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**LUNAR BASE THERMAL MANAGEMENT/POWER SYSTEM ANALYSIS AND DESIGN**

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**Abstract**

A compilation of several lunar surface thermal management and power system studies completed under contract and IR&D is presented. The work includes analysis and preliminary design of all major components of an integrated thermal management system, including loads determination, active internal acquisition and transport equipment, external transport systems (active and passive), passive insulation, solar shielding, and a range of lunar surface radiator concepts. Several computer codes were utilized in support of this study, including RADSIM to calculate radiation exchange factors and view factors, RADIATOR (developed in-house) for heat rejection system sizing and performance analysis over a lunar day, SURPOWER for power system sizing, and CRYSTORE for cryogenic system performance predictions. Although much of the work was performed in support of lunar rover studies, any or all of the results can be applied to a range of surface applications.

Output data include thermal loads summaries, subsystem performance data, mass, and volume estimates (where applicable), integrated and worst-case lunar day radiator size/mass and effective sink temperatures for several concepts (shielded and unshielded), and external transport system performance estimates for both single and two-phase (heat pumped) transport loops. Several advanced radiator concepts are presented, along with brief assessments of possible system benefits and potential drawbacks. System point designs are presented for several cases, executed in support of the contract and IR&D studies, although the parametric nature of the analysis is stressed to illustrate applicability of the analysis procedure to a wide variety of lunar surface systems. The reference configuration(s) derived from the various studies will be presented along with supporting criteria. A preliminary design will also be presented for the reference basing scenario, including qualitative data regarding TPS concerns and issues.



## ROVER HEAT REJECTION SYSTEM STUDIES OVERVIEW

A top level overview is presented for the heat rejection analyses performed in support of a pressurized lunar rover definition/design study. This subject received significant attention in the studies because the problem of rejecting large amounts of heat from a pressurized module over long periods of time can be quite imposing, due to the harsh lunar day environment. Surface temperatures approach 380° K during the day, which makes rejecting heat at 275 -291° K (pressurized habitat requirements) difficult to impossible. The heat rejection system must also deal with the large temperature variations experienced in the lunar day/night cycle, which can be as high as 260° K. Past lunar heat rejection systems utilized thermal storage or water evaporator systems. Although these systems were adequate for lower rejection load levels and mission durations. The system investigated in this study was sized to actively reject ~4.71 kW of thermal load for prolonged periods. Several alternate radiator concepts were evaluated, in order to arrive at a system design which is both flexible to varying loads and conditions, and minimizes system mass and size. This accomplished by utilizing designs which have lower radiating sink temperatures (effective surrounding temp.), or increasing the radiator surface temperature artificially (i.e. heat pump).

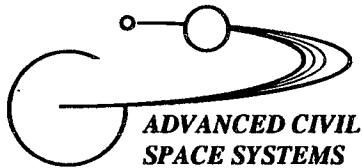
In order to trade the various radiator options, a methodology for determining the radiator effectiveness was needed. Heat balance equations were formulated for each concept, taking into account solar, reflected and diffuse surface, and shield radiation inputs. These equations were utilized to calculate effective sink temperatures, which were in turn used to size the radiator. It should be noted that all two sided radiators were analyzed taking into account the "shading" effect of the "hot" side of the radiator on the "cold" side. This can be seen in the figure, where the left side of the radiator is shielded by the right side, so that it "sees" a lower effective sink temperature.

### *Radiator/Heat Transport System Size vs. Rejection Temperature Trade*

In order to reject heat at the required temperatures (275 & 291° K) during the lunar day with most radiator options, a heat pump was utilized to increase the radiator rejection temperature. Since higher radiator temperatures require more heat pump power (i.e. higher system mass), but reduce radiator temperatures. An interesting note about the heat pumped system is that its heat rejection capacity may be changed at any time (within reasonable limits), by varying the heat pump compressor power level, and the fluid level in the system. The trade resulted in a range of acceptable radiator temperatures between ~330 and 400° K, before the heat pump and power system mass begin to override radiator mass savings. The selected rejection temperature, 360° K, was chosen as a reasonable compromise between radiator area and power requirements (roughly half way between endpoints). Higher or lower rejection temperatures may be required depending on design or operational requirements. The major assumptions made to carry out the trade are shown on the chart. They were chosen to represent as closely as possible the system investigated in this study. Different power levels, rejection loads, surface properties, etc. may shift the chosen temperature range.

### *Heat Pumped and Passive System Functional Schematic*

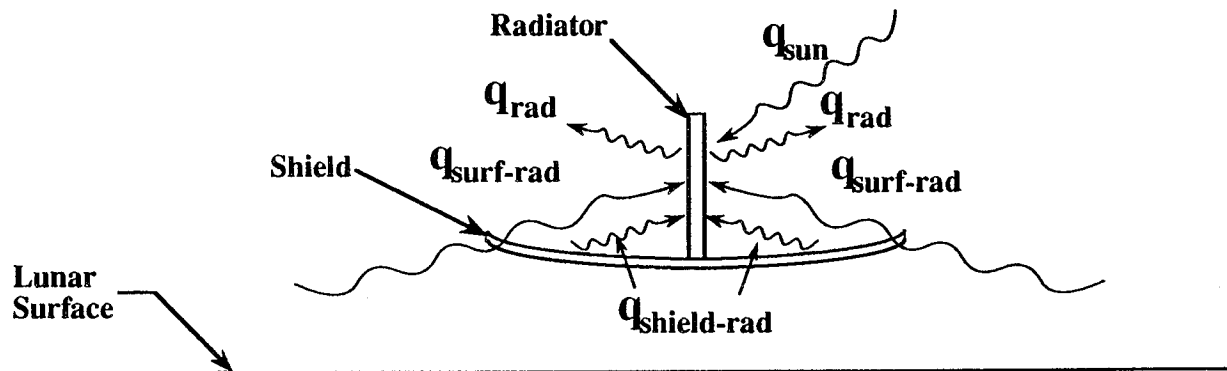
Schematics showing fluid routing, and energy inputs are shown for the active (heat pumped) and passive (single phase pumped loop) heat rejection systems. Each system utilizes a two stage heat exchanger to provide heat removal for both the 40 and 70° F loops (275, 291° K). The passive system external loop would utilize liquid ammonia, while the active system would use Freon 11 (R11) during the daytime, and ammonia or other suitable fluid during the night when the heat pump is not required. It should be noted that the work required by the passive system pump is much



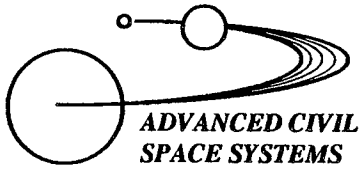
# Rover Heat Rejection System (HRS) Studies Overview

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- **Significantly harder to reject heat on the surface during the lunar day than during night or in space.**
- **Innovative radiator concepts required to reduce radiator area by dropping effective sink temperatures, and/or increasing rejection temp.**
- **Heat balance equations formulated for each radiator, taking into account surface, solar, and shield radiation exchange where applicable.**
- **Two sided radiator sink temperatures determined over range of sun angles for both shaded and lighted ('hot') sides.**

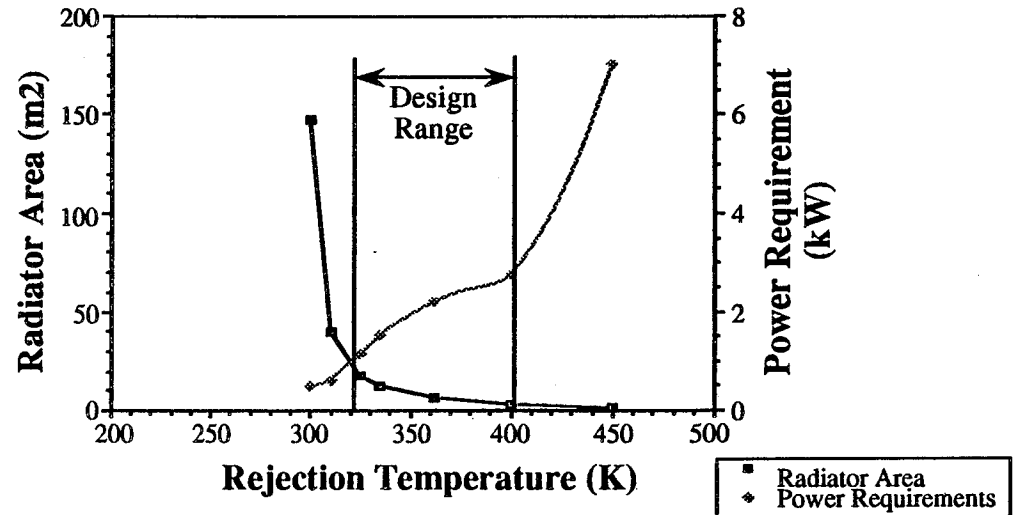
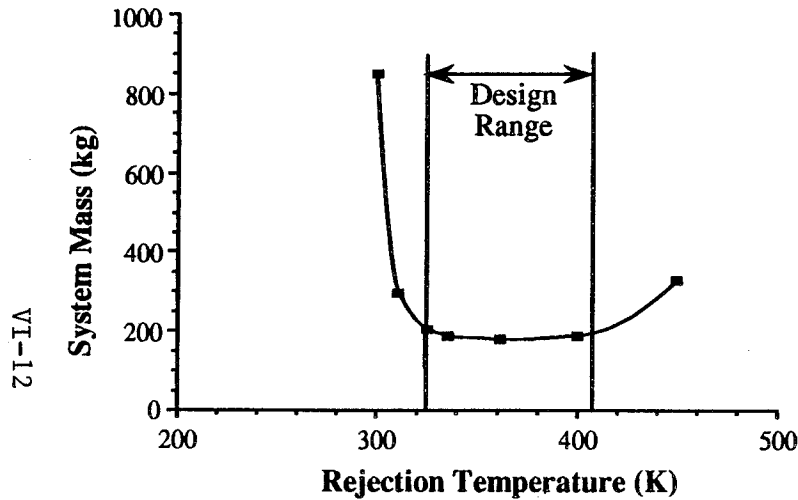


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# Radiator/Heat Transport System Size vs. Rejection Temperature Trade

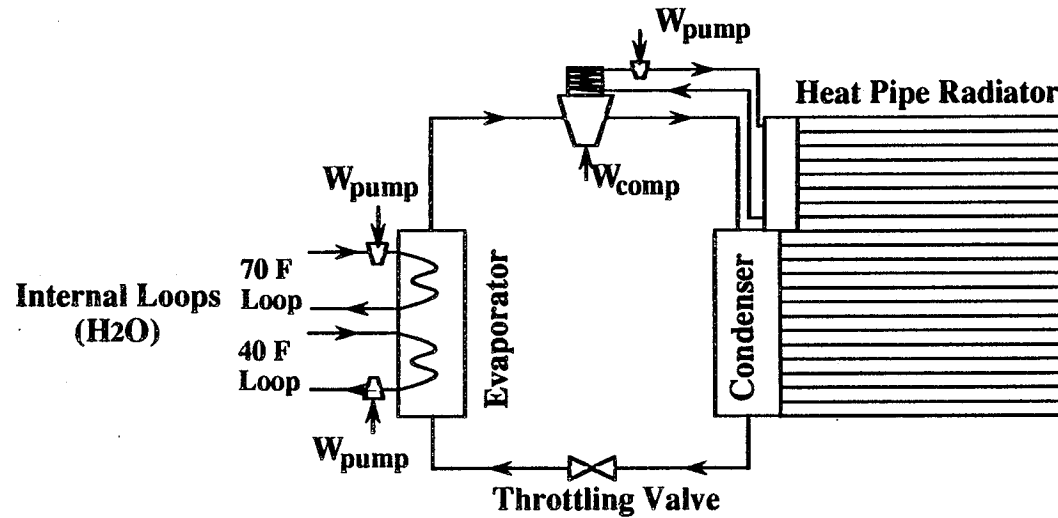
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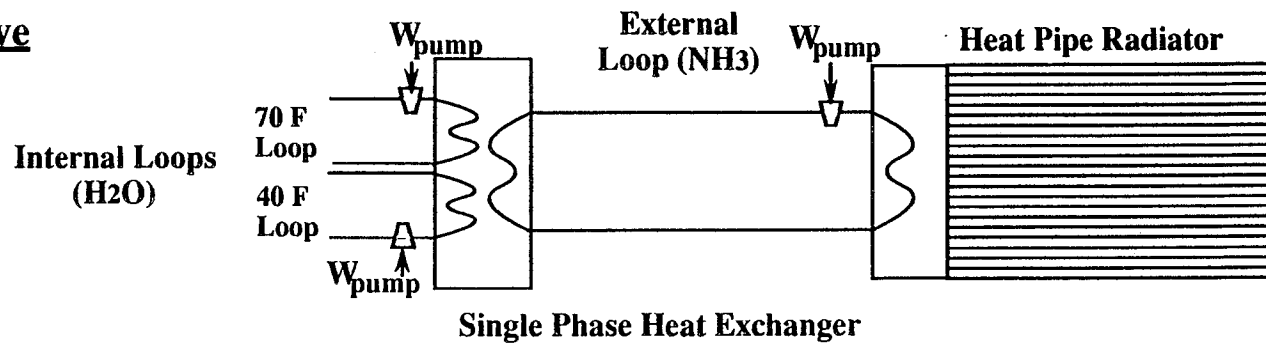
- $T_{\text{sink}} = 296 \text{ K}$  - Payload temp. =  $275, 290 \text{ K}$
- R11 refrigerant
- Rejection load =  $5 \text{ kW}$
- $\alpha = 0.3, \epsilon = 0.8$
- Compressor isentropic efficiency =  $60 \%$

# Heat Pumped and Passive System Functional Schematic

## Heat Pumped



## Passive



lower than that required for the active system (~200 W vs. over 2 kW).

#### *Solar angle and Radiator/Shield Configuration*

Schematics of the various radiator types investigated are shown, including relevant dimensions and explanation. In particular, the geometric and operational parameters of the selective field of view radiator are shown. The equilibrium temperatures (sides, top, sink) were determined from materials properties and a heat balance. The overall sink temperature of the conservative design was determined to be 165° K, which is only slightly below a typical effective sink temperature of a space based radiator. The bulky and heavy shielding required for the selective field of view radiator, along with its operational considerations (tracking, etc.), make it more suitable for high power, static applications (bases, processing plants, etc).

#### *Radiator Sizing Code Capabilities*

A computer program was developed to automate the sizing process developed for the rover study. The code is applicable to all lunar surface systems which utilize radiators to reject waste heat. The inputs of the code are listed, and are the same as required for the earlier study. Radiation view factors were entered into the code based on curve fits of data derived from a Monte Carlo ray trace radiation exchange computer code. The outputs of the code are the same as before, except the mass, sink temperature, etc. are calculated at each time step. The program selects the worst thermal case, and sizes the system accordingly.

#### *Investigated Radiator Design Options*

A summary of the worst case sink temperatures is presented in this chart. As stated before, the sink temperatures were different for the 2 sided options in order to account for the shielding effect provided by the radiator. The "sun" and "dark" sides of the 2 sided radiators may have to be insulated from each other to take advantage of this (MLI should be a relatively low cost option for this). This point may be more easily illustrated on the sink temperature vs. sun angle plot, shown on the next chart.

#### *Vertical Radiator Effective Sink Temperature vs. Sun Angle*

A plot is shown of the effective sink temperature for both shielded and unshielded vertical, and horizontal radiators. The hot and cold side temperatures are shown for the vertical radiator options, and as should be expected, they meet at a solar angle of 90°. The lunar surface temperature is also plotted versus sun angle as a reference. Although the horizontal radiator sees a slightly lower overall sink temperature than the vertical unshielded radiator, the vertical radiator is significantly small, since its radiating area is two times its platform area (radiates from both sides). The shielded radiator plot shows the effectiveness of increasing shield size. As noted on the chart, and verified with view factor calculations, the shield width effects on the sink temperature are not as great as varying shield height. The decrease in sink temperature for the largest shield ( $H_s/H_r = 3$ ) as compared to the middle shield ( $H_s/H_r = 2$ ) is not as great as the decrease between no shield and the smallest shield ( $H_s/H_r = 1$ ), and between the smallest and middle sized shield.

#### *Vertical Radiator to Shield View Factor vs. Shield Size*

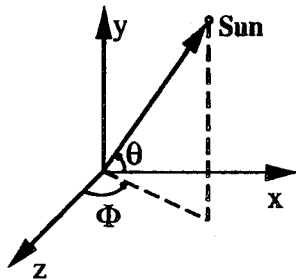
This chart is shown to illustrate the selection process for shield size for the vertical radiator. This graph also illustrates more clearly the relative insensitivity of the overall view factor (and therefore sink temperature) to the shield width / radiator width ratio. A view factor of 80% of the maximum

value was chosen somewhat arbitrarily, in order to choose a reasonable design point for the vertical radiator shield. As can be seen on the graph, a shield height / radiator height of ~2 resulted for all values of  $W_s / W_r$ . The selected ratio was only 1.5, however, due to operational constraints (i.e. mobility and clearance) of the manned rover. The  $H_s/H_r = 1.5$  point seems to be a good design point, since it is just above where the view factor curve begins to flatten out (decreasing advantage for larger shield sizes).

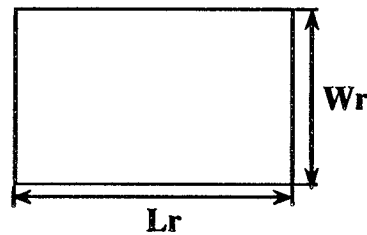


# Solar Angle and Radiator / Shield Configuration

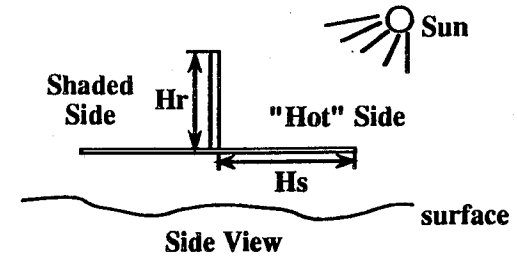
Solar Angles for Sink Temperature Determination



Horizontal Radiator

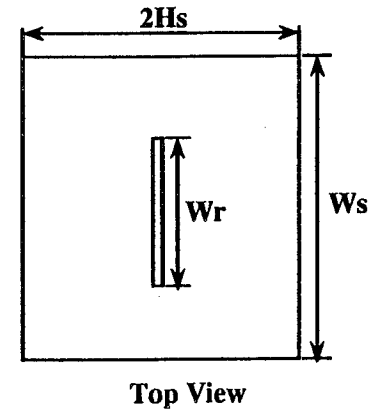
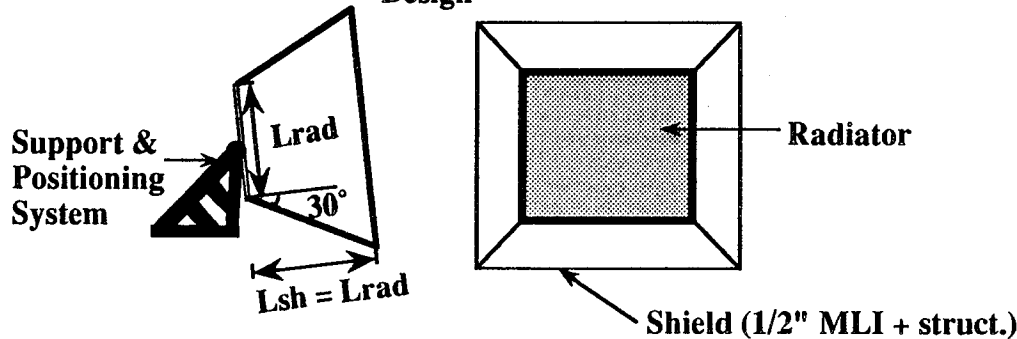


Shielded Radiator Concept

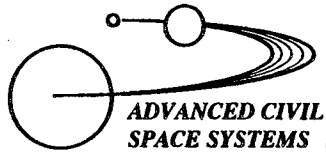


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Selective Field of View Radiator Design



- $T_{\text{bottom}} = T_{\text{sides}} = 202^\circ \text{ K}$ ;  $T_{\text{top}} = 255^\circ \text{ K}$
- $T_{\text{sink}} \sim 165^\circ \text{ K}$
- Spec. mass varies from 15 -24 kg/m<sup>2</sup>, dep. on profile (H/W)

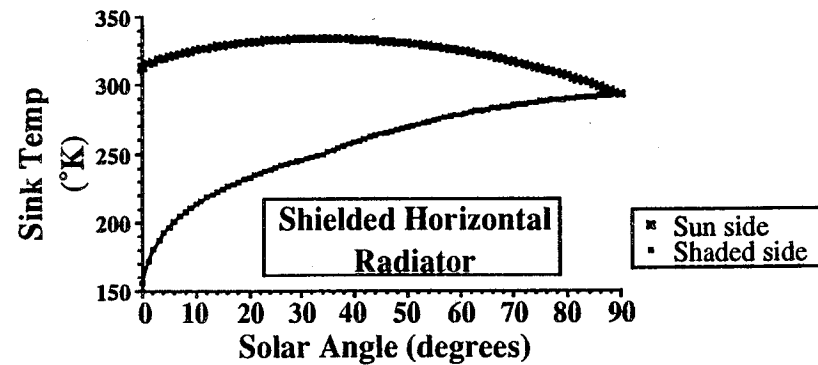
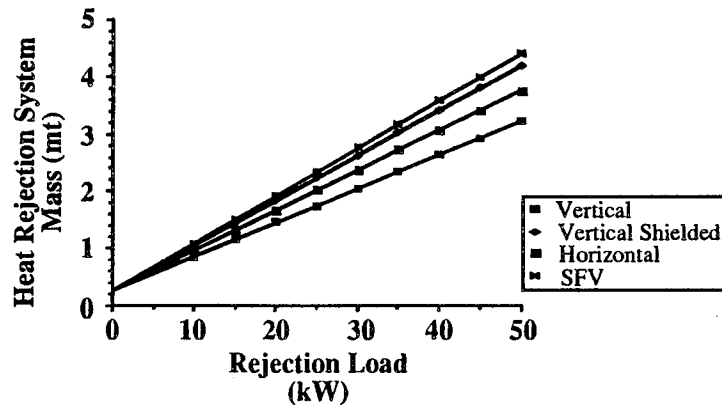


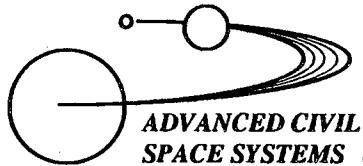
## Radiator Sizing Code Capabilities

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- **RADIATOR** code developed on IR&D to automate sizing process
- **Inputs** include radiator & shield surface properties, radiator type, rejection temp. desired, heat load, and shield/radiator aspect ratios
- **RADIATOR** output includes:
  - radiator & shield surface areas/sink temps vs. solar angle
  - worst case areas, masses, and sink temperatures
  - shield/radiator view factors & dimensions
  - heat pump mass & power requirements






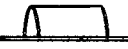
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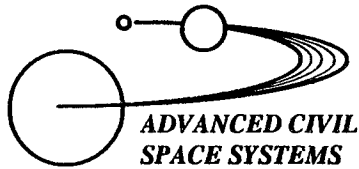


# Investigated Radiator Design Options

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	Radiator Concept	Approx. Tsink (°K)
	<b>I. Vertical Unshielded (2 sided)</b>	Hot side <b>321</b> Cold side <b>311</b>
	<b>II. Vertical Shielded (2 sided)</b>	Hot side <b>310</b> Cold side <b>275</b>
	<b>III. Horizontal (1 sided)</b>	<b>303</b>
	<b>IV. Selective Field of View (1 sided)</b>	<b>165</b>
	<b>V. BMR - Unshielded (1 sided)</b>	Hot side <b>321</b> Cold side <b>311</b>
	<b>VI. BMR - Shielded (1 sided)</b>	Hot side <b>310</b> Cold side <b>275</b>

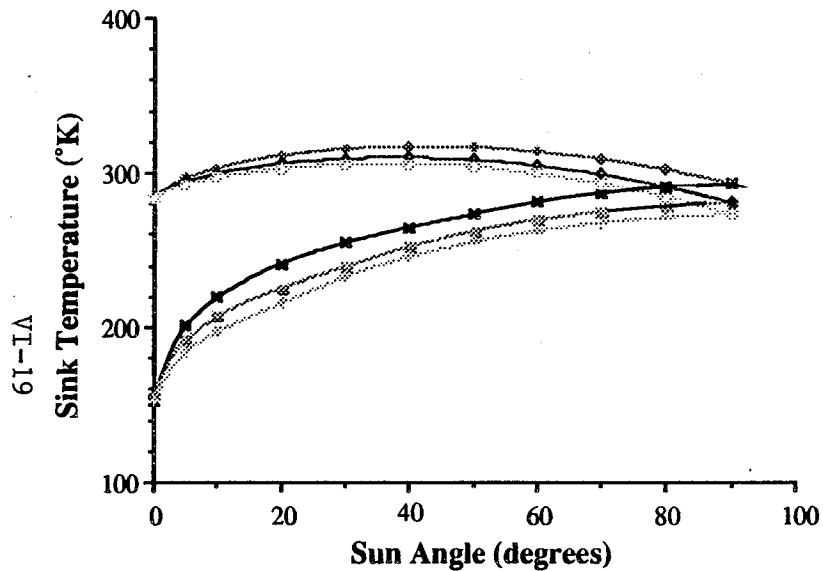
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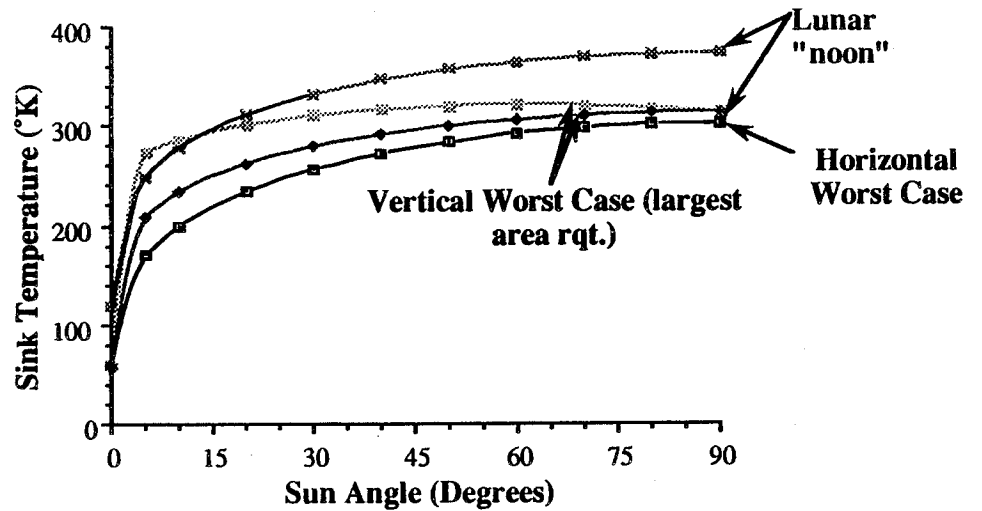
# Vertical Radiator Effective Sink Temperature vs. Sun Angle

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**Shielded**



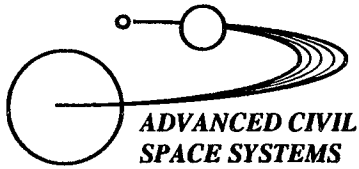
**Unshielded**



- Hs/Hr=1 Shaded side
- ◆ Hs/Hr=1 Hot Side
- ⊠ Hs/Hr=2 Shaded Side
- ◇ Hs/Hr=2 Hot Side
- ⋄ Hs/Hr=3 Shaded Side
- ⋈ Hs/Hr=3 Hot Side

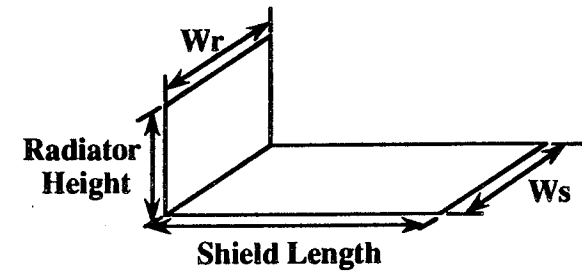
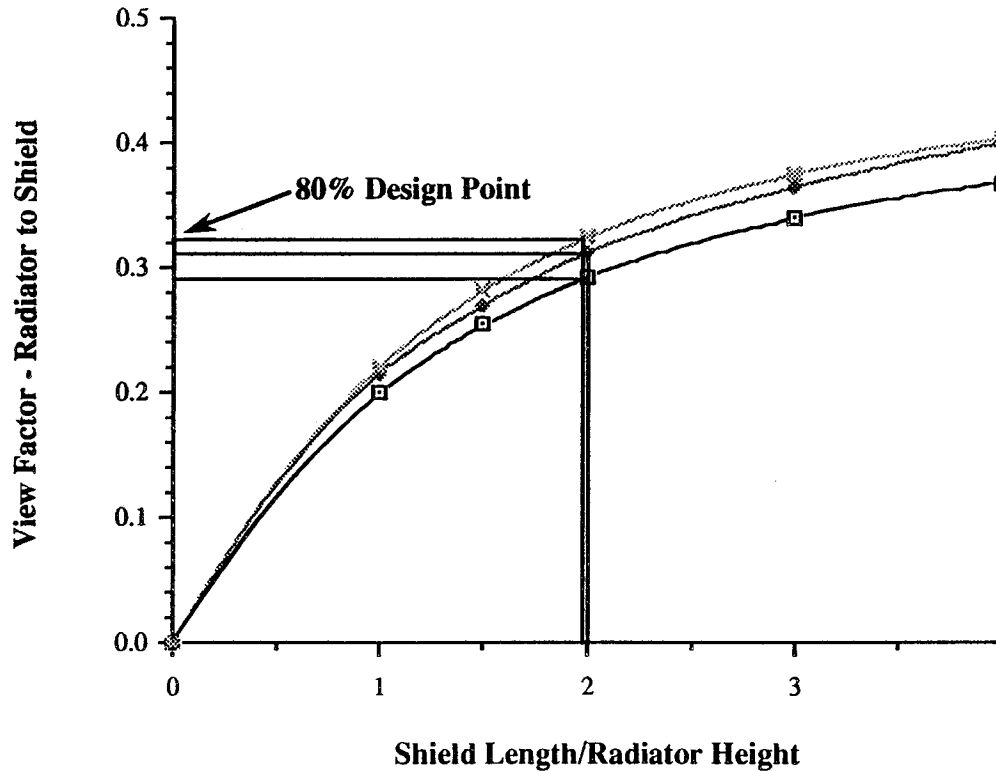
- Horiz. radiator
- ⊠ Surface Temp.
- ⊠ Vert. Radiator Hot Side
- ◇ Vert. Radiator Cold Side

- Hs/Hr ratio increase from 1 to 2 results in greater sink temp. decrease than Hs/Hr increase from 2 to 3
- Ws/Wr increases not as effective as Hs/Hr increases in reducing effective sink temp.



# Vertical Radiator to Shield View Factor vs. Shield Size

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Selected Length / Height Ratio = 1.5

□	$W_s/W_r=1$
◆	$W_s/W_r=2$
※	$W_s/W_r=3$

**Note: 80% design point (80% of max. value) shown for reference only; slightly lower value chosen to further minimize shield size**

