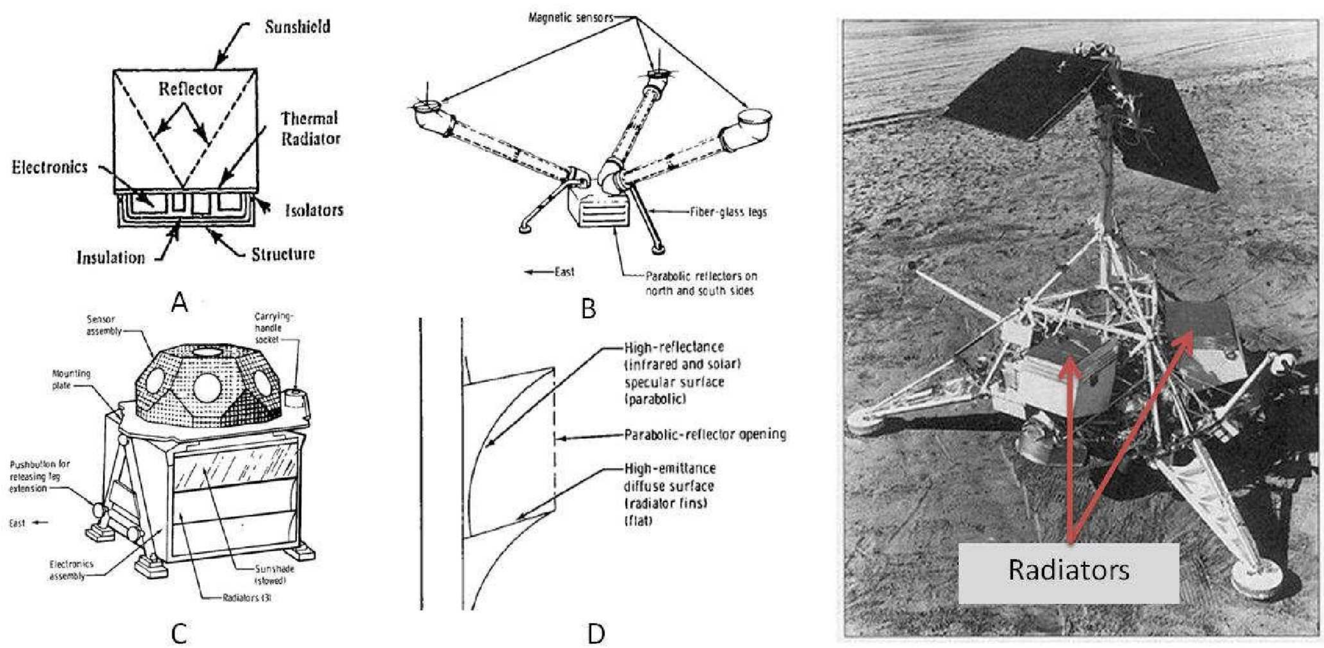


Figure 2: ALSEP (left) and Surveyor Spacecraft (right)

A: Main Station - Side View B: Lunar Surface Magnetometer C: Solar Wind Spectrometer D: Parabolic Radiator - Side View

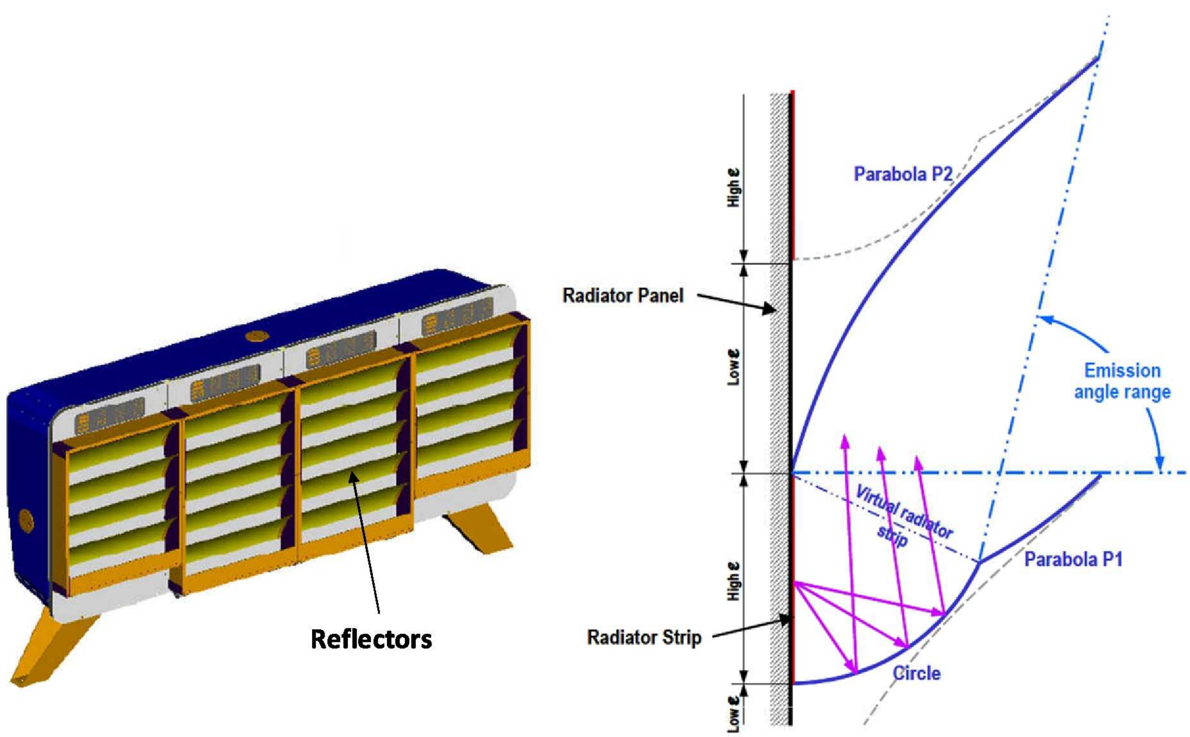


Figure 3: JWST Radiator: Baffled Assembly (left) and Reflector Side View (right) (5)

Paper Outline

The following section defines the radiator design space. This includes the project parameters and analytical assumptions. Next, in the thermal modeling section the technique used to analyze the radiators is described. Many preliminary concepts are shown in the Case Study I section. The concepts draw inspiration from the previous radiator designs described above. They were analyzed and optimized for the ILN mission. A few of the most promising candidates were then selected and placed in different configurations on the lander thermal model. As described in Case Study II, the configurations were subjected to a set of landing conditions, and their heat rejection capabilities were calculated. By keeping the set of landing conditions constant, a direct comparison between each configuration could be performed. Two of the configurations which best meet the requirements were selected for recommendation.

DESIGN SPACE

Project Parameters

A number of parameters for this project are easily defined at this point in the design process. These are shown in Table 1 and include rejection capability, dimensions, and environmental factors among others. Table 2 lists the parameters that are inherently harder to define because there are no exact ways of knowing what will happen during landing. These parameters were analyzed in two different ways. One was to define a specific value, say an 8 degree hill, in order to baseline each concept. The other was to analyze a range of values in order to assess the sensitivity of the parameter.

For the hot case design assumptions, the radiator rejection temperature includes a 10°C knockdown value associated with the heat transport system for the expected temperature drop between the electronics box and the radiator. A lesson learned from Surveyor was there is a large benefit in turning off higher dissipating components during the hottest part of the day. For ILN this will be done by turning the transmitter off. A preliminary thermal model of the electronics box predicts a 10 Watt heat leak through the insulation during the hottest part of the day. The maximum radiator dimensions are determined from the space between the upper and lower decks and the legs. The maximum solar flux and surface temperature are located on the sub-solar point at the equator.

For the baseline study values, the maximum terrain slope was determined from a statistical analysis of the lunar terrain for the landing sites being considered. Probable rock size was determined from which a lander tilt angle was calculated. This value was also used to represent a hole or crater. The maximum Azimuth error, which will skew a north facing radiator to the east or west, was provided by the guidance and navigation team. There is not a good method for determining the maximum dust coverage, and more research must be done in this area. Dust coverage of 50 and 15 percent were chosen for this study to provide conservative estimates of deposition while not being so conservative that no radiator concept could survive. More information about lunar dust and its effect can be found in the next subsection. The sensitivity ranges for the terrain and landing error were chosen by taking half of the baseline value then subtracting and adding it to the baseline value. For sensitivity to dust, many points were taken throughout the range.

Table 1: Hot Case Design Assumptions and Design Targets

Assumption or Target	Value	Rationale (if appropriate)
Maximum Radiator rejection temperature	40 °C	Assumes a 10C delta between the WEB at 50 and the radiator
Electronics dissipation heat load	66W (transmitter on), 52W (transmitter off)	notional
Max environmental heat leak also to be rejected	10W	
Life	6 years	
Lunar albedo	0.2	values ranged from .1 to .2, .2 chosen to impart max reflected on radiator
Max radiator dimensions	21" (height) x 50" (width)	notionally constrained by lander dimensions – some growth could probably be entertained
Max solar flux	1414 W/m^2	
Maximum lunar surface temperature	116°C	
Radiator surface absorptivity/emissivity (beginning of life)	0.07/0.8 (OSR) (6)	
Reflector surface absorptivity/emissivity (beginning of life)	0.06/0.03 (VDS) (6)	

Table 2: Baseline and Sensitivity Study Values

	Baseline Study	Sensitivity Study
Max terrain slope	8°	4°, 8°, 12°
Max leg tilt caused by a hill or hole	6°	3°, 6°, 9°
Max Azimuth error	5°	2.5°, 5°, 7.5°
Max dust coverage	50% upward facing, 15% downward facing surfaces	0-100% upward facing, 0-50% on downward facing surfaces

Dust Assumptions

Two basic types of materials were considered for the radiator. The heat rejection surfaces used a low solar absorptivity, high emissivity material such as an optical surface reflector (OSR). The emission direction controlling surfaces used a low absorptivity, low emissivity, and specularly reflective material such as vapor deposited silver (VDS). The top layer of the lunar surface has been described as a fine dust and caused problems with past surface missions. Two unknowns associated with the regolith are the amount of dust deposition and the effect it will cause on optical properties.

During landing a single thruster will cause the dust to follow a ballistic trajectory away from the lander and have little chance of being deposited on the spacecraft surfaces. However multiple thrusters may invalidate this claim. Dust may also be deposited over time while on the Moon. This happens because of charging associated with the Sun during the day and plasma currents at night.

Gaier has published results pertaining to the change in the absorptivity and emissivity to percent dust coverage.(7) The paper focuses on common radiator materials with high emissivity and low absorptivity properties, such as white thermal control paint (AZ93) and a second surface mirror (Ag coated FEP/Teflon). Also the paper assumes a monolayer of dust. Using his results and assuming that for a high emissivity surface the addition of lunar dust, which also has a high emissivity, does not affect the emissivity. The following equation was developed to determine the change in absorptivity.

$$\alpha_{D,BOL} = (0.025 * d + 1)\alpha_{BOL}$$

Where d is the amount of dust coverage in percentage and α_{BOL} is the beginning of life solar absorptivity. The final equation used to determine the solar absorptivity for the radiator surface included factors for dust and time.

Vapor deposited metal is the other type of material chosen for the parabolic reflectors. It is similar to the radiator material in that it has a low absorptivity, but it differs because it has a low emissivity. Also its reflectance is specular, meaning that the energy will be reflected as shown in the top-right picture of Figure 4. Currently no study like Gaier's is known that measures the change in optical properties of a reflective surface due to lunar dust. Because of this, as a starting point, it was assumed that the equation for the change in absorptivity interpreted from Gaier's paper also applies to the change in emissivity of the reflector. Another assumption is the specularity of a material is not affected by dust. This can be interpreted to mean that while the addition of dust decreases the reflectance, because dust has a low reflectance, the areas of the surface that are undusted will remain the same specularity. This is shown in bottom of Figure 4. These are two big assumptions and should be tested if this type of material is selected for additional studies.

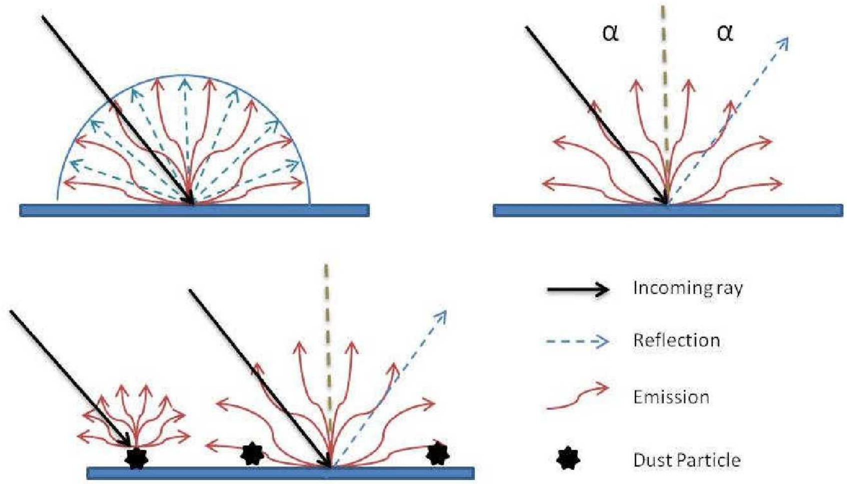


Figure 4: Types of Reflection

Clockwise from Top Left: Diffuse Reflection, Perfectly Specular Reflection, Perfectly Specular Reflection for Non-dust Portion and Perfect Absorption by Dust

THERMAL MODEL

Radiation and thermal math models for the thermal analysis were built using Cullimore and Ring's Thermal Desktop 5.4 and solved using Sinda/Fluent. Because the radiator was the focus of the analysis, the rest of the spacecraft was modeled to provide a representative radiative environment and conduction from one lander component to another was ignored. Figure 5 shows an overview of the thermal model. A total of five articulators were attached to the model: one to model Azimuth landing error, one for each leg to simulate landing on a rock or in a hole, and one attached to the radiator to model a one dimensional tilting mechanism.

Modeling of a parabolic reflector was done through AutoCAD. At the time Thermal Desktop did not have a command to create a 2D parabolic trough, though this feature is now available. To create the trough a LISP code was written in AutoCAD where the user inputs focus distance, optical axis, and number of points. AutoCAD then iterated the polyline command determined by the number of points to create the trough, which was then converted to a Thermal Desktop entity.

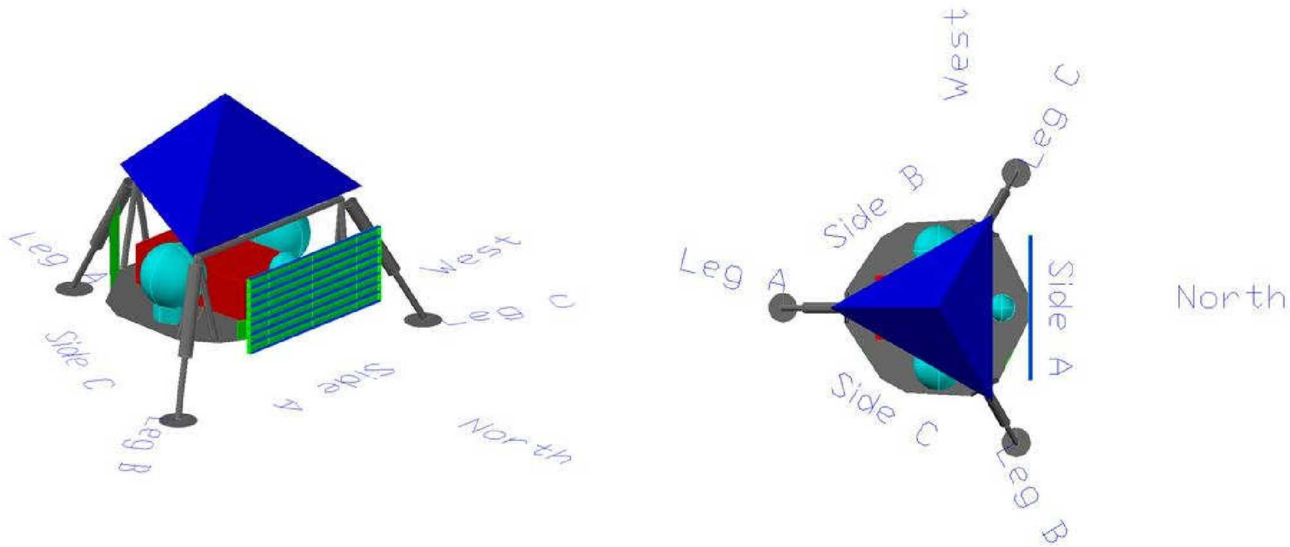


Figure 5: Lander Thermal Model Nomenclature (as landed in the northern hemisphere)

Environmental Modeling

The environment was modeled using the Thermal Desktop Orbit command. With this command the user defines the solar vector, solar flux, planet vector and distance, planet temperature, and albedo. Thermal Desktop uses a ray tracing algorithm to calculate the environmental flux for each surface and then applies it as a boundary condition. Defining a negligible planet distance results in the planetary surface being modeled as infinitely large, flat, and isothermal. This is a disadvantage because it does not take into account shadows cast by the lander. Another way of modeling the surface is to use Thermal Desktop surfaces. However, to calculate the albedo correctly would require many nodes and a large amount of rays, which would increase the run time. Using the worst case tilt of the radiator to the surface, a comparison study was done between the two methods of modeling. It was found that shadows did not affect the radiator performance. However, it does affect the lander structure temperature, and therefore a system model of the lander should use Thermal Desktop surfaces to model the surface ground plane.

Another disadvantage of the Orbit command is its lack of ability to model a hill. This was overcome within the Orbit menu by defining the planet vector corresponding to the hill slope. Three different landing scenarios are shown in Figure 6. The top left models the spacecraft as nominally landed on a flat surface with no hills. The top right is landed next to a hill. This is a conservative model because the hill is infinitely long. Finally the bottom picture is landed on a hill. Articulators were used to model a leg landed on a rock or in a hole.

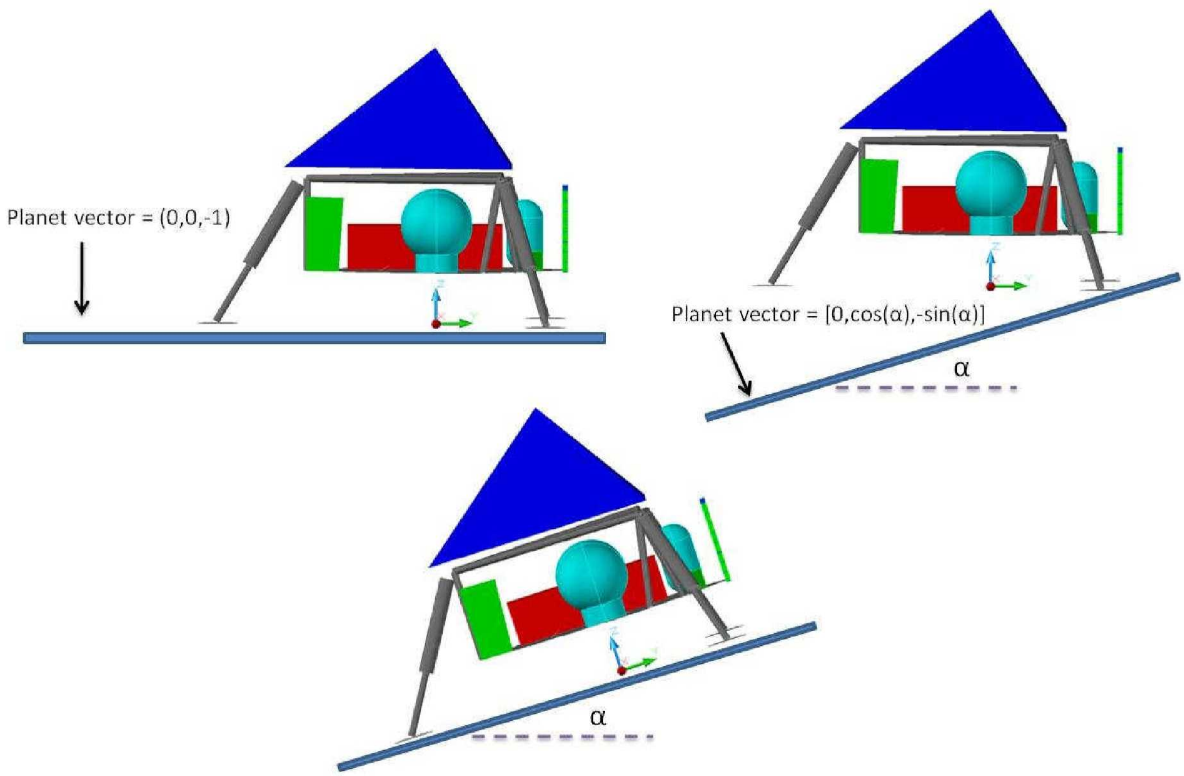


Figure 6: Surface Modeling using Thermal Desktop Orbit Command.

Clockwise from Top-left: Landed on Flat Ground, Looking at a Hill, On a Hill

DESIGN STUDY I

Purpose

Four types of radiator designs were inspired from the literature review: the flat plate from Surveyor, the single parabolic reflector from ALSEP, and the baffled assembly from JWST. Each of the designs have different parameters that control the performance of the radiator. The purpose of Design Study I was to analyze each concept and optimize any parameters for the ILN mission. The study also considered configuration layouts including one versus multiple radiators. Once the concepts were optimized with their best configuration, a more detailed analysis was performed in order to compare the concepts against each other. This is described in the Design Study II section

Method

Using the thermal models described in the preceding section the design parameters were varied parametrically and the radiator thermal performance was plotted. From this plot, the optimal value could be read. Some parameters were varied at the same time to see if there were any correlations. For the flat plate the parameter that was varied was the tilt. For the flat reflector, similar to ALSEP's main station, the angle between the reflector and radiator was varied. A circular reflector was compared to a parabolic reflector. Three parameters were varied for the parabolic reflector design: the tilt of the reflector, the length of the reflector, and the tilt of the radiator. The baffled assembly adds another two variables which are the tilt and length of the additional reflector.

Configuration layouts were analyzed for the parabolic designs. Because the parabolic design is vertical, this allowed for configurations with multiple radiators. The radiators could be located on different sides of the spacecraft viewing different directions. The multiple radiator analysis assumed that when a radiator produced negative rejection, the heat transport system would turn off conduction to that radiator.

Results

Some of the designs and the parameters that were varied are shown in Table 3 while the different configurations are shown in Table 4. For the flat plate, varying the tilt reduced the solar load into the radiator but increased the input from the surface. The heat rejection versus tilt plot was not linear and there was an optimal tilt angle. This angle is a function of latitude and the assumed solar absorptivity and emissivity. Three reflector designs were analyzed: flat, circular, and parabolic. Out of the three the parabolic performed the best. Tilting the optical axis and/or the radiator of the parabolic design did not provide much benefit. The baffled assembly is highly sensitive to the lunar environment. Because of the nature of the design any hills, tilts, or landing errors that caused the radiator to view the surface or the sun dramatically reduced its performance.

Different stacked radiator configurations are shown in Table 4. Usually changing the configuration would diminish the sensitivity to one type of off-nominal landing while increasing the sensitive in another. Even with multiple radiators, there was always a landing scenario that would substantially diminish the total rejection.

Based on the results of the Design Study I, the following concepts were recommended: tilted flat plate, tilted parabolic, horizontal flat plate with a dust cover, vertical parabolic with a dust cover, vertical parabolic with a tilting mechanism, and three parabolic radiator in the fourth configuration of Table 4. These concepts will be described in greater detail in the next section.

Table 3: Radiator Designs

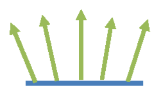
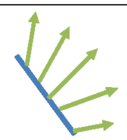
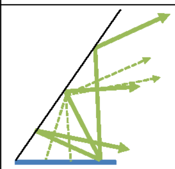
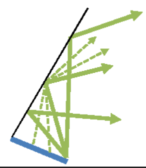
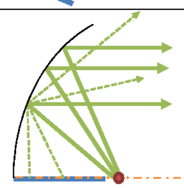
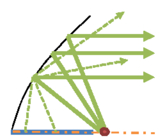
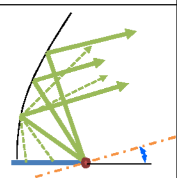
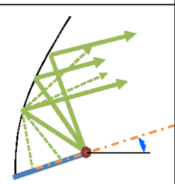
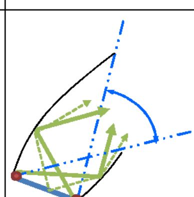
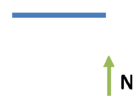
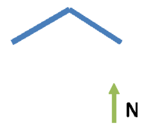
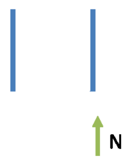
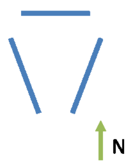
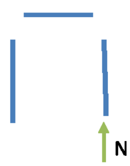
Description	Picture	Comments
Horizontal radiator		Design recommended, sensitive to dust because of view to sun, low sensitivity to landing errors and lunar surface
Tilted radiator		The greater the tilt angle the less input from the sun (therefore less sensitivity to dust), however it increases heat input from the lunar surface
Horizontal radiator with a flat reflector		Similar to ALSEP main station, no direct view to the sun, some heat from the lunar surface will be reflected onto the radiator
Tilted radiator with a flat reflector		Increases heat input from the lunar surface
Horizontal radiator with a circular reflector		Reflects lunar heat away from radiator, parabolic reflector has as a tighter focus
Horizontal radiator with a parabolic reflector		Design recommended , insensitive to dust because no view to sun, no heat reflected onto radiator (nominal landing), highly sensitive to landing errors
Horizontal radiator and a parabolic reflector with a tilted optical axis		Optical axis can be tilted so as when the assembly is tilted towards the surface the lunar heat will not be reflected onto the radiator, sensitive to tilts towards the sun
Titled radiator and a parabolic reflector with a tilted optical axis		When the assembly is tilted towards the surface the lunar heat will not be reflected onto the radiator, sensitive to tilts towards the sun
Baffled radiator		Baffles designed so that the radiator will not receive heat when either tilted towards the surface or sun. Requires significant more area, and extremely sensitive to seeing the sun or surface

Table 4: Vertical Radiator Configurations - Top View (see Figure 5 for lander nomenclature)

Description	Picture	Comments
One radiator looking North on A-side		Design recommended, on nominal landing in the Northern hemisphere radiator will not view the sun, sensitive to landing errors especially with A-leg
Two radiators – Northeast & Northwest on A-side		Less sensitive to landing errors caused by A-leg
Two radiators – West (B-side) & East (C-side)		Insensitive to A-leg landing errors, has a potential landing scenario where one radiator views the hot surface while the other views the sun.
Three radiators – North (A-side), Southwest (B-side), Southeast (C-side)		Less sensitive to landing error, but there are some landing scenario where two will see the sun at one point in the day while the other sees the surface, performance decreases with higher latitude
Three radiators – North (A-side), West (B-side), East (C-side)		Performs better at higher latitudes

DESIGN STUDY II

Purpose

The result from Design Study I was six different configurations involving the flat plate and the parabolic radiator. Two designs using these can be seen in Figure 7 at the end of this paper. The purpose of Design Study II was to subject each configuration to the same set of landing conditions and compare the results. By doing this, each radiator configuration was compared against to the others and the best one selected.

Designs

The six concepts, which are shown in Table 5 below, are: tilted flat plate, tilted parabolic, horizontal flat plate with a dust cover, tilted parabolic with dust cover, parabolic with mechanism, and 3 parabolic radiators. The minimum latitude is where each concept meets the rejection requirement for the hot case assumptions in Table 1 and the baseline design values in Table 2.

The tilted flat plate is tilted to an optimal angle from the horizontal. This is the simplest of the designs because it has no dust cover. Also it is the one with the highest heritage. The tilted parabolic is tilted away from the surface to an optimal angle. This is the simplest of the parabolic designs because it contains no dust cover or mechanism.

The next two concepts are the horizontal flat plate and tilted parabolic with a dust cover. The rationale for using a dust cover follows from the assumption that the highest probability of dust deposition is during landing. The dust cover would cover the radiator during landing after which a simple mechanism would release the cover. A radiator with a dust cover was assumed to have 15% dust coverage on upward facing and 5% on downward facing surfaces, as opposed to 50% and 15% for without a dust cover. These concepts are a bit more complex and extra heater power might be required during flight to keep the release mechanism from freezing. Also there is a potential mass penalty associated with extra covers or mechanisms.

During the Design Study I it was found that the parabolic design was sensitive to off-nominal landings, which could cause the radiator to view either the surface or the Sun. This motivated the use of a one dimensional tilting mechanism to counteract the off-nominal landings. It would be activated one time after landing and would tilt the radiator either towards or away from the surface. A three dimensional mechanism was also analyzed, but controlling the other two dimension did not have enough reward to justify the associated complexity.

The three parabolic radiator configuration consists of three vertical parabolic radiators placed in the north, southeast, and southwest orientation. This is shown as the forth configuration in Table 4. The configuration is more complex because the heat transport system would have to run to all three and be able to switch off individual radiators when they produced negative rejection.

Table 5: Six Concepts

	Tilted Flat Plate	Tilted Parabolic	Horizontal Flat Plate w/ Dust Cover	Tilted Parabolic w/ Dust Cover	Parabolic w/ Mechanism	3 Parabolic Radiators
Minimum Latitude	22°	9°	Equator	Equator	Equator	Equator
Complexity	Simple	Reflectors, fins	Cover	Reflectors, fins, cover	Reflectors, fins, mechanism	Reflectors, fins plumbing, control
Heritage	High	Limited (ALSEP)	High	Limited (ALSEP)	Limited	Limited
Additional Comments			Heater power for mechanism	Heater power for mechanism	Heater power for mechanism	Increase transport mass

Method

Design Study II compared the radiators on a number of criteria. Using the hot case assumptions in Table 1 and the baseline design values in Table 2 each concept performance was calculated for nominal and off-nominal landings. The off-nominal landing used the baseline values from Table 2: 8^{o} hill, 6^{o} rock or hole, and 5^{o} Azimuth error. The duration of time a concept's performance fell below the heat rejection required during transmitter operation was also calculated.

The sensitivity of each concept was measured using the range of values in Table 2. Also the sensitivity to latitude and life time was calculated. The method for measuring sensitivity was to calculate and plot the performance at each value for both nominal and off-nominal landing. By comparing the plots between the concepts a scale from one to five was assigned where a value of one demonstrates either low sensitivity to the parameter or meeting the requirement, and a value of five signifies either high sensitivity or failing the requirement.

Results

The concept performance is shown in Table 6 below. On nominal landing, the flat plate does not exhibit heat reject capability as high as that exhibited by the parabolic design. However the flat plate is a lot less sensitive to off-nominal landing than the parabolic, because the parabolic will collect and focus the energy if it views the Sun or surface. This affect can be alleviated somewhat by using a tilting mechanism. The three parabolic radiators had the shortest amount of time for turning the transmitter off, but had the greatest drop in rejection between nominal and off-nominal landing.

Table 6: Concept Performance

	Tilted Flat Plate (min_latitude)	Biased Parabolic (min-latitude)	Horizontal Flat Plate w/ Dust Cover	Biased Parabolic w/ Dust Cover	Parabolic w/ Mechanism	3 Parabolic Radiators
Minimum Heat Rejection --Nominal Landing	87 W	102 W	66 W	92 W	99 W	110 W
Minimum Heat Rejection - Off-Nominal Landing	62 W	58 W	62 W	47 W	64 W	57 W
Short Fall Duration Below Transmit Limit for Off-Nominal Landing	2.5 Earth days	5.7 Earth days	4.1 Earth days	6.5 Earth days	4.1 Earth days	2.4 Earth days

The concept sensitivities are shown in Table 7. There is a lot that can be drawn from the table so some of the key points will be discussed here. The flat plate in general is a lot less sensitive to off-nominal landing errors that would increase the view to the surface. This is especially true for the horizontal flat plate. The tilted flat plate received a higher sensitivity in latitude because it could not meet requirements below 22^{o} latitude. The performance of the horizontal flat plate increased quickly with latitude. The flat plate is extremely sensitive to dust and life because these two factors increase the solar absorptivity and the plate is directly exposed to the Sun. If it is reasoned that the highest probability for dust deposition is during landing, this sensitivity motivates the use of a dust cover.

The parabolic radiators are very sensitive to off-nominal landing errors, except for Azimuth errors. The three radiator design was very sensitive to latitude because both the southeast and southwest radiators become exposed to the Sun with latitude. Because of this, the concept is only feasible at the equator. The use of a mechanism helps alleviate the sensitivity to rocks and holes/craters but does little for hills. This is because at the equator, pointing away from a hill exposes the radiator to the Sun. This effect will lessen with latitude. The biased parabolic is sensitive to dust and lifetime because its potential sun exposure is increased .

Table 7: Concept Sensitivities (1 - low sensitivity and/or meets requirements 5 - high sensitivity and/or fails requirements)

	Tilted Flat Plate (min_latitude)	Biased Parabolic (min-latitude)	Horizontal Flat Plate w/ Dust Cover	Biased Parabolic w/ Dust Cover	Parabolic w/ Mechanism	3 Parabolic Radiators
Sensitivity to Latitude	4	3	1	3	2	5
Sensitivity to Hills	4	5	1	5	4	4
Sensitivity to Rocks and Holes	2	4	1	4	2	4
Sensitivity to Azimuth Errors	1	1	1	1	2	2
Sensitivity to Dust	5	2	5 (cover would mitigate this sensitivity)	3	1	2
Sensitivity to Lifetime	5	3	5	4	2	2

Concept Recommendation

Based on the results in Design Study II the horizontal flat plate with a dust cover and the parabolic with a tilting mechanism were recommended to the project. Both of these concepts are shown in Figure 7. The flat plate is recommended because of its low sensitivity to off-nominal landing scenarios. However, it is sensitive to dust and life. For dust the amount of deposition will always be an unknown, but with the addition of a dust cover or other repelling devices the amount of deposition can be reduced. The sensitivity to life is better understood and accounted for by oversizing the radiator.

The parabolic radiator has a higher performance on nominal landing than the flat plate, and it is also less sensitive to dust and life. However it is much more sensitive to off-nominal landing scenarios. The use of a tilting mechanism helps alleviate this but does little for hills at the equator. Another difference between the two is that the parabolic design is vertical while the flat plate is horizontal. Depending on the spacecraft design, one orientation could be more beneficial.

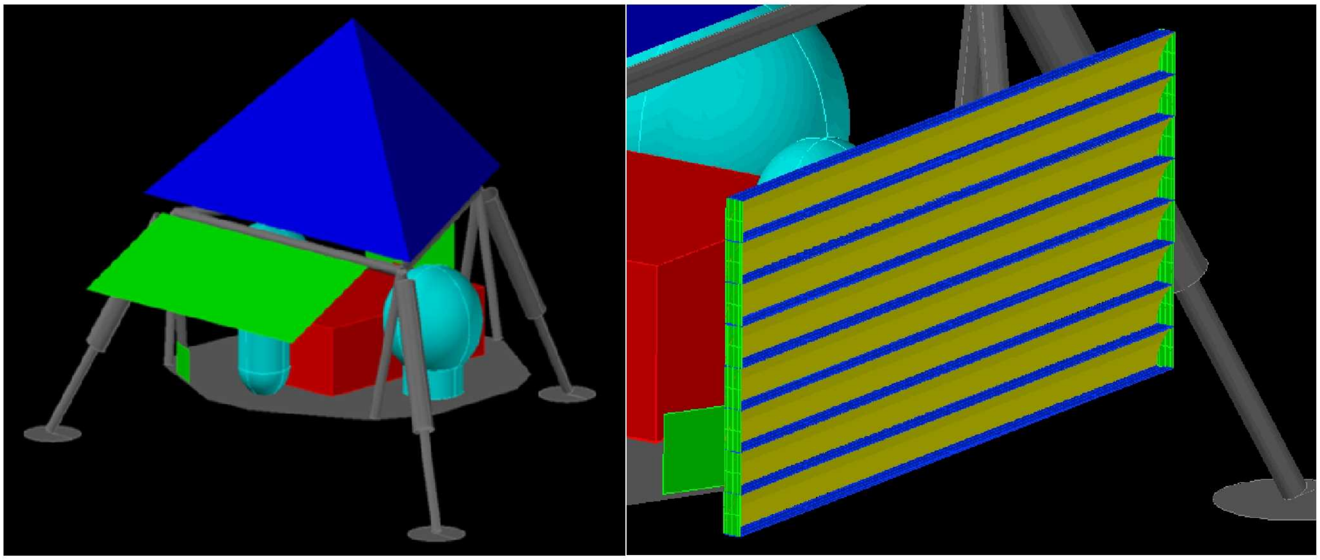


Figure 7: Radiators: Flat Plate Radiator (left) and Parabolic Radiator (right) - Fins (blue) with Parabolic Reflectors (yellow). For the recommended configuration the flat plate is placed above the solar arrays which requires a design change from what is shown.

Conclusion

A radiator study for a general latitude stationary lander was performed for the International Lunar Network lander design risk mitigation activities. In conjunction with a switchable heat transport system, the radiator would reject the electronics' dissipated heat during the day. Radiator designs were analyzed for the hot case, assumed to be at the equator with sun overhead. There are, however, many unknowns associated with the mission that make the specifics of this hot case difficult to define including topographical features such as hills, rocks, and holes/craters and the possibility of dust deposition. Using Thermal Desktop-generated models and analysis capabilities, an initial trade study of several conceptual designs was performed. These designs drew inspiration from past radiators designed for ALSEP, Surveyor, and JWST. From this trade, two of the most promising designs were selected for further detailed analysis: the flat plate design and a vertically stacked array with parabolic reflectors as well as modifications of these. Each option was evaluated qualitatively and quantitatively to assess radiator rejection capabilities and characterize the sensitivities to the mission unknowns. From the results, two radiator designs were selected for recommendation to the project: the flat plate with a dust cover, and a stacked radiator with parabolic reflectors including a one-dimensional tilting mechanism. Both of these radiators have sensitivities to different parameters. The flat plate is sensitive to dust deposition and life, while the parabolic is sensitive to topographical features and landing errors. The final selection will depend on these findings as well as other configuration considerations. While these concepts were evaluated with ILN type mission in mind, the conclusions may have applicability to other lunar missions that have to endure the similar thermal environments.

ACKNOWLEDGEMENTS

The authors would like to extend appreciation to Jeff Farmer of MSFC, the thermal lead for the ILN project. He provided a great deal of guidance and feedback during this study.

ACRONYMS

ALSEP – Apollo Lunar Scientific Experiment Package

APL – Applied Physics Laboratory

ASRG – Advanced Stirling Radioisotope Generator

ILN – International Lunar Network

JWST – James Webb Space Telescope

LSM – Lunar Surface Magnetometer

MSFC – Marshall Space Flight Center

OSR – Optical Surface Reflector

RPS - Radioisotope Power Source

SWS – Solar Wind Spectrometer

VDS – Vapor Deposited Silver

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TFAWS Paper Session

Radiator Study for Stationary Lunar Landers

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Thermal & Fluids Analysis Workshop
TFAWS 2010
August 16-20, 2010
Houston, TX

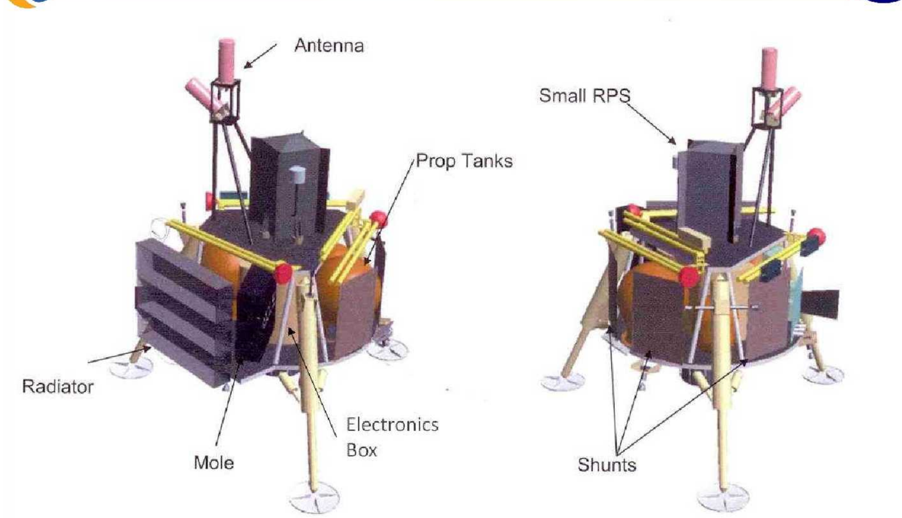
Outline

- ILN Project Overview
- Thermal System
- Design Space
- Literature Review
- Thermal Model
- Case Study I
- Case Study II
- Conclusion

ILN Project Overview

- International Lunar Network (ILN)
  - NASA/MSFC & John Hopkins University/APL
- Small autonomous landers capable of operating any where on the Moon
- Radiator study was done to address potential thermal control subsystem risks
- Landing at the equator became driving scenario for the study

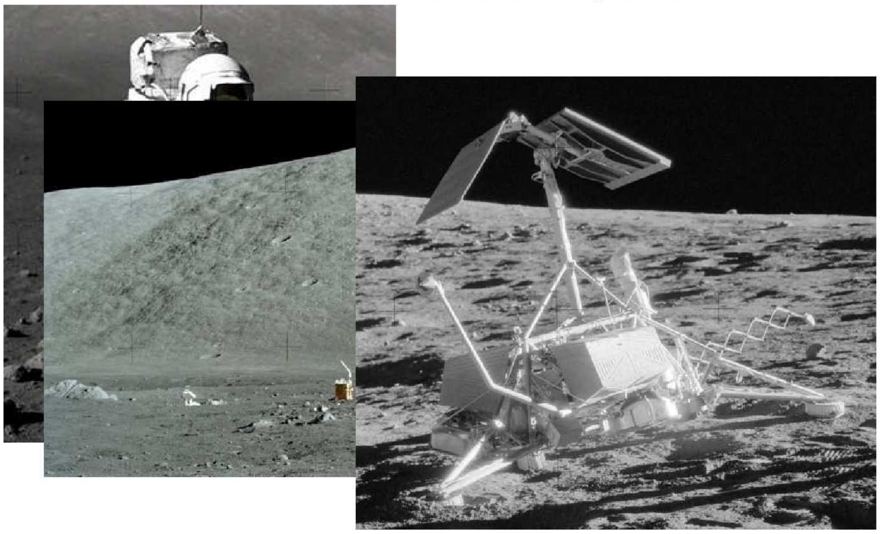
General Latitude Lander – Thermal System



- Purpose of the radiator is to keep the electronics box cool during the day.

Design Space

Multi variable – some are more complex to define

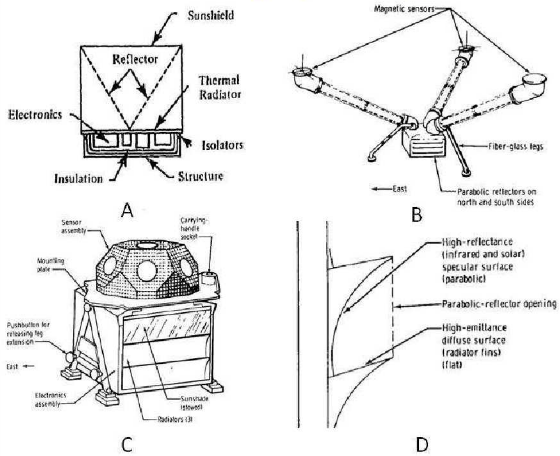


Design Space

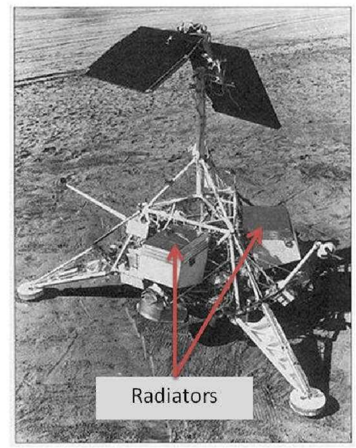
Radiator rejection temperature	40 °C
Rejection amount	66 Watt (transmitter on) 52 Watt (transmitter off)
Max environmental heat leak also to be rejected	10W
Minimum life	2 years
Lunar albedo	0.2
Max radiator dimensions	21" (height) x 50" (width)
Max solar flux	1414 W/m^2
Maximum lunar surface temperature	116°C

Radiator Literature Review

Apollo Lunar Scientific Experiment Package (ALSEP) (1) (2)

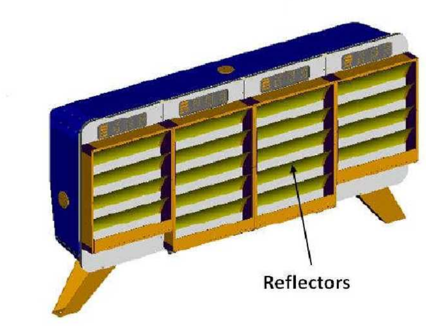


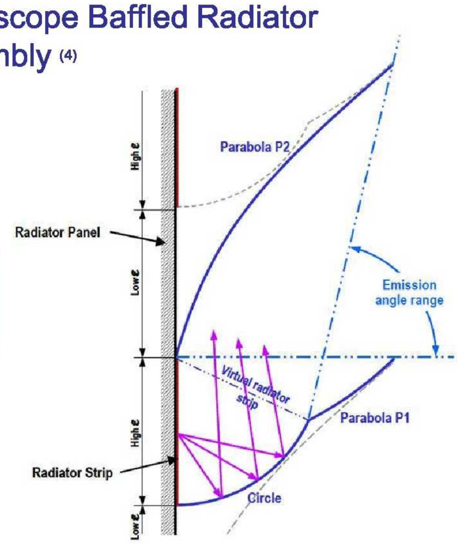
Surveyor (3)



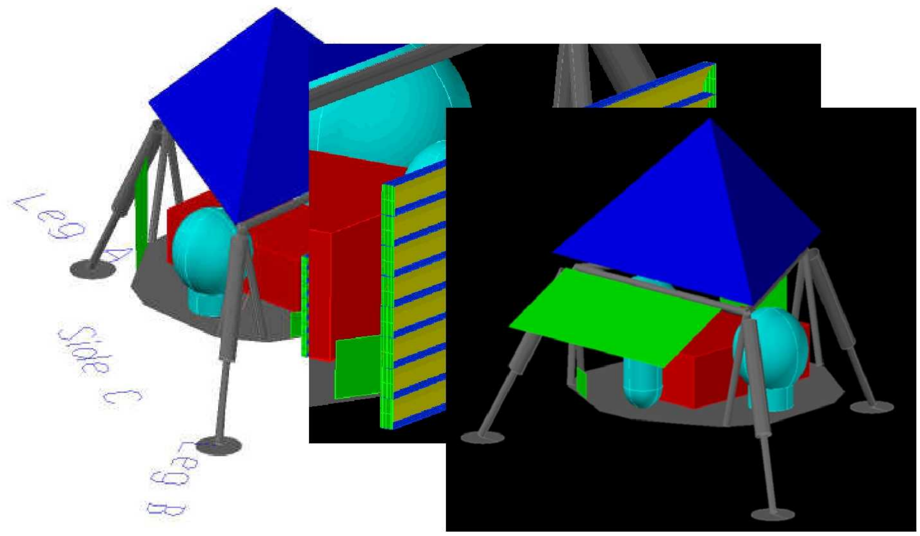
Radiator Literature Review

James Webb Space Telescope Baffled Radiator Assembly (4)

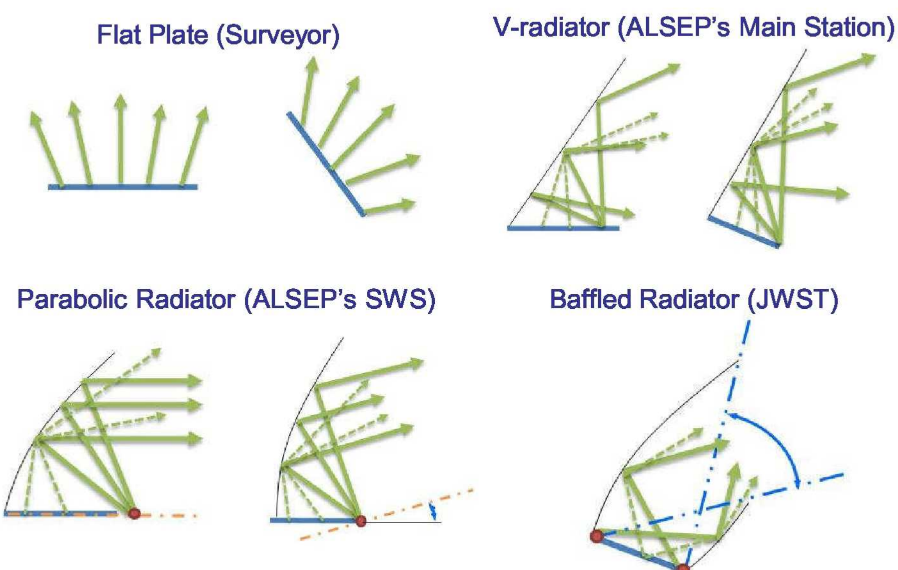




Thermal Model

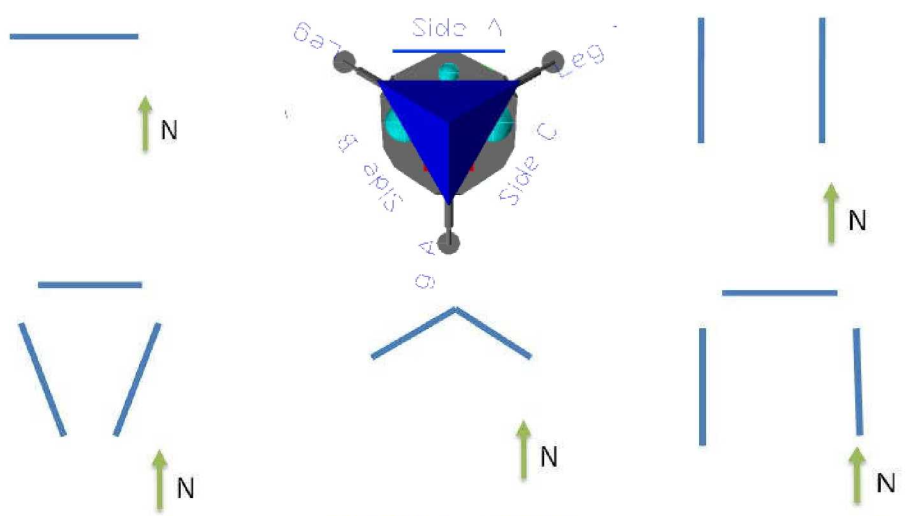


Case Study I - Designs



Design Study I - Layouts

Top view of spacecraft



Design Study II - Concepts

Tilted Flat Plate

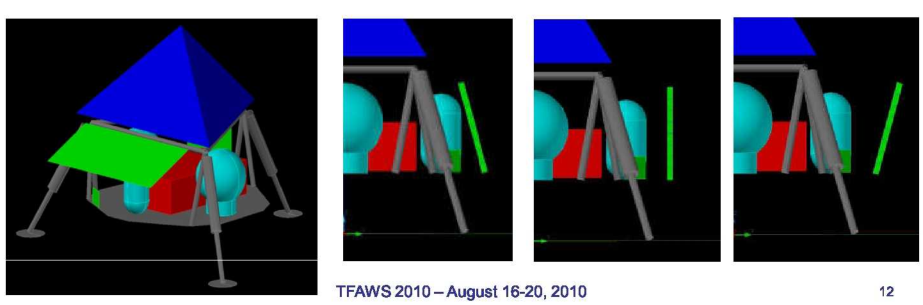
Tilted Parabolic

Horizontal Flat Plate w/ Dust Cover

Tilted Parabolic w/ Dust Cover

Parabolic w/ Tilting Mechanism

3 Parabolic Radiators



Design Study II - Method

- Analyzed each of the 6 concepts and compared on performance & sensitivity.
- Heat rejection capability was calculated and compared for different scenarios

	Performance	Sensitivity
Max terrain slope	8°	4°, 8°, 12°
Max lander tilt caused by a rock or crater	6°	3°, 6°, 9°
Max Azimuth error	5°	2.5°, 5°, 7.5°
Max dust coverage	50% upward facing, 15% downward facing surfaces*	0-100% upward facing, 0-50% on downward facing surfaces
Latitude	Equator**	0° to 40°
Life	2 yrs	2 – 6 yrs

* Concept with dust cover: 15% upward facing, 5% downward facing surfaces
** Tilted flat plate = 22°
Tilted parabolic = 9°

Design Study II - Results

- Performance results:

	22° Latitude	9° Latitude	Equator			
	Tilted Flat Plate (min_latitude)	Biased Parabolic (min-latitude)	Horizontal Flat Plate w/ Dust Cover	Biased Parabolic w/ Dust Cover	Parabolic w/ Mechanism	3 Parabolic Radiators
Minimum Heat Rejection –Nominal Landing	87 W	102 W	66 W	92 W	99 W	110 W
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Design Study II - Results

- General observations:
  - Nominal landing – parabolic design outperforms the flat plate
  - Off nominal landing – parabolic is much more sensitive
  - Flat plate is sensitive to dust and life
  - Parabolic is sensitive to hills and tilts
- Design study recommended concepts:
  1) Horizontal flat plate w/ dust cover
  2) Parabolic w/ tilting mechanism

Conclusion

- Radiator study completed for the ILN mission:
  - Small, autonomous, general latitude lander
- Literature review resulted in four types of designs
- Designs were optimized for mission – six concepts resulted
- Six concepts were analyzed for performance and sensitivities
- Two concepts were chosen for recommendation

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BACKUP SLIDES

Dust Assumption

- Two types of materials considered:
  1) Low absorptivity, high emissivity for radiative surfaces
  2) Low absorptivity, low emissivity, and specular for reflective surfaces
- James Gaier has studied the effects of lunar dust simulant on common radiative materials (5)
- Based on his results, a dust knock-up equation was developed for change in absorptivity
- Other assumptions:
  – The dust does not affect the emissivity of a radiative surface
  – The dust equation applies to both absorptivity and emissivity for the reflective surfaces
  – Dust does not change the specularity of a reflective material, it only changes the amount of reflectance.

Modeling Hills