Thermal Analysis
And
Thermal Control System Requirements
For A Solar Sail Mars Mission

by

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(ABSTRACT)

The objective of this study was to determine temperatures that would be experienced by a solar-sail designed at Virginia Tech for a journey to Mars. Knowledge of these temperatures is necessary in the design process of the spacecraft. The temperatures are determined for thermal equilibrium cases during spirals around Earth and Mars. To verify the validity of the equilibrium temperatures the cool-down times are calculated, i. e., the time periods needed for the sail and hub to cool down from a certain temperature to an equilibrium temperature after a sudden change in the thermal environmental conditions (e.g. at the Earth shadow entry point). This calculation shows that the cool-down for the sail requires a very small amount of time, so that the procedure of estimating the temperatures in thermal equilibrium cases is a reasonably good assumption. The hub cool-down, however, needs much more time so that the hub shadow temperatures are probably higher than the equilibrium temperatures. Because of their high dependence upon material properties, the temperatures are calculated for three different sets of parameters and presented in graphs and tables. Furthermore, the temperatures which would occur during a heliocentric transfer are calculated. These temperatures are dependent upon the distance from the sun and the angle of incidence of the sun rays. The results show how close to the sun a solar sail may travel without experiencing any damage. Suitable sets of material properties for the sail are presented in this report. Finally, the temperature distribution over the hub is determined. This distribution is needed to determine the heat exchange between the hub and the equipment contained in the hub. The chosen passive thermal control of the hub (coating) ensures temperature ranges which make it possible to

accomplish this mission without a cooling system. However, due to the non-uniform temperature distribution over the hub, the heating system, which is needed for the hub, needs to be capable of distributing the heat non-uniformly. That means the system must supply the bottom and top part of the spacecraft with different amounts of heat. The maximum energy which is needed at Mars is approximately 35 W. No heating will be needed at Earth.

Acknowledgements

This work profited greatly from advice and recommendations by Dr. A. K. Jakubowski. Furthermore, the discussions and talks with the members of the Virginia Tech Solar Sail design group had a great positive influence on this study. We also would like to thank Dr. Spencer for his help in evaluating the optical properties of the spacecraft materials.

Table of Contents

List of Illustrations

List of Tables

Chapter 1

1. Introduction

The Virginia Tech Solar Sail is a solar radiation pressure propelled spacecraft designed for a trip from Earth to Mars. The ultimate goal of the project will be to prove that the solar sail concept is a feasible means of interplanetary travel. The spacecraft is composed of a circular sail supported by an outer hoop surrounding a central hub (see Figure 1 on page 3 and Figure 2 on page 4). The sail is made of a thin, lightweight material and is covered with a highly reflective coating on one side. This coating is intended to maximize the force generated by the sail. On the other side the sail is covered with a less reflective material which is thought to increase the emission of heat and thereby prevent the sail from overheating. The sail has a diameter of approximately 150 m and an area of 17100 m^2. The sail itself is divided into 360 segments or petals; of these, 20 are movable and are used for attitude control. The sail is made of mylar, covered with aluminum on one side and a less reflective metal on the other. The hoop which supports the sail is made of a tube divided into 360 segments, one for each petal. The hub is the main body of the craft and contains the control systems, computers, electrical power, guidance, navigation, and the communication systems. Its structure is composed of a cylindrical section approximately 1.5 m high that is topped off with a hexagonal section about 0.4 m high. The hub has a diameter of 2.88 m. In this study the hub was assumed to be a cylinder.

On its way to Mars the spacecraft will spiral out from an initial orbit around Earth, go to Mars on a heliocentric transfer, and spiral into the final orbit around Mars.

An analysis was made to evaluate the temperatures which can be expected during this mission. Accurate predictions of hub and solar sail temperatures are essential for a successful design of a solar sail powered spacecraft. They are needed to choose the materials of the craft and to define precise thermal control system requirements, for the protection of the power system, the computer system and the communication system against thermal damage.

In order to determine these temperatures, this study was divided into four basic steps. First, calculations were made of hub and sail temperatures for eight thermal equilibrium cases corresponding to the initial orbit around Earth and the final orbit around Mars. Next, the times needed to reach these stationary states were estimated. Then, the temperatures associated with a heliocentric transfer were evaluated in order to determine the closest possible trajectory to sun. And finally, the hub temperature distribution was determined. This distribution is needed to determine the heat exchange between the hub and a thermally insulated enclosure containing temperature sensitive components. This heat exchange sets heat system requirements.

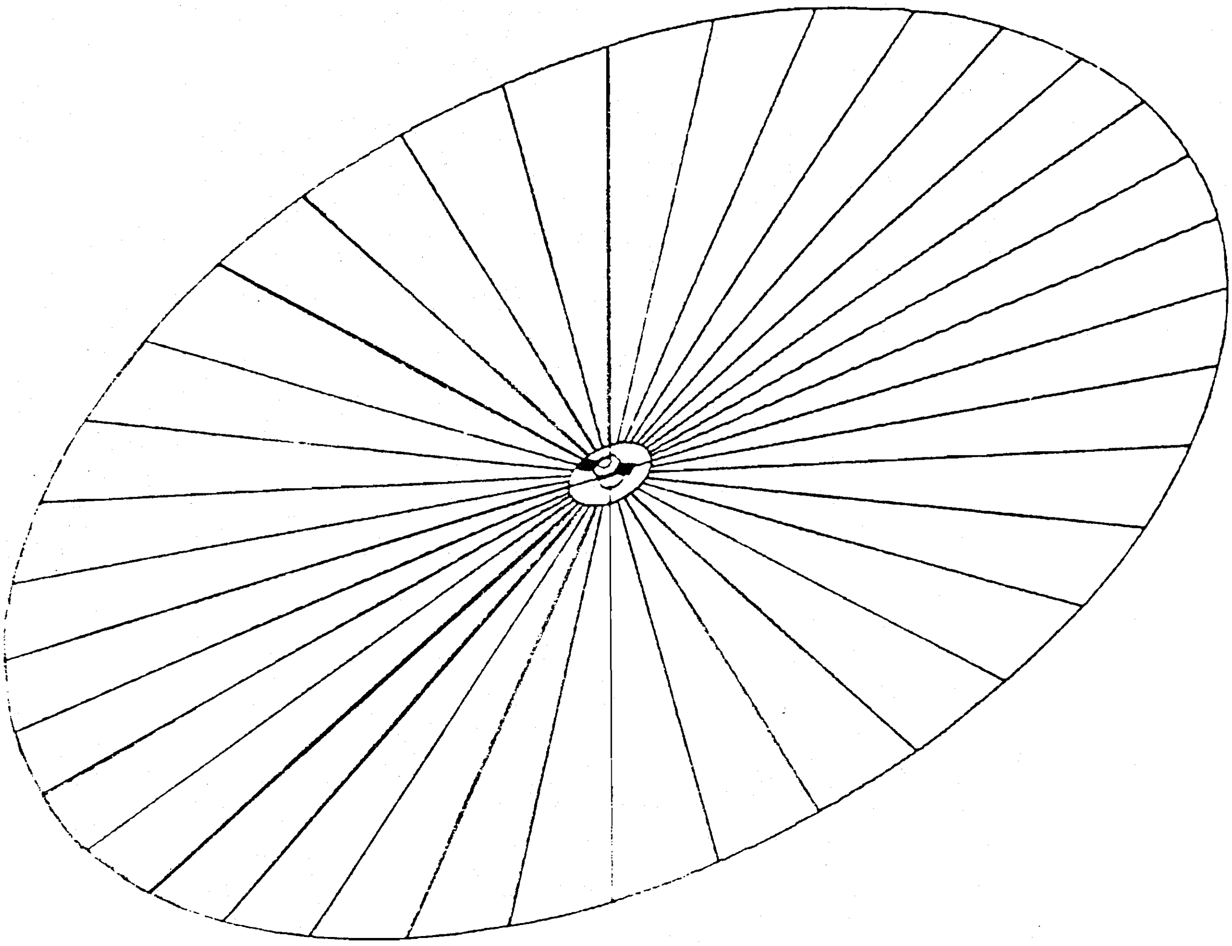


Figure 1. Configuration of the Solar-Sail Spacecraft

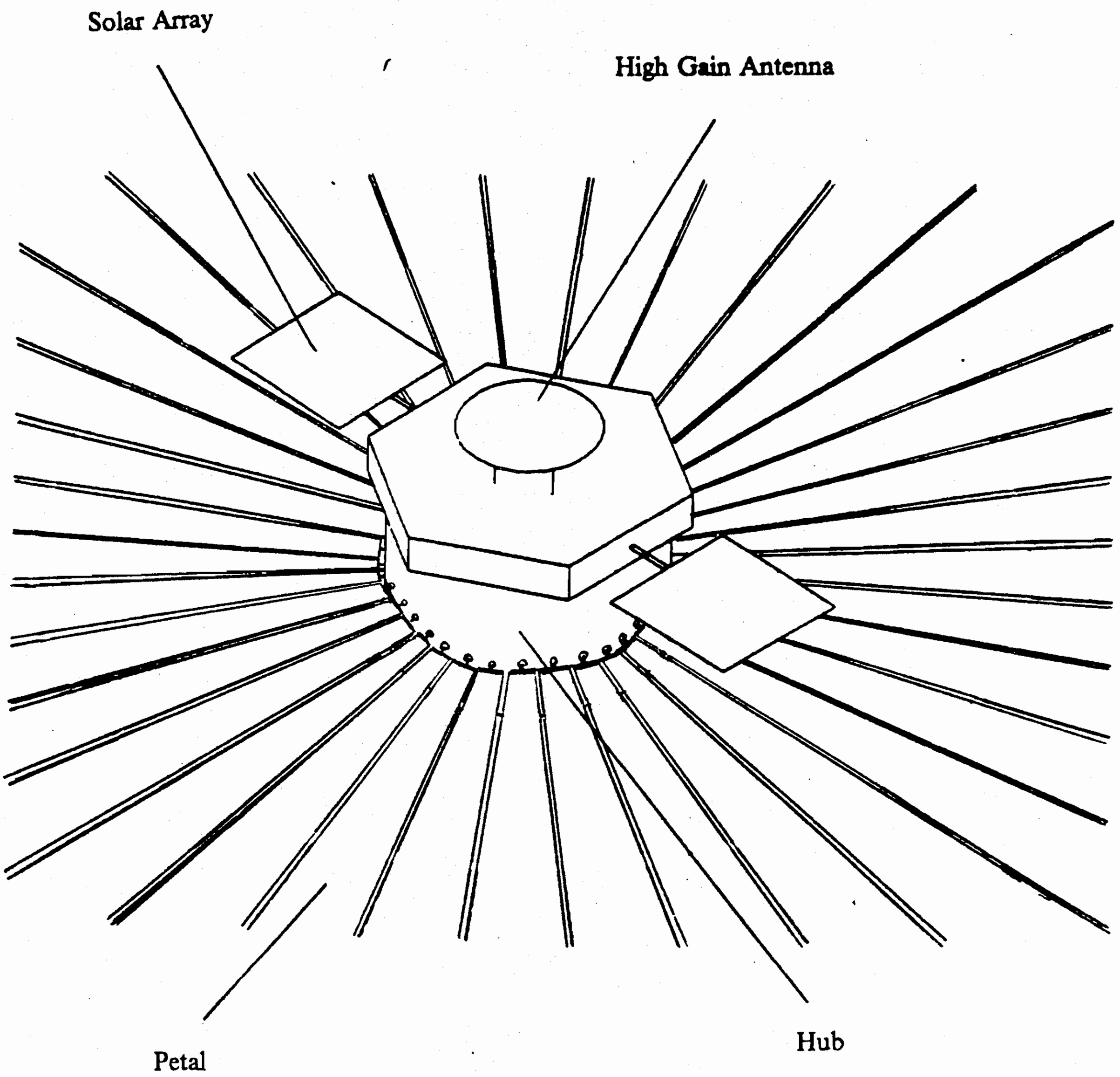


Figure 2. Configuration of the Hub

Chapter 2

2. Thermal Analyses

2.1. Types Of Heat Exchange Between The Spacecraft And Its Environment

Due to an almost ideal vacuum in space, there is no convective heat exchange between a spacecraft and its environment. In addition, the craft can not get in touch with any other solid body; and therefore, there is no conductive heat exchange. Thus, the only type of heat exchange between a spacecraft and its space environment is radiation. There are four different kinds of heat radiation to a spacecraft: solar radiation, radiation which has been reflected off a planet′s atmosphere, planetary radiation, and the internal radiation of the craft. The latter is the heat radiated from the spacecraft equipment inside the hub. Its contribution to the total irradiation is typically negligible. The following formulas were taken from reference [1].

1. Solar radiation : $\dot{q}_{Sun} = \alpha_S \, A_\perp \, I_S$ (1)

where : $\dot{q}_{Sun}$ = Heat flux sun to craft

α_S = Absorptivity of surface facing the sun (*ABAL*, *ABCR*)*

$A_\perp$ = Area perpendicular to sun rays (ARPER)

$\mathbf{I}_S$ = Solar constant (ISE, ISM)

2. Reflected radiation : $\dot{q}_{Refl} = a\,\alpha_S\,\mathbf{F}_{s,spl}\,\mathbf{A}_\perp\,\mathbf{I}_S$ (2)

where : $\dot{q}_{Refl}$ = On atmosphere reflected heat flux to craft (QR)

a = Albedo factor (EA, MA)

$\mathbf{F}_{s,spl}$ = View factor spacecraft to sunlit planet (FSSPL)

3. Planetary radiation : $\dot{q}_{Pl} = \mathbf{W}_{Pl}\,\alpha_{Pl}\,\mathbf{F}_{s,pl}\,\mathbf{A}_\perp$ (3)

where : $\dot{q}_{Pl}$ = Heat flux from planet to spacecraft (QE, QM)

$\mathbf{W}_{Pl}$ = Heat flux constant (WE, WM)

α_{Pl} = Absorptivity of surface facing planet (ABAL, ABCR)

$\mathbf{F}_{s,pl}$ = View factor spacecraft to planet (FSE, FSM)

4. Internal radiation : $\dot{q}_{int}$ (neglected)

The outgoing heat flux, like the incident flux, is radiative. According to Ref. [1] it is given by:

Space radiation : $\dot{q}_{sp} = \sigma\,\varepsilon_s\,\mathbf{F}_{s,sp}\,\mathbf{A}_r\,(\mathbf{T}_s^4 - \mathbf{T}_{sp}^4)$ (4)

where : $\dot{q}_{sp}$ = Heat flux from spacecraft to space

σ = Stefan Boltzmann constant = $5.67 \times 10^{-8}\,\frac{\mathrm{W}}{\mathrm{m^2\,K^4}}$ (SIGMA)

ε_s = Emission coefficient of spacecraft (EMM)

$\mathbf{F}_{s,sp}$ = View factor from spacecraft to space = $1 - \mathbf{F}_{s,pl}$ (FSSP)

$\mathbf{A}_r$ = Radiating area

$\mathbf{T}_s$ = Temperature of spacecraft (T)

*(The expressions in parenthesis are the names used in the FORTRAN program "TEMPEST" which was developed to determine the results of this study)

2.2. Radiative Equilibrium

In the equilibrium case the outgoing energy must be of the same magnitude as the incoming energy :

$$\dot{q}_{sp} = \dot{q}_{Sun} + \dot{q}_{Refl} + \dot{q}_{Pl} + \dot{q}_{int}$$
$$\sigma\, \varepsilon_s\, \mathbf{F}_{s,sp}\, \mathbf{A}_r\, \mathbf{T}_s^4 = \alpha_S\, \mathbf{A}_\perp\, \mathbf{I}_S \;+\; a\, \alpha_S\, \mathbf{F}_{s,spl}\, \mathbf{A}_\perp\, \mathbf{I}_S \;+\; \mathbf{W}_{Pl}\, \alpha_{Pl}\, \mathbf{F}_{s,pl}\, \mathbf{A}_\perp \tag{5}$$

Since the radiating area of the sail is composed of two surfaces, we have to take their different emissivities into account. Therefore the space radiation, i.e. the left-hand side of equation (5), is given by :

$$\dot{q}_{sp} = \sigma\, (\varepsilon_{\text{top}}\, \mathrm{A} \;+\; \varepsilon_{\text{bot}}\, \mathrm{A})\, \mathbf{F}_{s,sp}\, (\mathbf{T}_s^4 - \mathbf{T}_{sp}^4) \tag{6}$$

where : Subscripts "top" and "bot" stand for the top and the bottom surface

A = Area of the sail (AREA)

Using :

$$\mathrm{A}_r = 2\,\mathrm{A}$$

This may be written as :

$$\dot{q}_{sp} = \sigma\, \mathbf{A}_r\, \varepsilon\, \mathbf{F}_{s,sp}\, (\mathbf{T}_s^4 - \mathbf{T}_{sp}^4) \tag{7}$$

where : $\varepsilon = \dfrac{\varepsilon_{\text{top}} + \varepsilon_{\text{bot}}}{2}$ is the mean emissivity (EMM)

The absorptivity for solar radiation, α_S, is not necessarily the same as the one for planetary radiation α_{Pl}; however, the spectrum of sunlight expands the spectrum of planetary radiation only by the visible light, which makes only a small contribution to the thermal radiation. Therefore we can assume : $\alpha_S \simeq \alpha_E \simeq \alpha_M$. Where the subscripts E and M stand for Earth and Mars.

In some cases the view factors, spacecraft to planet and spacecraft to sunlit planet ($\mathbf{F}_{s,pl}$, $\mathbf{F}_{s,spl}$), are not of the same magnitude. To take this difference into account the contributions of the reflective and the planetary radiation are to be divided by the respective view factors.

Calculation of the view factors : $$F = \frac{(R_{Pl})^2}{(R_{Pl} + H_s)^2} \qquad (8)$$

where : R_{Pl} = Radius of planet

H_s = Altitude of spacecraft

Due to the fact that the sail is very thin (3-7 μm), we may assume that the conductive heat transfer inside the sail does not need an appreciable amount of time. As a result, the temperature is constant throughout the entire sail.

Taking into account all the facts mentioned above and assuming that the radiation temperature of space is 0 K, the solar sail temperature yields :

$$T_{sail} = \left[\frac{\alpha_S A_\perp I_S + \frac{a\, \alpha_S F_{s,spl} A_\perp I_S}{1 - F_{s,spl}} + \frac{W_{Pl}\, \alpha_S F_{s,pl} A_\perp}{1 - F_{s,pl}}}{\sigma\, \varepsilon\, A_r} \right]^{0.25} \qquad (9)$$

In addition to direct radiation, the hub also receives radiation which is reflected off the solar sail. Since we can assume that the radiation which is reflected off the hub is of the same order of magnitude as the radiation loss due to the hub shadow, the hub-to-sail radiation can be neglected. However, the sail-to hub radiation contribution was taken into account in the temperature formula for the hub :

$$T_{Hub} = \left[\frac{\alpha_S I_S (A_\perp + r A_{\perp r}) + \frac{a\, \alpha_S F_{s,spl} I_S (A_\perp + r A_{\perp r})}{1 - F_{s,spl}} + \frac{W_{Pl}\, \alpha_S F_{s,pl} (A_\perp + r A_{\perp r})}{1 - F_{s,pl}}}{\sigma\, \varepsilon\, A_r} \right]^{0.25} \qquad (10)$$

where : r = reflectivity of the solar sail = $1 - \alpha_S$ (RAL, RCR)

$A_{\perp r}$ = Area perpendicular to the radiation reflected off the sail (APR)

The area of the sail which is perpendicular to the incident rays is : $A \cos(\theta)$, where θ is the angle between the normal to the sail and the incident rays.

$$A_\perp = A \cos\theta \tag{11}$$

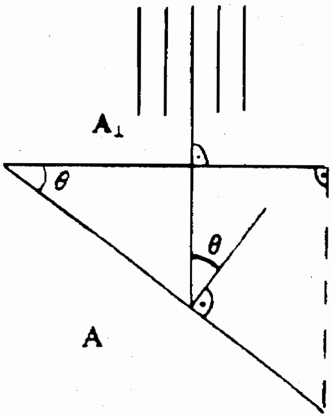


Figure 3. Sail Area Perpendicular to Irradiation

The area of the hub for direct absorption is given by:

$$A_\perp = D\,H\,\sin(\theta) + \frac{\pi D^2 \cos(\theta)}{4} \tag{12}$$

where : D = Diameter of the hub (HDIA)

H = Height of the hub (HHGT)

θ = Angle between center line of hub and incident rays (same as θ for the sail) (THETA)

Since, due to shadow, only one half of the hub receives radiation the term $D\,H\,\sin(\theta)$ must be divided by 2. In the cases 4 and 5 the area of the hub which is perpendicular to the solar radiation can be computed by means of Eq.12. However, the area perpendicular to Earth radiation and reflected radiation is equal to the area of the disk of the cylinder, which is given by :

$$\frac{\pi D^2}{4}$$

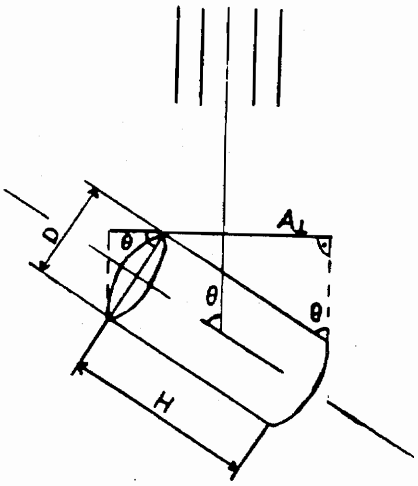


Figure 4. Hub area perpendicular to direct irradiation

The area of the hub for the absorption of the reflected radiation is

$$A_{\perp r} = \frac{D\,H\,\sin(\theta)}{2} \tag{13}$$

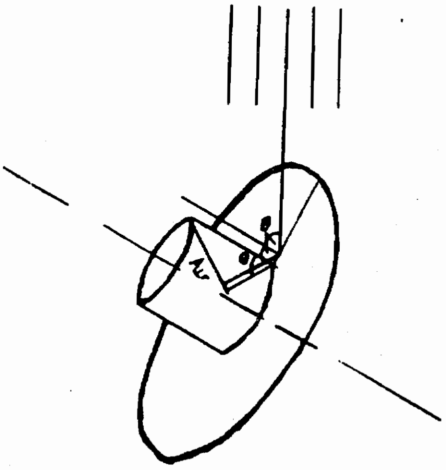


Figure 5. Hub Area Perpendicular to reflected Irradiation

The radiating area of the sail A_r is simply twice the sail area :

$$A_{rsail} = 2\,A \tag{14}$$

The hub which is assumed to be a cylinder radiates heat over its entire surface :

$$A_r = \pi H D + \frac{\pi D^2}{2} \tag{15}$$

2.3. Configuration Of The Calculated Cases

To estimate the equilibrium temperatures of the solar sail spacecraft on a Mars mission, nine different cases were chosen. Figure 6 on page 12 illustrates the distribution of these cases.

Parameters:

All parameters were taken from references [1], [2] and [3].

Earth :

$\mathbf{R}_E = 6{,}370\text{km}$; $\mathbf{I}_{SE} = 1377 \frac{\text{W}}{\text{m}^2}$; $\mathbf{a}_E = 0.34$; $\mathbf{W}_E = 250 \frac{\text{W}}{\text{m}^2}$.

Mars :

$\mathbf{R}_M = 3{,}390\text{ km}$; $\mathbf{I}_{SM} = 590 \frac{\text{W}}{\text{m}^2}$; $\mathbf{a}_M = 0.15$; $\mathbf{W}_M = 150 \frac{\text{W}}{\text{m}^2}$.

The parameters for the initial orbit around Earth and the final orbit around Mars are [5] :

$r_a = 42{,}378$ km ;	Apogee
$r_p = 7{,}378$ km ;	Perigee
$\tau = 10\text{ h } 12\text{ min } 11\text{ s}$;	Orbital period
$r_a = 5{,}186$ km ;	Apoapsis of Mars orbit
$r_p = 4{,}890$ km ;	Periapsis of Mars orbit
$\tau = 1$ solar day ;	Orbital period

The spacecraft is composed of a central "hub", which is the actual craft body, and a solar sail which is covered with different metals on each side. The hub will probably consist of an aluminum honeycomb material. The base material of the sail will most likely be mylar. The sides of the sail should have different absorption and emission coefficients to provide maximum solar force on one side and reasonable emission on the other. The emission is needed to prevent the sail from overheating. In a first preliminary design, aluminum and chromium were chosen for the sail coatings.

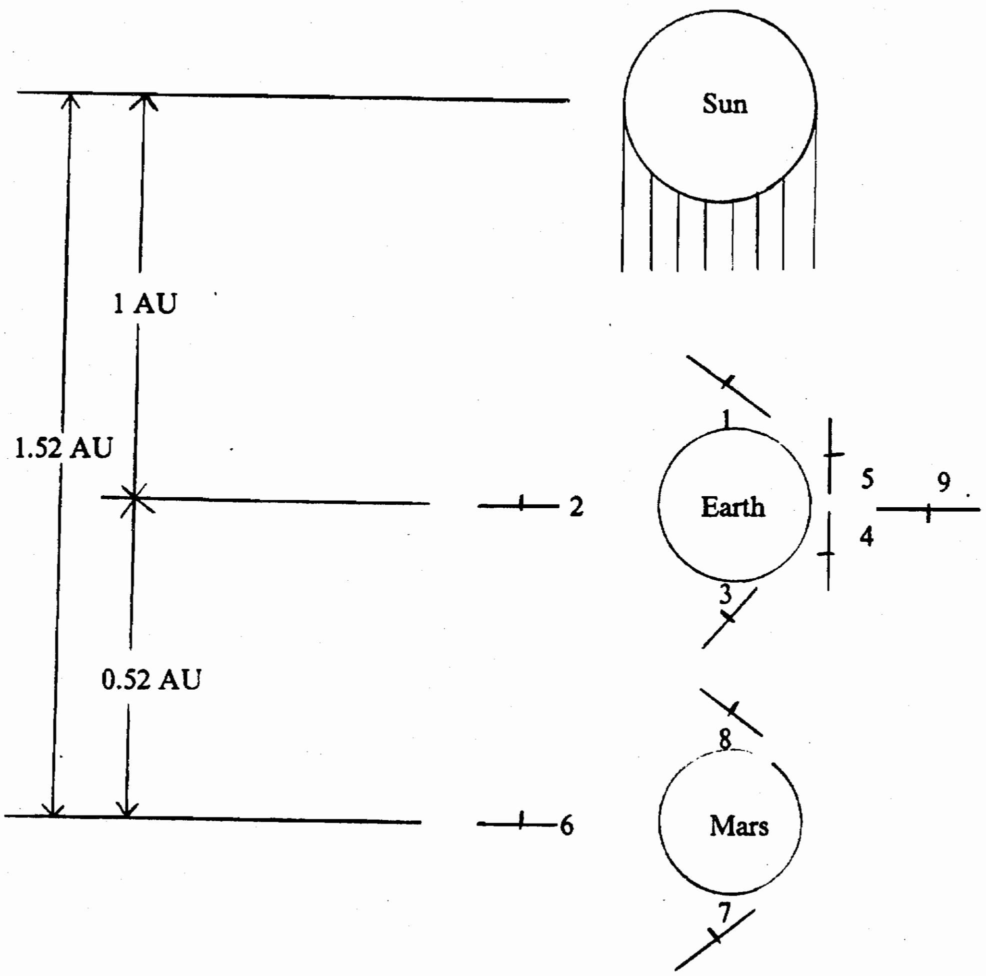


Figure 6. Configuration of the Nine Calculated Cases

Heat Flux Contributions In The Nine Cases

case 1

Aluminum side and upper hub : Solar radiation

Chromium side and lower hub : Radiation reflected from Earth's atmosphere
Earth radiation

$\theta = 35°$

case 2

Aluminum side and upper hub : Solar radiation

Chromium side : No radiation

Hub : Radiation reflected from Earth's atmosphere
Earth radiation

$\theta = 0°; \quad \theta_{Earth} = 90°$

case 3

Aluminum side and upper hub : Earth radiation

Chromium side and lower hub : No radiation

$\theta = 35°$

case 4

Aluminum side and upper hub : Radiation reflected from Earth's atmosphere
Earth radiation

Chromium side : No radiation

Hub : Solar radiation

$\theta_{Sun} = 90°; \quad \theta_{Earth} = 0°$

case 5

Aluminum side : No radiation

Chromium side and lower hub : Radiation reflected from Earth's atmosphere
Earth radiation

Hub : Solar radiation

$\theta_{Sun} = 90°$; $\theta_{Earth} = 0°$

case 6

Aluminum side and upper hub : Solar radiation

Chromium side : No radiation

Hub : Radiation reflected from Mars atmosphere
Mars radiation

$\theta = 0°$; $\theta_{Mars} = 90°$

case 7

Aluminum side and upper hub : Mars radiation

Chromium side and lower hub : No radiation

$\theta = 35°$

case 8

Aluminum side and upper hub : Solar radiation

Chromium side and lower hub : Radiation reflected from Mars atmosphere
Mars radiation

$\theta = 35°$

case 9

Aluminum side : No radiation

Chromium side : Solar radiation

Hub : Same as case 2

$\theta = 0°$; $\theta_{Earth} = 90°$

The upper hub is the half cylinder above the aluminum side of the sail and the lower hub is that one above the chromium side.

Because of the large diameter of the sun, the sail will receive solar radiation in cases 4 and 5. The following calculation was made to estimate this heat flux contribution.

The distance between the spacecraft and the Earth in case 2, 4, and 5, respectively, is half the latus rectum (p) of the orbit.

$$p = a \times (1 - e^2) \tag{16}$$

where : a = $(r_a + r_p)/2$ Half of the major axis

e = $(r_a - r_p)/(r_a + r_p)$ Eccentricity

This yields p = 12567.9 km for the initial orbit around Earth. The radius of the Sun is 696000 km and the distance between Sun and the craft is 1 astronomic unit = 1.495×10^8 km. Figure 7 on page 16 shows the geometry of the cases 4 and 5.

Geometry of front side (surface facing the earth) :

$$\begin{aligned} \tan \beta_f &= \frac{708567.9}{1.495 \times 10^8} \\ \therefore \quad \beta_f &= 0.272° \end{aligned}$$

The minimum angle equals 0; therefore, we may assume that the mean angle is given by :

$$\overline{\beta_f} = \frac{\beta_{f\,\max}}{2} = 0.13578°$$

Area perpendicular to sun rays : $A_\perp = A_S \times \sin \overline{\beta_f} = 40.52 \text{ m}^2$

Geometry of rear side (surface facing space) :

$$\overline{\beta_r} = 0.13096°$$

$$A_\perp = 39.09 \text{ m}^2$$

Resulting solar heat flux incident on surface : $\dot{q}_{s\beta} = \alpha_s A_\perp I_{SE}$

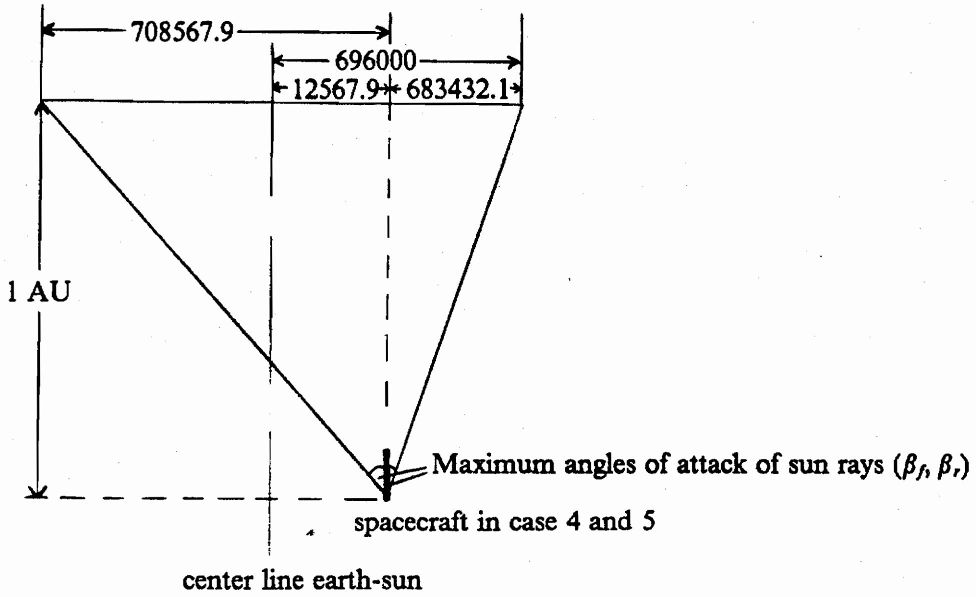


Figure 7. Solar Radiation to the Spacecraft in Cases 4 and 5

Total resulting solar heat flux incident on spacecraft (case 4) :

$$\dot{q}_S = \alpha_{AL} \times 40.52 \times I_{SE} + \alpha_{CR} \times 39.09 \times I_{SE} \quad [W]$$

Total resulting solar heat flux incident on spacecraft (case 5) :

$$\dot{q}_S = \alpha_{CR} \times 40.52 \times I_{SE} + \alpha_{AL} \times 39.09 \times I_{SE} \quad [W]$$

In order to maintain maximum force in the direction of motion, the sail has to rotate around an in-plane axis once every orbit. This results in the requirement of a maneuver that ensures the reorientation of the reflective side when the sail receives no solar radiation (sail is parallel to the sunrays). Such a maneuver is referred to as a flip over (Ref.[5]).

2.4. Sail And Hub Equilibrium Temperatures

Assumptions :

$\dot{q}_{int}$ is negligible

The radiation temperature of the space is zero

$\alpha_S \simeq \alpha_E \simeq \alpha_M$

The heat reflected off the hub to the sail, is equal to the heat loss due to the hub shadow

A program was developed to determine the hub and sail temperatures. These temperatures are highly dependent upon the properties of the material (absorption and emission coefficients); therefore, three different sets of coefficients were chosen to calculate the temperatures. Using data from Ref.[1] the following ranges for the optical properties were selected :

$$\alpha_{S,aluminum} = 0.12 \quad - \quad 0.15$$
$$\alpha_{S,chromium} = 0.4 \quad - \quad 0.5$$
$$\varepsilon_{aluminum} = 0.04 \quad - \quad 0.05$$
$$\varepsilon_{chromium} = 0.1 \quad - \quad 0.3$$

The three sets of parameters chosen for the sail are :

Set 1 : $\alpha_{S,al} = 0.12$; $\varepsilon_{al} = 0.04$; $\alpha_{Scr} = 0.40$; $\varepsilon_{cr} = 0.10$

Set 2 : $\alpha_{S,al} = 0.15$; $\varepsilon_{al} = 0.05$; $\alpha_{Scr} = 0.47$; $\varepsilon_{cr} = 0.24$

Set 3 : $\alpha_{S,al} = 0.15$; $\varepsilon_{al} = 0.05$; $\alpha_{Scr} = 0.50$; $\varepsilon_{cr} = 0.30$

Set 2 was used in a study of the Johns Hopkins Solar Sail [4].

The parameter sets used for the hub temperature calculations are :

Set 1 : $\alpha_{S,hub} = 0.12$; $\varepsilon_{hub} = 0.04$

Set 2 : $\alpha_{S,hub} = 0.12$; $\varepsilon_{hub} = 0.05$

Set 3 : $\alpha_{S,hub} = 0.15$; $\varepsilon_{hub} = 0.04$

The calculations showed that the solar radiation makes the biggest contribution to the overall incident heat flux (about 50 to 70%).

The results are shown in Figure 8 on page 20 and Figure 9 on page 25 and listed in Table 1 on page 21 through Table 4 on page 27. If the final orbit around Mars is tilted, which will probably be the case, the craft would not have to pass through any shadow and the case 7 would not occur.

For this reason, the results were listed with and without the case 7. Since the case 9 for the hub is identical with the conditions in the case 2, case 9 is not plotted for the hub.

As the plots for the sail show, an increase in emissivity reduces the temperatures even if the absorptivity increases also. The largest increase in emissivity is given for the chromium side; thus, the decrease in temperature is mainly due to the changes on the bottom side. This is expected, since the purpose of the bottom coating is to reject heat. However, an increase in emissivity usually goes along with an increase in absorptivity, i.e. for high emissivity we have also high absorptivity which in turn means high temperatures in case the bottom side faces the sun. This can be seen in the case 9. As a matter of fact, the temperatures in case 9 exceed the allowable margins for mylar; therefore we can not stay with our preliminary design and use chromium on the bottom side of a mylar sail. If we have to use a mylar sail, we will have to find a suitable material for the coating on the bottom side (see Section 3.1).

2.5. Calculation Of The Cool-Down Times

Assumptions :

Circular orbit in Earth's shadow

Cylindrical circular Earth shadow

$\theta = \text{const.}$

$\dot{q}$ (T) is partially linear for small increments of T

The calculation of the time needed to reach the equilibrium temperature after a sudden change in the irradiation is made to test the validity of the stationary case assumption. We performed these calculations between the Earth shadow entry point and case three. In this part of the trajectory only planetary radiation is incident on the craft. Assuming a cylindrical Earth shadow, the configuration of the shadow entry point is shown in Figure 10 on page 28.

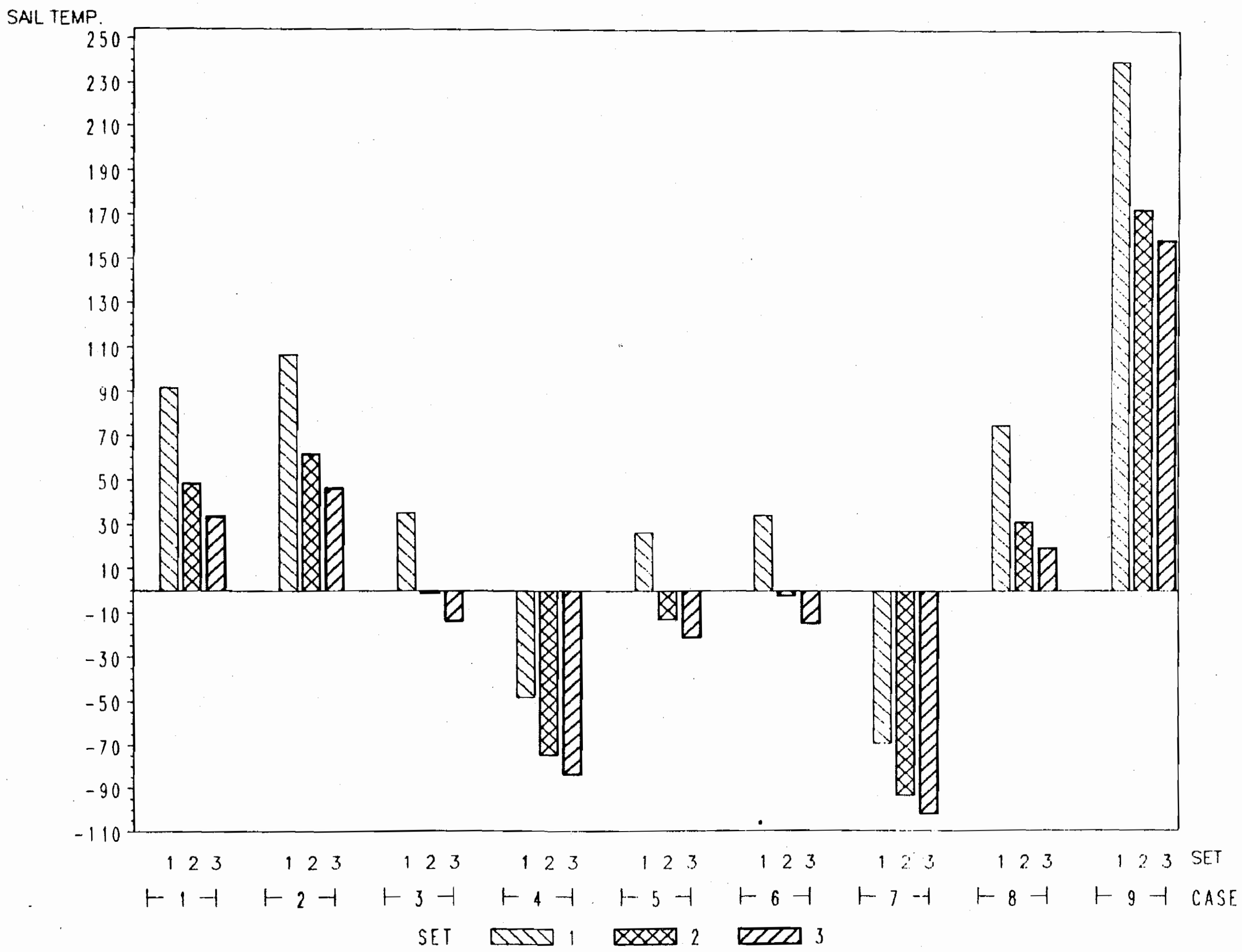


Figure 8. Sail Temperatures in the Nine Cases for Three Different Sets of Parameters

Table 1. Minimum and Maximum Sail Temperatures for Different Sets of Parameters

```
TEMPERATURE ESTIMATION  (SAIL RANGE)

RPE :    7378.00 KM          RAE :  42378.00 KM          EA : 0.340

RPM :    4890.00 KM          RAM :   5186.47 KM          MA : 0.150

AREA :    17100.00 M**2      HHGT :     1.88 M     HDIA :     2.88 M

THETA :    35.00

| ABAL   | EMAL   | ABCR   | EMCR   | TMIN (C) | TMAX (C) | CMIN | CMAX |
=========================================================================
| 0.120  | 0.040  | 0.400  | 0.100  |   -69.55 |   240.08 |  7   |   9  |
| 0.120  | 0.040  | 0.400  | 0.200  |   -95.22 |   175.38 |  7   |   9  |
| 0.120  | 0.040  | 0.400  | 0.300  |  -110.06 |   137.97 |  7   |   9  |
| 0.120  | 0.040  | 0.450  | 0.100  |   -69.55 |   255.42 |  7   |   9  |
| 0.120  | 0.040  | 0.450  | 0.200  |   -95.22 |   188.78 |  7   |   9  |
| 0.120  | 0.040  | 0.450  | 0.300  |  -110.06 |   150.26 |  7   |   9  |
| 0.120  | 0.040  | 0.500  | 0.100  |   -69.55 |   269.53 |  7   |   9  |
| 0.120  | 0.040  | 0.500  | 0.200  |   -95.22 |   201.11 |  7   |   9  |
| 0.120  | 0.040  | 0.500  | 0.300  |  -110.06 |   161.56 |  7   |   9  |
| 0.120  | 0.045  | 0.400  | 0.100  |   -71.33 |   235.60 |  7   |   9  |
| 0.120  | 0.045  | 0.400  | 0.200  |   -96.13 |   173.07 |  7   |   9  |
| 0.120  | 0.045  | 0.400  | 0.300  |  -110.65 |   136.48 |  7   |   9  |
| 0.120  | 0.045  | 0.450  | 0.100  |   -71.33 |   250.80 |  7   |   9  |
| 0.120  | 0.045  | 0.450  | 0.200  |   -96.13 |   186.41 |  7   |   9  |
| 0.120  | 0.045  | 0.450  | 0.300  |  -110.65 |   148.72 |  7   |   9  |
| 0.120  | 0.045  | 0.500  | 0.100  |   -71.33 |   264.79 |  7   |   9  |
| 0.120  | 0.045  | 0.500  | 0.200  |   -96.13 |   198.67 |  7   |   9  |
| 0.120  | 0.045  | 0.500  | 0.300  |  -110.65 |   159.98 |  7   |   9  |
| 0.120  | 0.050  | 0.400  | 0.100  |   -73.03 |   231.30 |  7   |   9  |
| 0.120  | 0.050  | 0.400  | 0.200  |   -97.02 |   170.82 |  7   |   9  |
| 0.120  | 0.050  | 0.400  | 0.300  |  -111.23 |   135.00 |  7   |   9  |
| 0.120  | 0.050  | 0.450  | 0.100  |   -73.03 |   246.38 |  7   |   9  |
| 0.120  | 0.050  | 0.450  | 0.200  |   -97.02 |   184.09 |  7   |   9  |
| 0.120  | 0.050  | 0.450  | 0.300  |  -111.23 |   147.20 |  7   |   9  |
| 0.120  | 0.050  | 0.500  | 0.100  |   -73.03 |   260.25 |  7   |   9  |
| 0.120  | 0.050  | 0.500  | 0.200  |   -97.02 |   196.30 |  7   |   9  |
| 0.120  | 0.050  | 0.500  | 0.300  |  -111.23 |   158.42 |  7   |   9  |
| 0.135  | 0.040  | 0.400  | 0.100  |   -63.46 |   240.08 |  7   |   9  |
| 0.135  | 0.040  | 0.400  | 0.200  |   -89.90 |   175.38 |  7   |   9  |
| 0.135  | 0.040  | 0.400  | 0.300  |  -105.18 |   137.97 |  7   |   9  |
| 0.135  | 0.040  | 0.450  | 0.100  |   -63.46 |   255.42 |  7   |   9  |
| 0.135  | 0.040  | 0.450  | 0.200  |   -89.90 |   188.78 |  7   |   9  |
| 0.135  | 0.040  | 0.450  | 0.300  |  -105.18 |   150.26 |  7   |   9  |
| 0.135  | 0.040  | 0.500  | 0.100  |   -63.46 |   269.53 |  7   |   9  |
| 0.135  | 0.040  | 0.500  | 0.200  |   -89.90 |   201.11 |  7   |   9  |
| 0.135  | 0.040  | 0.500  | 0.300  |  -105.18 |   161.56 |  7   |   9  |
| 0.135  | 0.045  | 0.400  | 0.100  |   -65.30 |   235.60 |  7   |   9  |
```

0.135	0.045	0.400	0.200	-90.84	173.07	7	9
0.135	0.045	0.400	0.300	-105.79	136.48	7	9
0.135	0.045	0.450	0.100	-65.30	250.80	7	9
0.135	0.045	0.450	0.200	-90.84	186.41	7	9
0.135	0.045	0.450	0.300	-105.79	148.72	7	9
0.135	0.045	0.500	0.100	-65.30	264.79	7	9
0.135	0.045	0.500	0.200	-90.84	198.67	7	9
0.135	0.045	0.500	0.300	-105.79	159.98	7	9
0.135	0.050	0.400	0.100	-67.05	231.30	7	9
0.135	0.050	0.400	0.200	-91.76	170.82	7	9
0.135	0.050	0.400	0.300	-106.40	135.00	7	9
0.135	0.050	0.450	0.100	-67.05	246.38	7	9
0.135	0.050	0.450	0.200	-91.76	184.09	7	9
0.135	0.050	0.450	0.300	-106.40	147.20	7	9
0.135	0.050	0.500	0.100	-67.05	260.25	7	9
0.135	0.050	0.500	0.200	-91.76	196.30	7	9
0.135	0.050	0.500	0.300	-106.40	158.42	7	9
0.150	0.040	0.400	0.100	-57.87	240.08	7	9
0.150	0.040	0.400	0.200	-85.01	175.38	7	9
0.150	0.040	0.400	0.300	-100.70	137.97	7	9
0.150	0.040	0.450	0.100	-57.87	255.42	7	9
0.150	0.040	0.450	0.200	-85.01	188.78	7	9
0.150	0.040	0.450	0.300	-100.70	150.26	7	9
0.150	0.040	0.500	0.100	-57.87	269.53	7	9
0.150	0.040	0.500	0.200	-85.01	201.11	7	9
0.150	0.040	0.500	0.300	-100.70	161.56	7	9
0.150	0.045	0.400	0.100	-59.75	235.60	7	9
0.150	0.045	0.400	0.200	-85.98	173.07	7	9
0.150	0.045	0.400	0.300	-101.33	136.48	7	9
0.150	0.045	0.450	0.100	-59.75	250.80	7	9
0.150	0.045	0.450	0.200	-85.98	186.41	7	9
0.150	0.045	0.450	0.300	-101.33	148.72	7	9
0.150	0.045	0.500	0.100	-59.75	264.79	7	9
0.150	0.045	0.500	0.200	-85.98	198.67	7	9
0.150	0.045	0.500	0.300	-101.33	159.98	7	9
0.150	0.050	0.400	0.100	-61.55	231.30	7	9
0.150	0.050	0.400	0.200	-86.92	170.82	7	9
0.150	0.050	0.400	0.300	-101.94	135.00	7	9
0.150	0.050	0.450	0.100	-61.55	246.38	7	9
0.150	0.050	0.450	0.200	-86.92	184.09	7	9
0.150	0.050	0.450	0.300	-101.94	147.20	7	9
0.150	0.050	0.500	0.100	-61.55	260.25	7	9
0.150	0.050	0.500	0.200	-86.92	196.30	7	9
0.150	0.050	0.500	0.300	-101.94	158.42	7	9

Table 2. Minimum and Maximum Sail Temperatures for Different Sets of Parameters (without Case 7)

```
TEMPERATURE ESTIMATION  W/O CASE 7 (SAIL RANGE)

RPE  :   7378.00 KM          RAE  :  42378.00 KM          EA  : 0.340

RPM  :   4890.00 KM          RAM  :   5186.47 KM          MA  : 0.150

AREA  :   17100.00 M**2       HHGT  :      1.88  M      HDIA  :      2.88  M

THETA  :   35.00

| ABAL   | EMAL   | ABCR   | EMCR   | TMIN (C) | TMAX (C) | CMIN | CMAX |
=========================================================================
| 0.120  | 0.040  | 0.400  | 0.100  |   -48.28 |   240.08 |   4  |   9  |
| 0.120  | 0.040  | 0.400  | 0.200  |   -76.63 |   175.38 |   4  |   9  |
| 0.120  | 0.040  | 0.400  | 0.300  |   -93.02 |   137.97 |   4  |   9  |
| 0.120  | 0.040  | 0.450  | 0.100  |   -47.84 |   255.42 |   4  |   9  |
| 0.120  | 0.040  | 0.450  | 0.200  |   -76.25 |   188.78 |   4  |   9  |
| 0.120  | 0.040  | 0.450  | 0.300  |   -92.67 |   150.26 |   4  |   9  |
| 0.120  | 0.040  | 0.500  | 0.100  |   -47.41 |   269.53 |   4  |   9  |
| 0.120  | 0.040  | 0.500  | 0.200  |   -75.87 |   201.11 |   4  |   9  |
| 0.120  | 0.040  | 0.500  | 0.300  |   -92.32 |   161.56 |   4  |   9  |
| 0.120  | 0.045  | 0.400  | 0.100  |   -50.24 |   235.60 |   4  |   9  |
| 0.120  | 0.045  | 0.400  | 0.200  |   -77.64 |   173.07 |   4  |   9  |
| 0.120  | 0.045  | 0.400  | 0.300  |   -93.67 |   136.48 |   4  |   9  |
| 0.120  | 0.045  | 0.450  | 0.100  |   -49.81 |   250.80 |   4  |   9  |
| 0.120  | 0.045  | 0.450  | 0.200  |   -77.26 |   186.41 |   4  |   9  |
| 0.120  | 0.045  | 0.450  | 0.300  |   -93.33 |   148.72 |   4  |   9  |
| 0.120  | 0.045  | 0.500  | 0.100  |   -49.38 |   264.79 |   4  |   9  |
| 0.120  | 0.045  | 0.500  | 0.200  |   -76.89 |   198.67 |   4  |   9  |
| 0.120  | 0.045  | 0.500  | 0.300  |   -92.98 |   159.98 |   4  |   9  |
| 0.120  | 0.050  | 0.400  | 0.100  |   -52.12 |   231.30 |   4  |   9  |
| 0.120  | 0.050  | 0.400  | 0.200  |   -78.62 |   170.82 |   4  |   9  |
| 0.120  | 0.050  | 0.400  | 0.300  |   -94.32 |   135.00 |   4  |   9  |
| 0.120  | 0.050  | 0.450  | 0.100  |   -51.70 |   246.38 |   4  |   9  |
| 0.120  | 0.050  | 0.450  | 0.200  |   -78.25 |   184.09 |   4  |   9  |
| 0.120  | 0.050  | 0.450  | 0.300  |   -93.97 |   147.20 |   4  |   9  |
| 0.120  | 0.050  | 0.500  | 0.100  |   -51.27 |   260.25 |   4  |   9  |
| 0.120  | 0.050  | 0.500  | 0.200  |   -77.87 |   196.30 |   4  |   9  |
| 0.120  | 0.050  | 0.500  | 0.300  |   -93.63 |   158.42 |   4  |   9  |
| 0.135  | 0.040  | 0.400  | 0.100  |   -41.96 |   240.08 |   4  |   9  |
| 0.135  | 0.040  | 0.400  | 0.200  |   -71.10 |   175.38 |   4  |   9  |
| 0.135  | 0.040  | 0.400  | 0.300  |   -87.95 |   137.97 |   4  |   9  |
| 0.135  | 0.040  | 0.450  | 0.100  |   -41.56 |   255.42 |   4  |   9  |
| 0.135  | 0.040  | 0.450  | 0.200  |   -70.76 |   188.78 |   4  |   9  |
| 0.135  | 0.040  | 0.450  | 0.300  |   -87.63 |   150.26 |   4  |   9  |
| 0.135  | 0.040  | 0.500  | 0.100  |   -41.16 |   269.53 |   4  |   9  |
| 0.135  | 0.040  | 0.500  | 0.200  |   -70.41 |   201.11 |   4  |   9  |
| 0.135  | 0.040  | 0.500  | 0.300  |   -87.32 |   161.56 |   4  |   9  |
| 0.135  | 0.045  | 0.400  | 0.100  |   -43.98 |   235.60 |   4  |   9  |
```

0.135	0.045	0.400	0.200	-72.14	173.07	4	9
0.135	0.045	0.400	0.300	-88.63	136.48	4	9
0.135	0.045	0.450	0.100	-43.58	250.80	4	9
0.135	0.045	0.450	0.200	-71.80	186.41	4	9
0.135	0.045	0.450	0.300	-88.31	148.72	4	9
0.135	0.045	0.500	0.100	-43.19	264.79	4	9
0.135	0.045	0.500	0.200	-71.45	198.67	4	9
0.135	0.045	0.500	0.300	-87.99	159.98	4	9
0.135	0.050	0.400	0.100	-45.91	231.30	4	9
0.135	0.050	0.400	0.200	-73.16	170.82	4	9
0.135	0.050	0.400	0.300	-89.29	135.00	4	9
0.135	0.050	0.450	0.100	-45.52	246.38	4	9
0.135	0.050	0.450	0.200	-72.81	184.09	4	9
0.135	0.050	0.450	0.300	-88.97	147.20	4	9
0.135	0.050	0.500	0.100	-45.13	260.25	4	9
0.135	0.050	0.500	0.200	-72.47	196.30	4	9
0.135	0.050	0.500	0.300	-88.66	158.42	4	9
0.150	0.040	0.400	0.100	-36.12	240.08	4	9
0.150	0.040	0.400	0.200	-66.00	175.38	4	9
0.150	0.040	0.400	0.300	-83.28	137.97	4	9
0.150	0.040	0.450	0.100	-35.75	255.42	4	9
0.150	0.040	0.450	0.200	-65.68	188.78	4	9
0.150	0.040	0.450	0.300	-82.98	150.26	4	9
0.150	0.040	0.500	0.100	-35.38	269.53	4	9
0.150	0.040	0.500	0.200	-65.35	201.11	4	9
0.150	0.040	0.500	0.300	-82.68	161.56	4	9
0.150	0.045	0.400	0.100	-38.19	235.60	4	9
0.150	0.045	0.400	0.200	-67.07	173.07	4	9
0.150	0.045	0.400	0.300	-83.97	136.48	4	9
0.150	0.045	0.450	0.100	-37.82	250.80	4	9
0.150	0.045	0.450	0.200	-66.74	186.41	4	9
0.150	0.045	0.450	0.300	-83.67	148.72	4	9
0.150	0.045	0.500	0.100	-37.45	264.79	4	9
0.150	0.045	0.500	0.200	-66.42	198.67	4	9
0.150	0.045	0.500	0.300	-83.38	159.98	4	9
0.150	0.050	0.400	0.100	-40.17	231.30	4	9
0.150	0.050	0.400	0.200	-68.10	170.82	4	9
0.150	0.050	0.400	0.300	-84.65	135.00	4	9
0.150	0.050	0.450	0.100	-39.81	246.38	4	9
0.150	0.050	0.450	0.200	-67.78	184.09	4	9
0.150	0.050	0.450	0.300	-84.35	147.20	4	9
0.150	0.050	0.500	0.100	-39.44	260.25	4	9
0.150	0.050	0.500	0.200	-67.46	196.30	4	9
0.150	0.050	0.500	0.300	-84.06	158.42	4	9

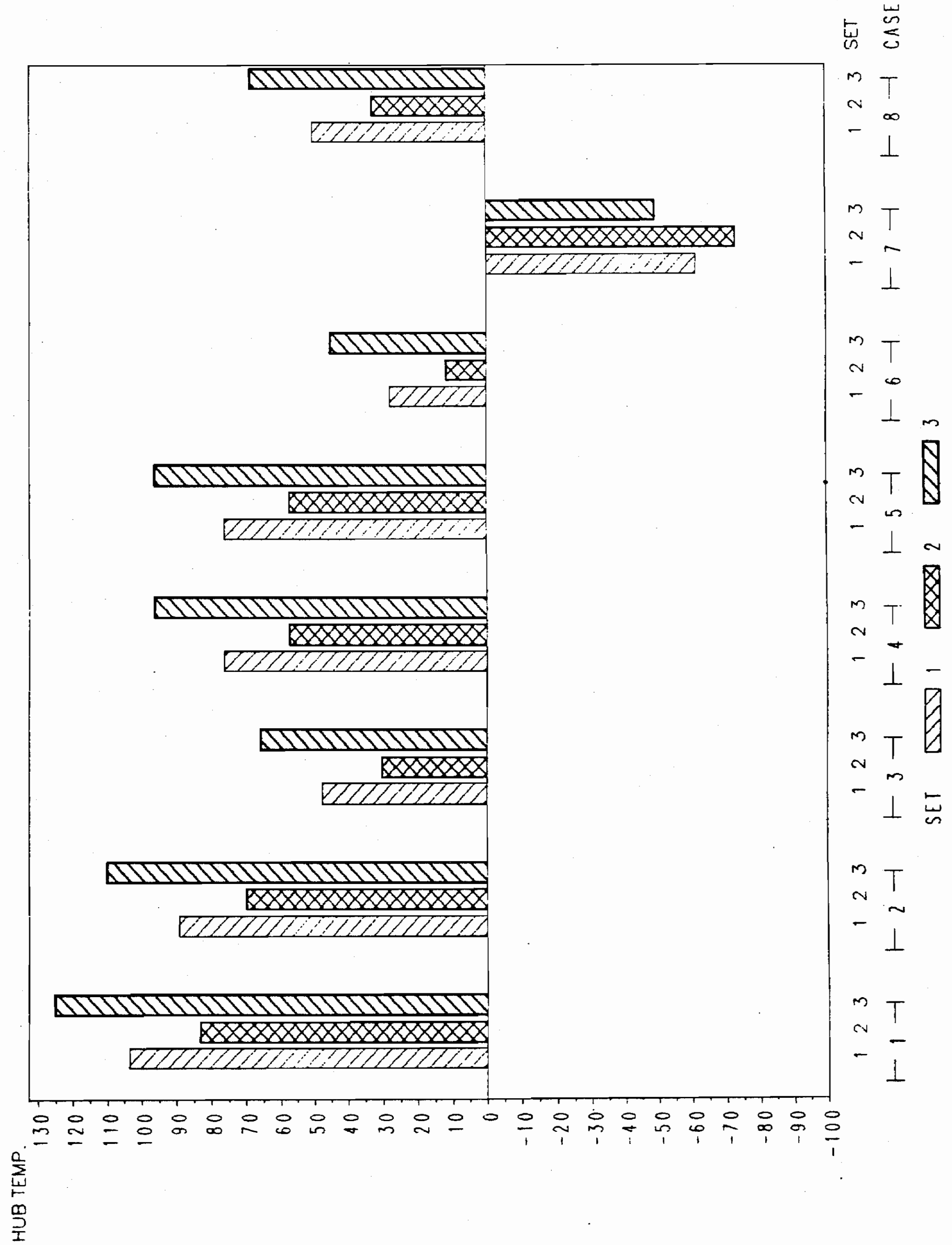


Figure 9. Hub Temperatures in Eight Cases for Three Different Sets of Parameters

Table 3. Minimum and Maximum Hub Temperatures for Different Sets of Parameters

```
TEMPERATURE ESTIMATION (HUB)


RPE :    7378.00 KM         RAE :  42378.00 KM         EA : 0.340

RPM :    4890.00 KM         RAM :    5186.47 KM        MA : 0.150

SET 2 (SOLAR SAIL) :

ABAL :  0.150      EMAL :  0.050      ABCR :  0.470      EMCR :  0.240


TMIN OCCURS ALWAYS IN CASE 7, TMAX OCCURS ALWAYS IN CASE 1.

 | ABH       | EMH       |   TMIN (C) |   TMAX (C) |
=================================================
 | 0.120     | 0.040     |     -61.50 |    103.54 |
 | 0.120     | 0.045     |     -67.65 |     92.61 |
 | 0.120     | 0.050     |     -72.99 |     83.10 |
 | 0.130     | 0.040     |     -57.23 |    111.15 |
 | 0.130     | 0.045     |     -63.49 |    100.00 |
 | 0.130     | 0.050     |     -68.94 |     90.30 |
 | 0.140     | 0.040     |     -53.19 |    118.34 |
 | 0.140     | 0.045     |     -59.57 |    106.98 |
 | 0.140     | 0.050     |     -65.12 |     97.10 |
 | 0.150     | 0.040     |     -49.36 |    125.15 |
 | 0.150     | 0.045     |     -55.86 |    113.59 |
 | 0.150     | 0.050     |     -61.50 |    103.54 |
```

Table 4. Minimum and Maximum Hub Temperatures for Different Sets of Parameters (without Case 7)

```
TEMPERATURE ESTIMATION (HUB) W/O CASE 7


RPE :    7378.00 KM          RAE :  42378.00 KM          EA : 0.340

RPM :    4890.00 KM          RAM :    5186.47 KM         MA : 0.150

SET 2 (SOLAR SAIL) :

ABAL :  0.150       EMAL :  0.050       ABCR :  0.470       EMCR :  0.240


TMIN OCCURS ALWAYS IN CASE 6, TMAX OCCURS ALWAYS IN CASE 1.

 | ABH      | EMH      |  TMIN (C) |  TMAX (C) |
================================================
 | 0.120    | 0.040    |     27.80 |    103.54 |
 | 0.120    | 0.045    |     19.07 |     92.61 |
 | 0.120    | 0.050    |     11.47 |     83.10 |
 | 0.130    | 0.040    |     33.89 |    111.15 |
 | 0.130    | 0.045    |     24.98 |    100.00 |
 | 0.130    | 0.050    |     17.23 |     90.30 |
 | 0.140    | 0.040    |     39.63 |    118.34 |
 | 0.140    | 0.045    |     30.55 |    106.98 |
 | 0.140    | 0.050    |     22.66 |     97.10 |
 | 0.150    | 0.040    |     45.07 |    125.15 |
 | 0.150    | 0.045    |     35.84 |    113.59 |
 | 0.150    | 0.050    |     27.80 |    103.54 |
```

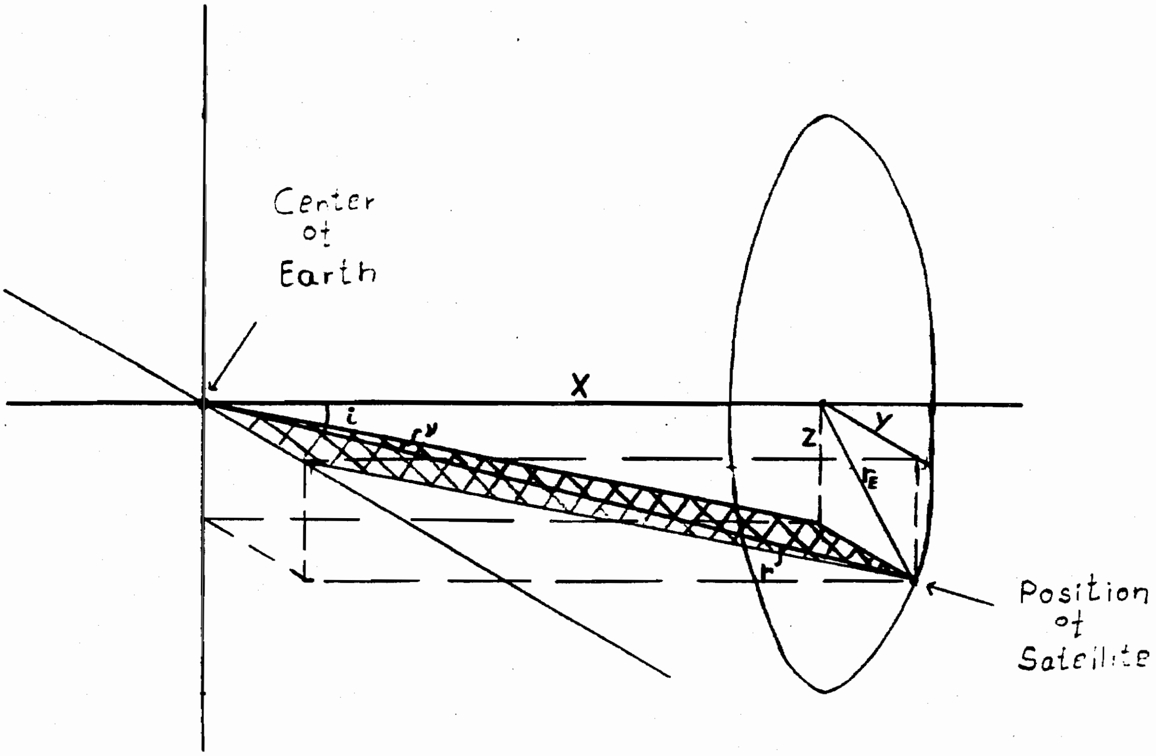


Figure 10. Configuration of the Shadow Entry Point

The radius r of a certain point on an ellipse is given by :

$$r = \frac{p}{1 + e \cos \nu} \tag{17}$$

where : ν = angle between periapsis and point of interest

Inspection of Figure 10 on page 28 shows that :

$$\begin{aligned} x &= \sqrt{r^2 - r_E^2} \\ z &= x \times \tan i \\ y &= \sqrt{r_E^2 - z^2} \\ \sin \nu &= \frac{y}{r} \end{aligned}$$

Putting all these formulas together we get a transcendent equation in ν. Knowing the initial inclination ($i_{orb} = 28.6°$), and adding the inclination of the equator to Earth's orbit around the sun (23.5°), we get $i = 52.1°$. If we now calculate p by using (Eq.16), we can apply a trial and error procedure and solve this equation for ν. For the initial orbit ν turns out to be 25.0195°; thus, $r = 7675.5\,\text{km}$.

The time needed to travel from the periapsis (case 3) to a particular point on an ellipse is given by :

$$t = \sqrt{\frac{a^3}{\mu_E}}\ (E - e \sin E) \tag{18}$$

where : μ_E $= 3.986 \times 10^5\ \frac{km^3}{s^2}$ Gravitational parameter ($G \times M$)

E $= arccos\left(\frac{e + \cos \nu}{1 + e\ \cos \nu}\right)$ Eccentric anomaly

This yields a value of t of 345 s which must be multiplied by 2 in order to get the time that the spacecraft stays in the Earth shadow. For this calculation only the first half of the shadow trajectory is important. We want to compare this time with the time the craft needs to cool down from the shadow entry temperature to the equilibrium temperature in the case 3. Using parameter set 2 of sail and hub, and using the above determined values for r and ν the temperatures at the shadow entry point are : 336.44 K for the sail and 410.23 K for the hub.

To obtain an approximate time needed to reach the equilibrium temperature after a sudden change in the irradiation, we may assume a circular orbit between the shadow entry point and case 3, and we may assume that the angle θ is constant in this part of the trajectory.

When the spacecraft enters the shadow, the solar radiation stops, leaving only planetary radiation. Thus, the heat flux in the shadow yields :

$$\dot{q}(T) = W_{pl}\, \alpha\, F_{s,pl}\, A_{\perp} - \sigma\, \varepsilon_s\, F_{s,sp}\, A_r\, T^4 \tag{19}$$

The energy balance is given by :

$$\dot{q}\; t = c_p\, (\Delta T)\, m \tag{20}$$

If we now assume that the function of the outgoing radiation $\dot{q}(T)$ is linear for small temperature increments ΔT we may re-arrange (20) and solve for Δt :

$$\Delta t = \frac{2\, c_p\, (\Delta T)\, m}{\dot{q}(T) + \dot{q}(T - \Delta T)} \tag{21}$$

Using a step of $\Delta T = 1\text{K}$ between the shadow entry temperature and the equilibrium temperature and adding up of all Δt's results in the cool-down times. The equilibrium temperatures for case 3 are : 271.96 K for the sail, and 323.68 K for the hub.

This procedure was applied for the sail and the hub. The cool-down times turned out to be :

$$t_{cd,s} \simeq 12\,\text{s} \quad \text{for the sail}$$
$$t_{cd,h} \simeq 18\,\text{h} \quad \text{for the hub}$$

This means that the sail reaches its equilibrium temperature 12 s after it has entered the shadow. Because of the fact that it takes at least 30 times as long to reach the position of the case 3, the thermal equilibrium cases are a reasonably good assumption for the sail. On the other hand, the cool-down time for the hub is longer than the period of the initial orbit; therefore, the temperatures of the hub are likely to be higher in the shadow cases and lower in the sun light cases than the calculated equilibrium temperatures.

Figure 11 on page 32 and Figure 12 on page 33 show the radiation curves of the sail and the hub, respectively. The temperature decay curves are shown in Figure 13 on page 34 and Figure 14 on page 35. Figure 15 on page 36 shows the temperature decay for the hub within the first 390 s after shadow entry. It can be seen in this figure that the hub temperature decays only by about 1.5 K between shadow entry point and the case 3 (t = 345 s), whereas the equilibrium calculation predicts a decay of 86.55 K.

2.6. Temperatures During The Heliocentric Transfer

The goal of this calculation is to determine how close to the Sun a trajectory to Mars may become without thermal damage of the spacecraft. The sail and hub temperatures are determined as functions of the distance to sun and θ. Since the craft would be far away from other planets only solar radiation was taken into account. The process is similar to the calculations above. According to Ref.[5], such a trajectory requires a range of θ of 35° to 45°, however, the moveable petals of the sail will move to smaller angles to ensure proper attitude control. Therefore, a range of θ of 20° to 50° was used in this calculation. The solar constant must be calculated for each distance to sun. The solar constant at a certain distance from sun is given by :

$$\mathbf{I}_S = \mathbf{I}_{SE}\ (1/r)^2 \tag{22}$$

where : r = Distance from Sun [AU]

The results are shown in Figure 16 on page 38 through Figure 21 on page 48 and Table 5 on page 39 through Table 10 on page 49. The dependency of the sail temperatures upon θ is obvious in these plots, whereas the hub temperatures are almost independent of this angle. Due to the fact that mylar gets soft at about 160° C the minimum distance to the sun will be determined by this temperature; the latter is indicated in the plots for the sail. The material of the hub is able to resist much higher temperatures than mylar; therefore the minimum distance to sun will be set by

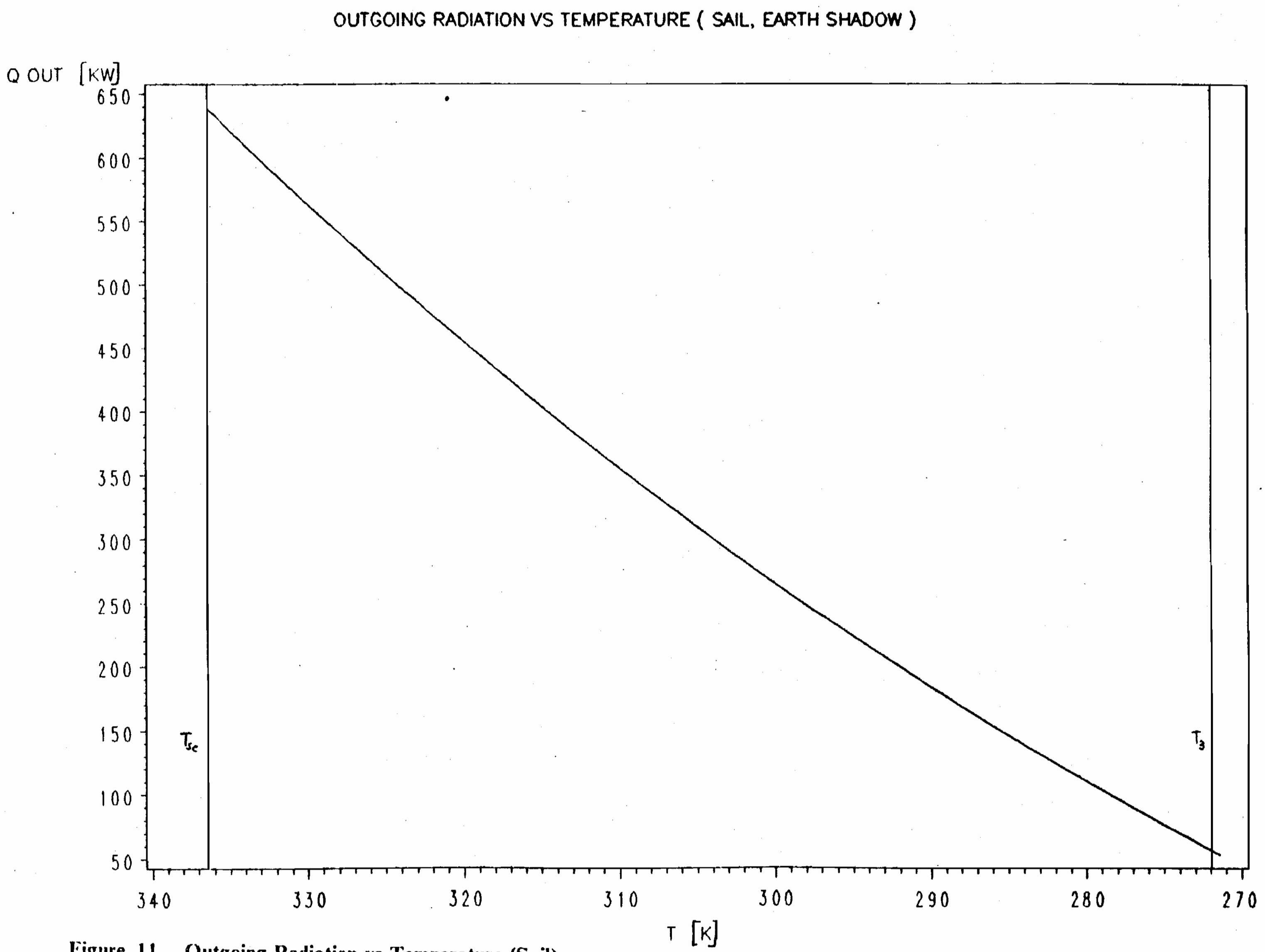


Figure 11. Outgoing Radiation vs Temperature (Sail)

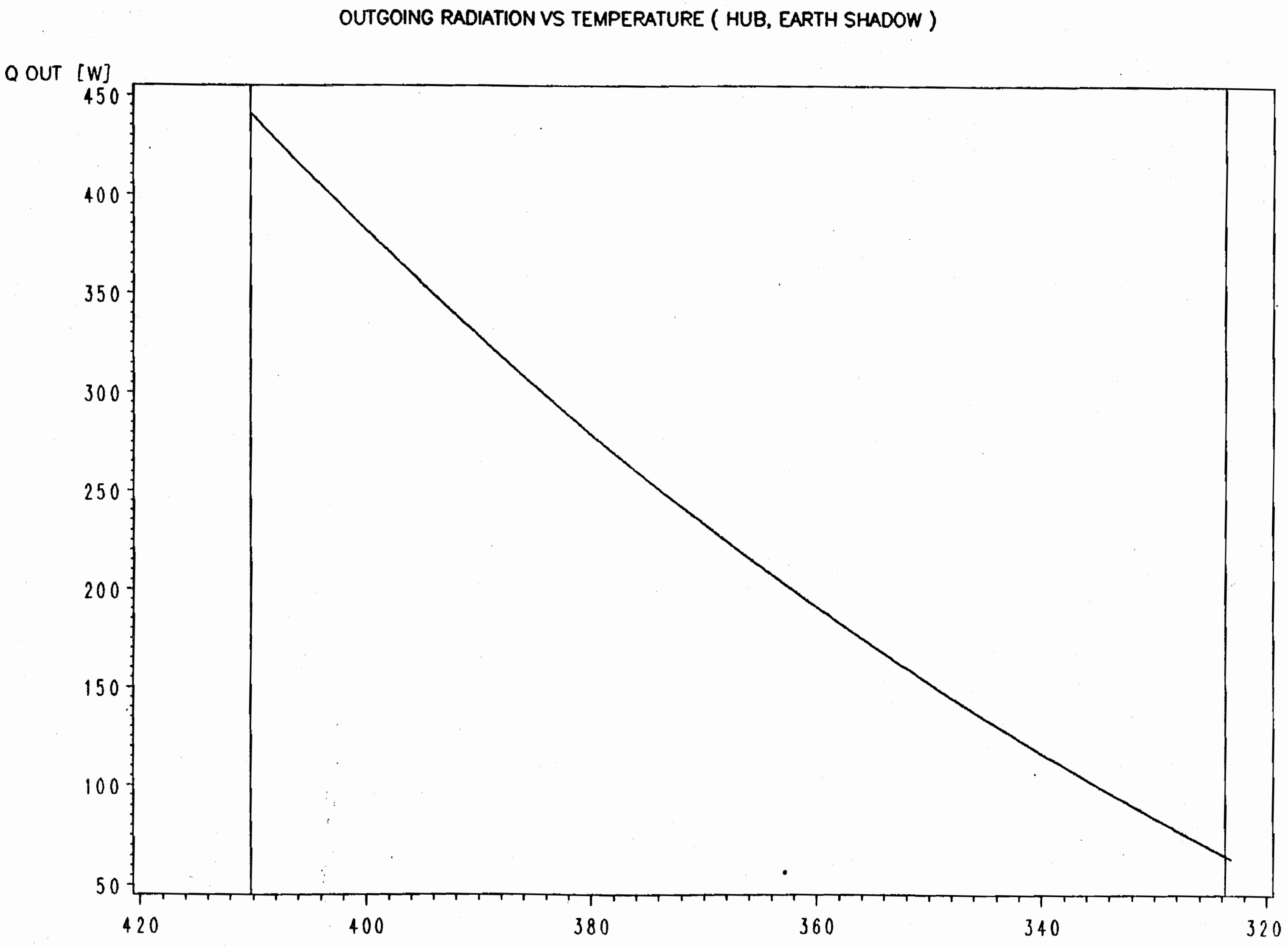


Figure 12. Outgoing Radiation vs Temperature (Hub)

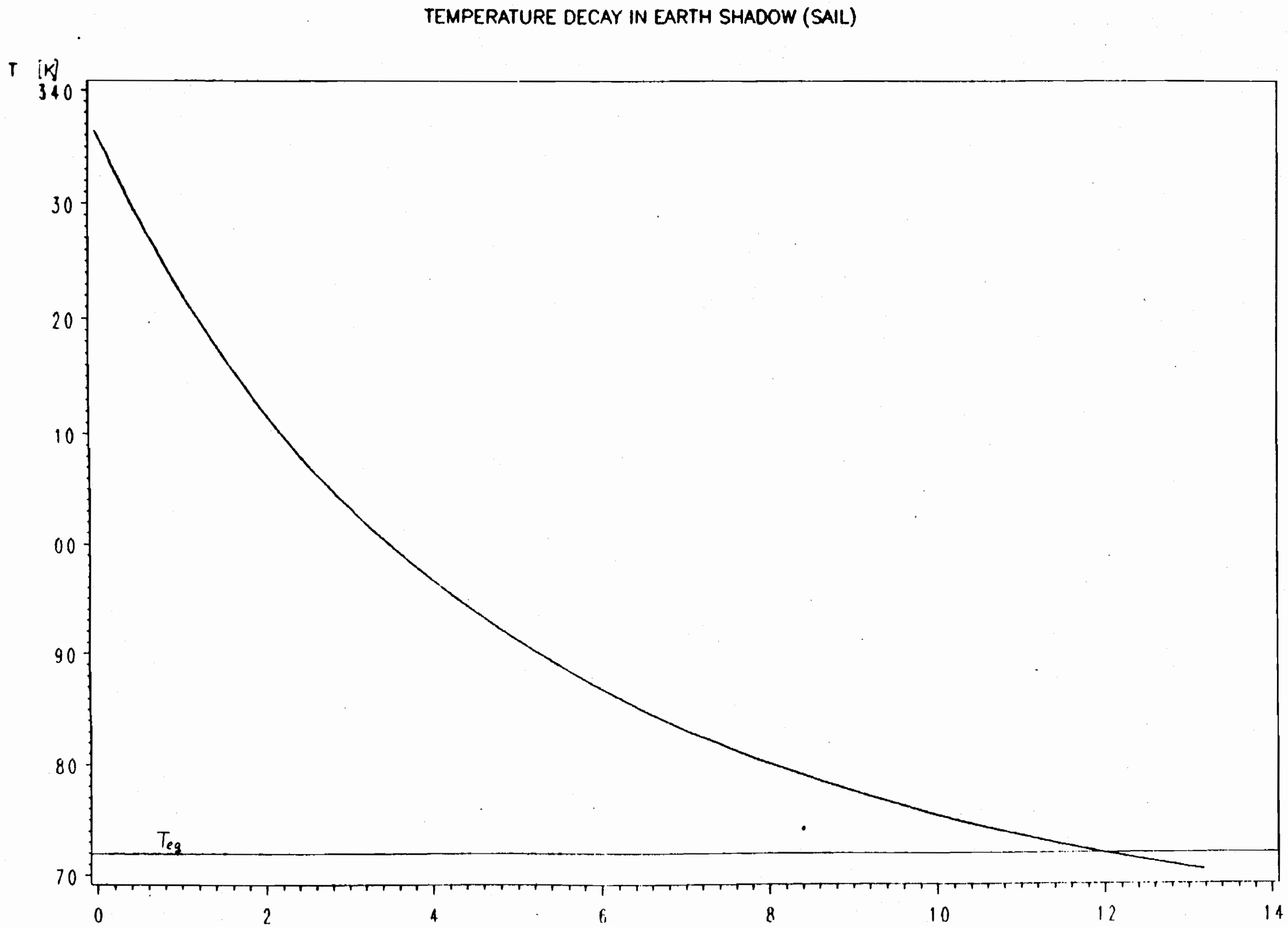


Figure 13. Temperature Decay in Earth Shadow (Sail)

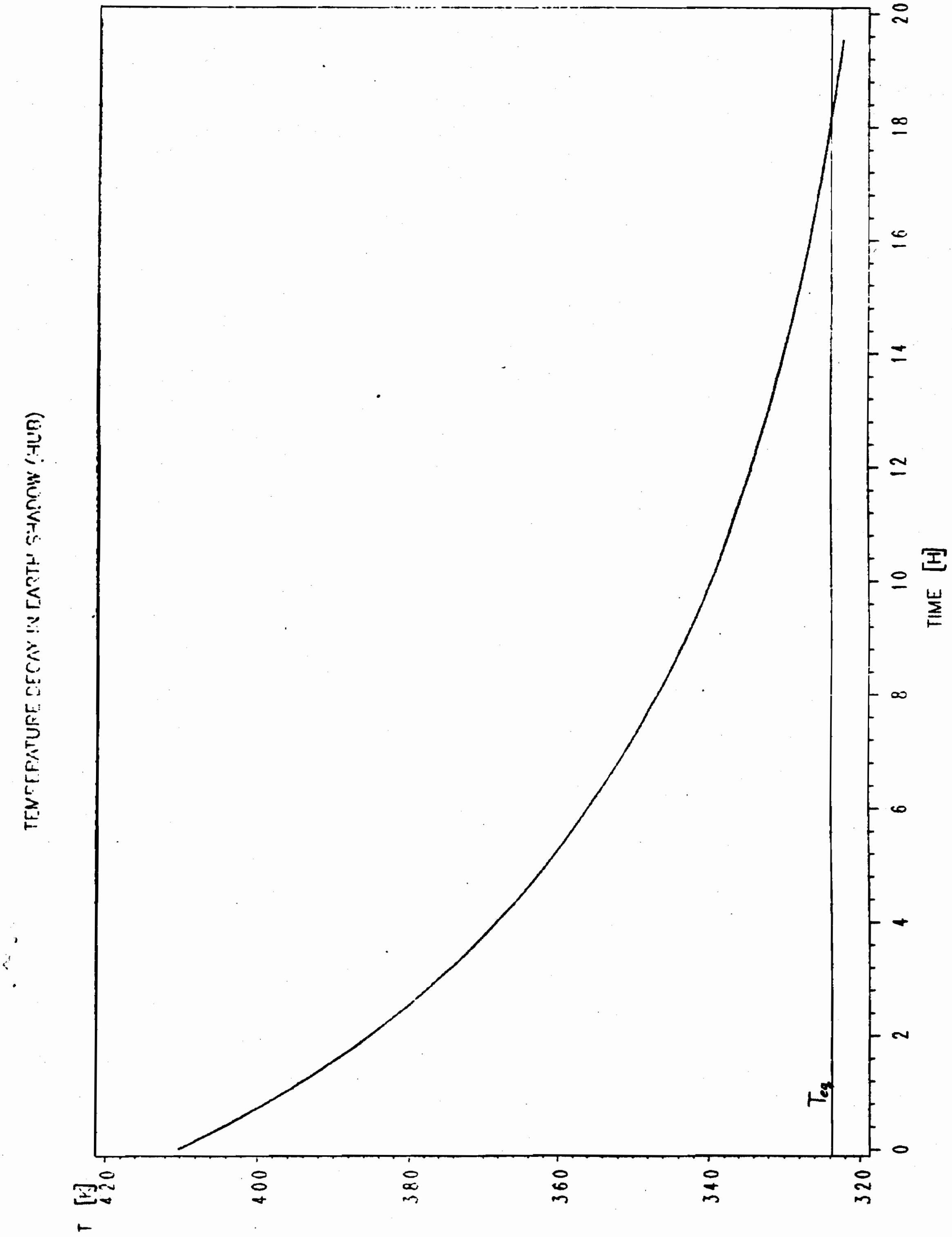


Figure 14. Temperature Decay in Earth Shadow (Hub)

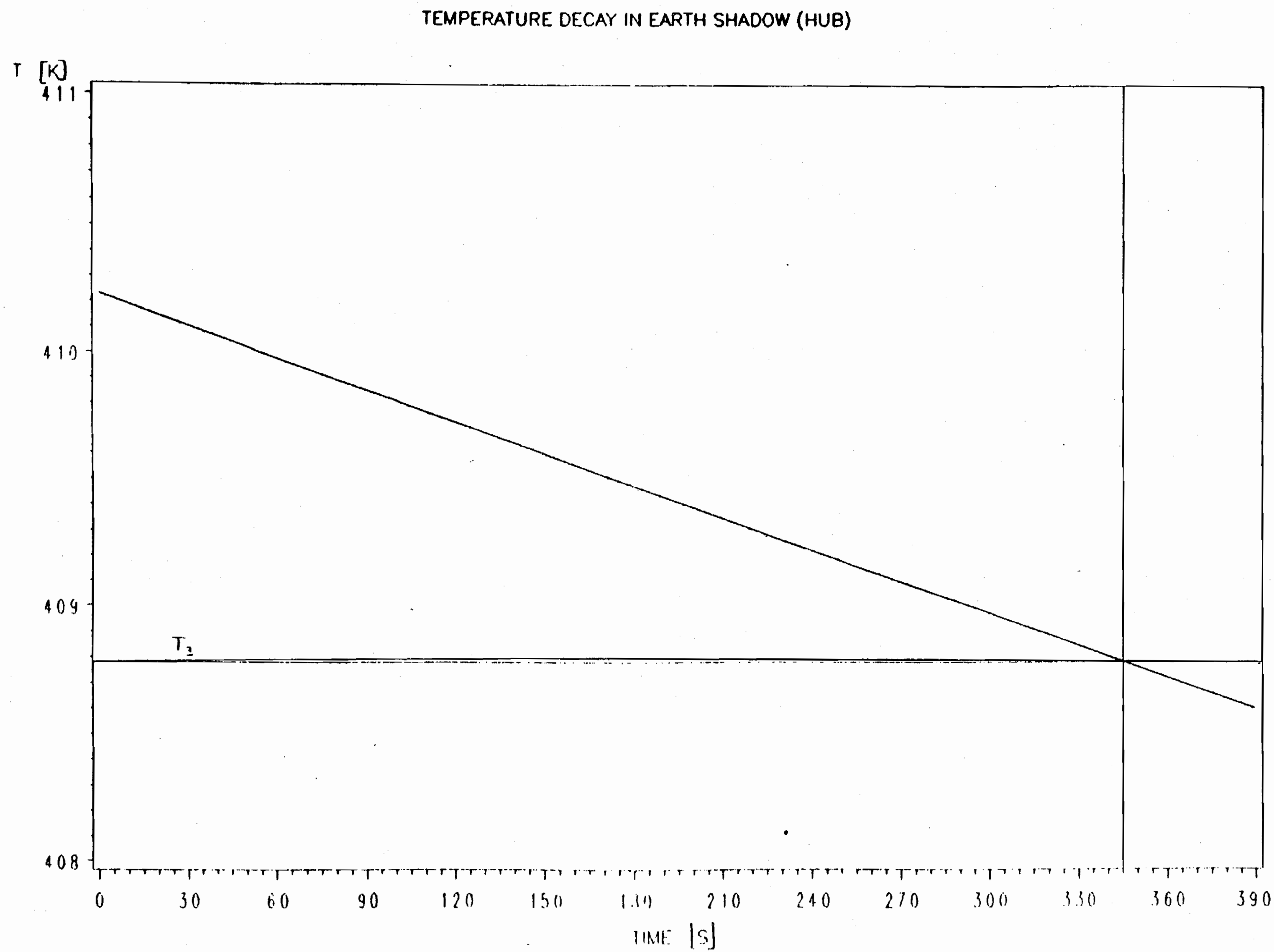


Figure 15. Temperature Decay in Earth Shadow (Hub, initial 390 s)

this temperature; the latter is indicated in the plots for the sail. The material of the hub is able to resist much higher temperatures than mylar; therefore the minimum distance to sun will be set by the sail material and by the maximum temperature that can be tolerated by the components inside the hub.

2.7. Conclusions

It turned out in this analysis that the assumed thermal equilibrium cases for the sail are comparable to reality; on the other hand, the hub temperatures are likely to be higher in the shadow cases and lower in the sun light cases. All temperatures are highly dependent upon the material properties. Thus, the exact values of the material of interest must be known in order to get accurate results. An error source which might decrease the accuracy of the results are the albedo factors. Depending upon atmospheric conditions these "constants" can vary by up to 100%, which could be a problem in the cases with mainly reflected radiation.

The temperatures during a heliocentric travel show how close to the sun a trajectory may pass without destroying the spacecraft. As shown in the graphs, the closest possible pass can be decreased by increasing the angle θ, however, this might cause problems for the spacecraft control.

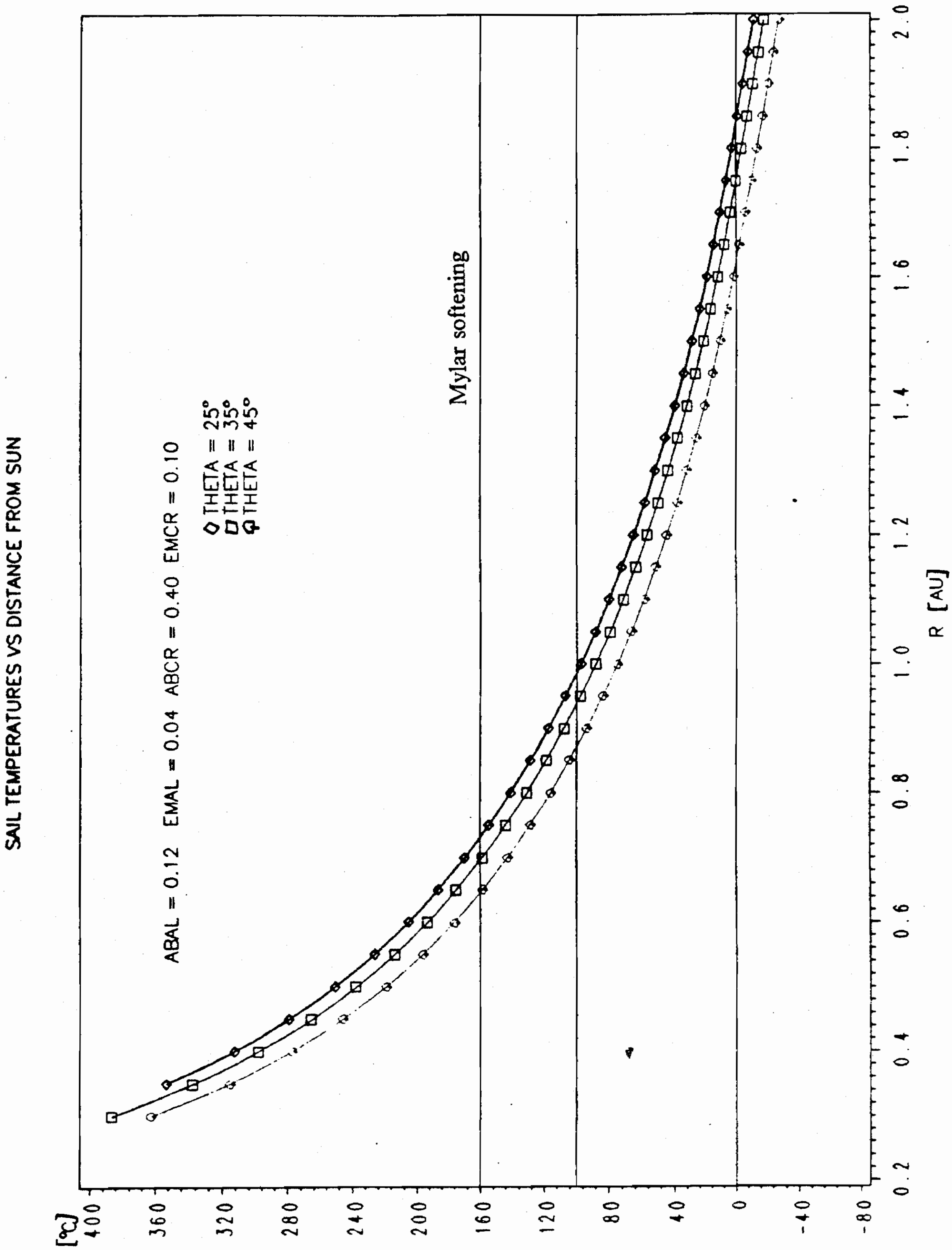


Figure 16. Sail Temperatures vs. Distance from Sun (Set 1)

Table 5. Sail Temperatures during a Heliocentric Transfer (Set 1)

```
SUN BYPASS TEMPERATURES (SOLAR SAIL)

SET 1 :

ABAL :    0.12     EMAL :    0.04    ABCR :    0.40    EMCR :    0.10

 R    | THETA  |   ARPER   |     IS     |    T (K)   |    T (C)
=====================================================================
0.20  |   20.0 |   16068.7 |  34425.00  |    836.24  |     563.08
0.20  |   25.0 |   15497.9 |  34425.00  |    828.71  |     555.55
0.20  |   30.0 |   14809.0 |  34425.00  |    819.35  |     546.19
0.20  |   35.0 |   14007.5 |  34425.00  |    808.03  |     534.87
0.20  |   40.0 |   13099.4 |  34425.00  |    794.60  |     521.44
0.20  |   45.0 |   12091.5 |  34425.00  |    778.86  |     505.70
0.20  |   50.0 |   10991.7 |  34425.00  |    760.51  |     487.35
---------------------------------------------------------------------
0.40  |   20.0 |   16068.7 |   8606.25  |    591.31  |     318.15
0.40  |   25.0 |   15497.9 |   8606.25  |    585.99  |     312.83
0.40  |   30.0 |   14809.0 |   8606.25  |    579.37  |     306.21
0.40  |   35.0 |   14007.5 |   8606.25  |    571.36  |     298.20
0.40  |   40.0 |   13099.4 |   8606.25  |    561.87  |     288.71
0.40  |   45.0 |   12091.5 |   8606.25  |    550.73  |     277.57
0.40  |   50.0 |   10991.7 |   8606.25  |    537.76  |     264.60
---------------------------------------------------------------------
0.60  |   20.0 |   16068.7 |   3825.00  |    482.80  |     209.65
0.60  |   25.0 |   15497.9 |   3825.00  |    478.46  |     205.30
0.60  |   30.0 |   14809.0 |   3825.00  |    473.05  |     199.89
0.60  |   35.0 |   14007.5 |   3825.00  |    466.52  |     193.36
0.60  |   40.0 |   13099.4 |   3825.00  |    458.76  |     185.60
0.60  |   45.0 |   12091.5 |   3825.00  |    449.67  |     176.51
0.60  |   50.0 |   10991.7 |   3825.00  |    439.08  |     165.92
---------------------------------------------------------------------
0.80  |   20.0 |   16068.7 |   2151.56  |    418.12  |     144.96
0.80  |   25.0 |   15497.9 |   2151.56  |    414.36  |     141.20
0.80  |   30.0 |   14809.0 |   2151.56  |    409.67  |     136.51
0.80  |   35.0 |   14007.5 |   2151.56  |    404.01  |     130.85
0.80  |   40.0 |   13099.4 |   2151.56  |    397.30  |     124.14
0.80  |   45.0 |   12091.5 |   2151.56  |    389.43  |     116.27
0.80  |   50.0 |   10991.7 |   2151.56  |    380.25  |     107.09
---------------------------------------------------------------------
1.00  |   20.0 |   16068.7 |   1377.00  |    373.98  |     100.82
1.00  |   25.0 |   15497.9 |   1377.00  |    370.61  |      97.45
1.00  |   30.0 |   14809.0 |   1377.00  |    366.42  |      93.26
1.00  |   35.0 |   14007.5 |   1377.00  |    361.36  |      88.20
1.00  |   40.0 |   13099.4 |   1377.00  |    355.36  |      82.20
1.00  |   45.0 |   12091.5 |   1377.00  |    348.31  |      75.16
1.00  |   50.0 |   10991.7 |   1377.00  |    340.11  |      66.95
```

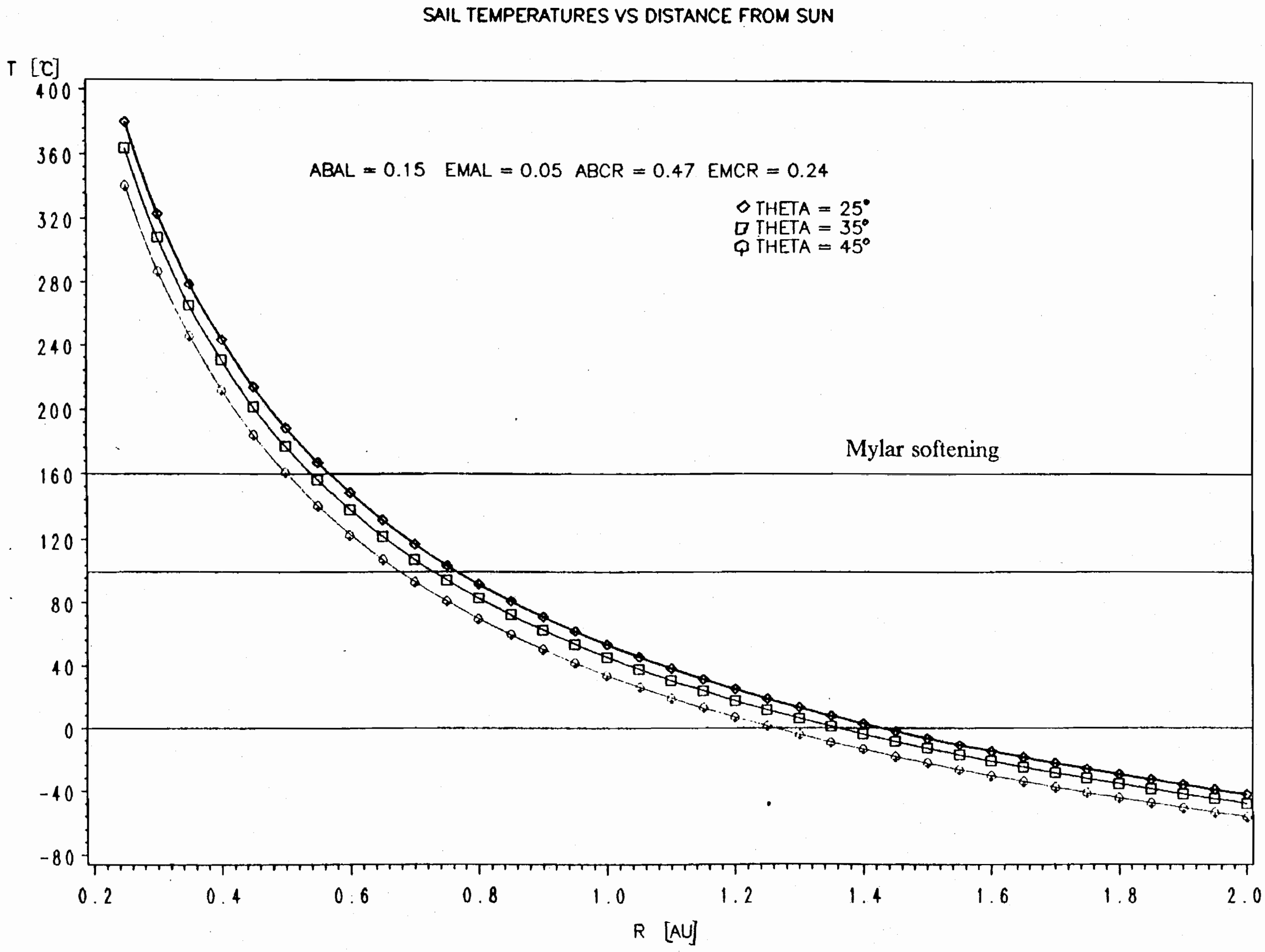


Figure 17. Sail Temperatures vs. Distance from Sun (Set 2)

Table 6. Sail Temperatures during a Heliocentric Transfer (Set 2)

```
SUN BYPASS TEMPERATURES (SOLAR SAIL)

SET 2 :

ABAL :    0.15    EMAL :    0.05    ABCR :    0.47    EMCR :    0.24

  R   | THETA  |   ARPER    |     IS      |   T (K)    |    T (C)
==============================================================
0.20  |   20.0 |   16068.7  |  34425.00   |     737.04 |     463.88
0.20  |   25.0 |   15497.9  |  34425.00   |     730.41 |     457.25
0.20  |   30.0 |   14809.0  |  34425.00   |     722.15 |     448.99
0.20  |   35.0 |   14007.5  |  34425.00   |     712.18 |     439.02
0.20  |   40.0 |   13099.4  |  34425.00   |     700.34 |     427.18
0.20  |   45.0 |   12091.5  |  34425.00   |     686.46 |     413.30
0.20  |   50.0 |   10991.7  |  34425.00   |     670.29 |     397.13
______________________________________________________________
0.40  |   20.0 |   16068.7  |   8606.25   |     521.17 |     248.01
0.40  |   25.0 |   15497.9  |   8606.25   |     516.48 |     243.32
0.40  |   30.0 |   14809.0  |   8606.25   |     510.64 |     237.48
0.40  |   35.0 |   14007.5  |   8606.25   |     503.58 |     230.42
0.40  |   40.0 |   13099.4  |   8606.25   |     495.22 |     222.06
0.40  |   45.0 |   12091.5  |   8606.25   |     485.40 |     212.24
0.40  |   50.0 |   10991.7  |   8606.25   |     473.97 |     200.81
______________________________________________________________
0.60  |   20.0 |   16068.7  |   3825.00   |     425.53 |     152.37
0.60  |   25.0 |   15497.9  |   3825.00   |     421.70 |     148.54
0.60  |   30.0 |   14809.0  |   3825.00   |     416.93 |     143.77
0.60  |   35.0 |   14007.5  |   3825.00   |     411.17 |     138.01
0.60  |   40.0 |   13099.4  |   3825.00   |     404.34 |     131.18
0.60  |   45.0 |   12091.5  |   3825.00   |     396.33 |     123.17
0.60  |   50.0 |   10991.7  |   3825.00   |     386.99 |     113.83
______________________________________________________________
0.80  |   20.0 |   16068.7  |   2151.56   |     368.52 |      95.36
0.80  |   25.0 |   15497.9  |   2151.56   |     365.20 |      92.04
0.80  |   30.0 |   14809.0  |   2151.56   |     361.08 |      87.92
0.80  |   35.0 |   14007.5  |   2151.56   |     356.09 |      82.93
0.80  |   40.0 |   13099.4  |   2151.56   |     350.17 |      77.01
0.80  |   45.0 |   12091.5  |   2151.56   |     343.23 |      70.07
0.80  |   50.0 |   10991.7  |   2151.56   |     335.15 |      61.99
______________________________________________________________
1.00  |   20.0 |   16068.7  |   1377.00   |     329.62 |      56.46
1.00  |   25.0 |   15497.9  |   1377.00   |     326.65 |      53.49
1.00  |   30.0 |   14809.0  |   1377.00   |     322.96 |      49.80
1.00  |   35.0 |   14007.5  |   1377.00   |     318.49 |      45.33
1.00  |   40.0 |   13099.4  |   1377.00   |     313.20 |      40.04
1.00  |   45.0 |   12091.5  |   1377.00   |     307.00 |      33.84
1.00  |   50.0 |   10991.7  |   1377.00   |     299.76 |      26.60
```

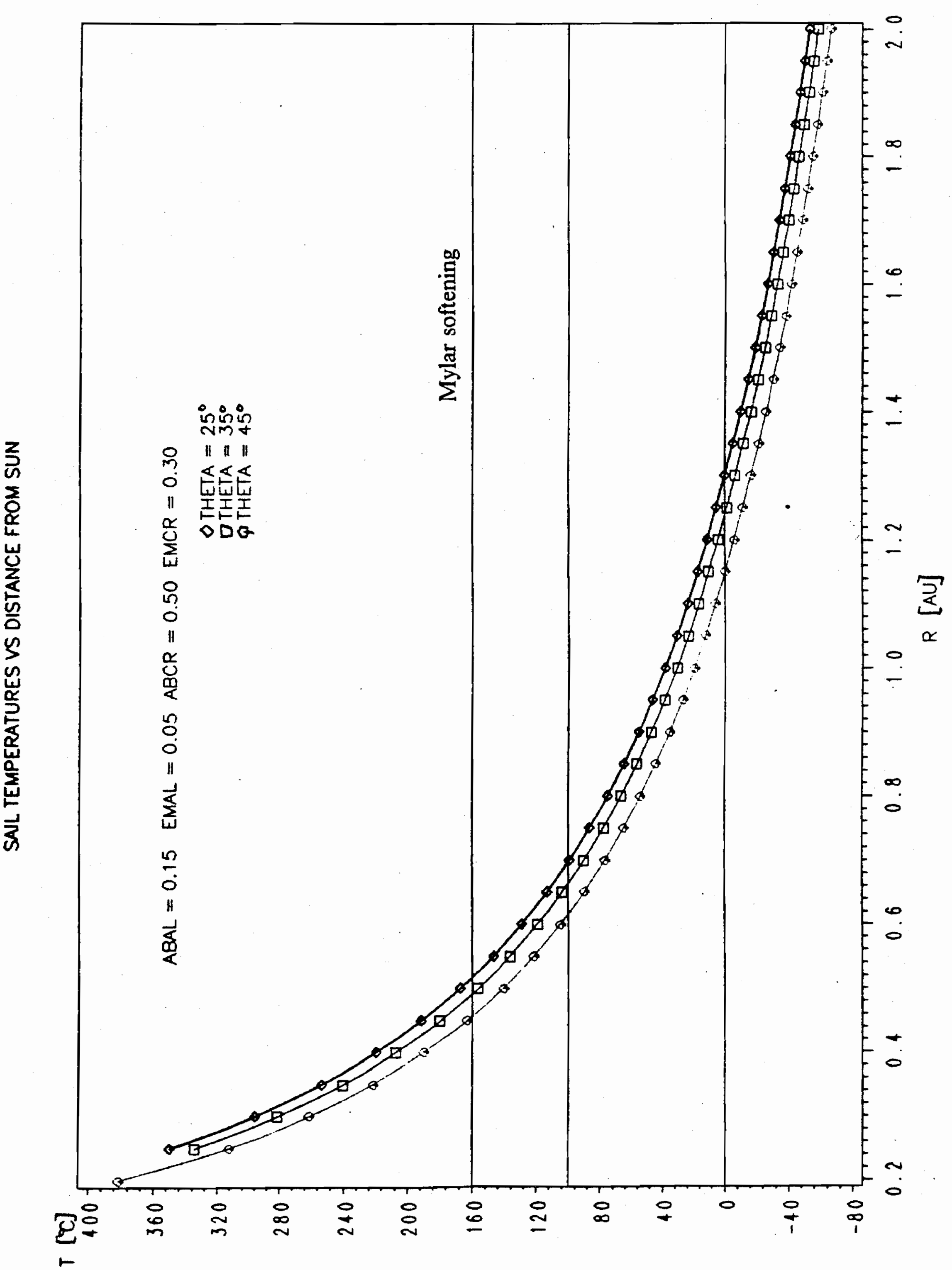


Figure 18. Sail Temperatures vs. Distance from Sun (Set 3)

Table 7. **Sail Temperatures during a Heliocentric Transfer (Set 3)**

```
SUN BYPASS TEMPERATURES (SOLAR SAIL)

SET 3 :

ABAL :   0.15    EMAL :   0.05   ABCR :   0.50   EMCR :   0.30

  R   | THETA  |   ARPER   |    IS     |   T (K)   |   T (C)
==========================================================
0.20  |  20.0  |  16068.7  | 34425.00  |   703.19  |   430.03
0.20  |  25.0  |  15497.9  | 34425.00  |   696.86  |   423.70
0.20  |  30.0  |  14809.0  | 34425.00  |   688.99  |   415.83
0.20  |  35.0  |  14007.5  | 34425.00  |   679.47  |   406.31
0.20  |  40.0  |  13099.4  | 34425.00  |   668.18  |   395.02
0.20  |  45.0  |  12091.5  | 34425.00  |   654.94  |   381.78
0.20  |  50.0  |  10991.7  | 34425.00  |   639.51  |   366.35
----------------------------------------------------------
0.40  |  20.0  |  16068.7  |  8606.25  |   497.23  |   224.07
0.40  |  25.0  |  15497.9  |  8606.25  |   492.76  |   219.60
0.40  |  30.0  |  14809.0  |  8606.25  |   487.19  |   214.03
0.40  |  35.0  |  14007.5  |  8606.25  |   480.46  |   207.30
0.40  |  40.0  |  13099.4  |  8606.25  |   472.47  |   199.31
0.40  |  45.0  |  12091.5  |  8606.25  |   463.11  |   189.95
0.40  |  50.0  |  10991.7  |  8606.25  |   452.20  |   179.04
----------------------------------------------------------
0.60  |  20.0  |  16068.7  |  3825.00  |   405.99  |   132.83
0.60  |  25.0  |  15497.9  |  3825.00  |   402.33  |   129.17
0.60  |  30.0  |  14809.0  |  3825.00  |   397.79  |   124.63
0.60  |  35.0  |  14007.5  |  3825.00  |   392.29  |   119.13
0.60  |  40.0  |  13099.4  |  3825.00  |   385.77  |   112.61
0.60  |  45.0  |  12091.5  |  3825.00  |   378.13  |   104.97
0.60  |  50.0  |  10991.7  |  3825.00  |   369.22  |    96.06
----------------------------------------------------------
0.80  |  20.0  |  16068.7  |  2151.56  |   351.60  |    78.44
0.80  |  25.0  |  15497.9  |  2151.56  |   348.43  |    75.27
0.80  |  30.0  |  14809.0  |  2151.56  |   344.49  |    71.33
0.80  |  35.0  |  14007.5  |  2151.56  |   339.73  |    66.57
0.80  |  40.0  |  13099.4  |  2151.56  |   334.09  |    60.93
0.80  |  45.0  |  12091.5  |  2151.56  |   327.47  |    54.31
0.80  |  50.0  |  10991.7  |  2151.56  |   319.75  |    46.59
----------------------------------------------------------
1.00  |  20.0  |  16068.7  |  1377.00  |   314.48  |    41.32
1.00  |  25.0  |  15497.9  |  1377.00  |   311.65  |    38.49
1.00  |  30.0  |  14809.0  |  1377.00  |   308.12  |    34.96
1.00  |  35.0  |  14007.5  |  1377.00  |   303.87  |    30.71
1.00  |  40.0  |  13099.4  |  1377.00  |   298.82  |    25.66
1.00  |  45.0  |  12091.5  |  1377.00  |   292.90  |    19.74
1.00  |  50.0  |  10991.7  |  1377.00  |   286.00  |    12.84
```

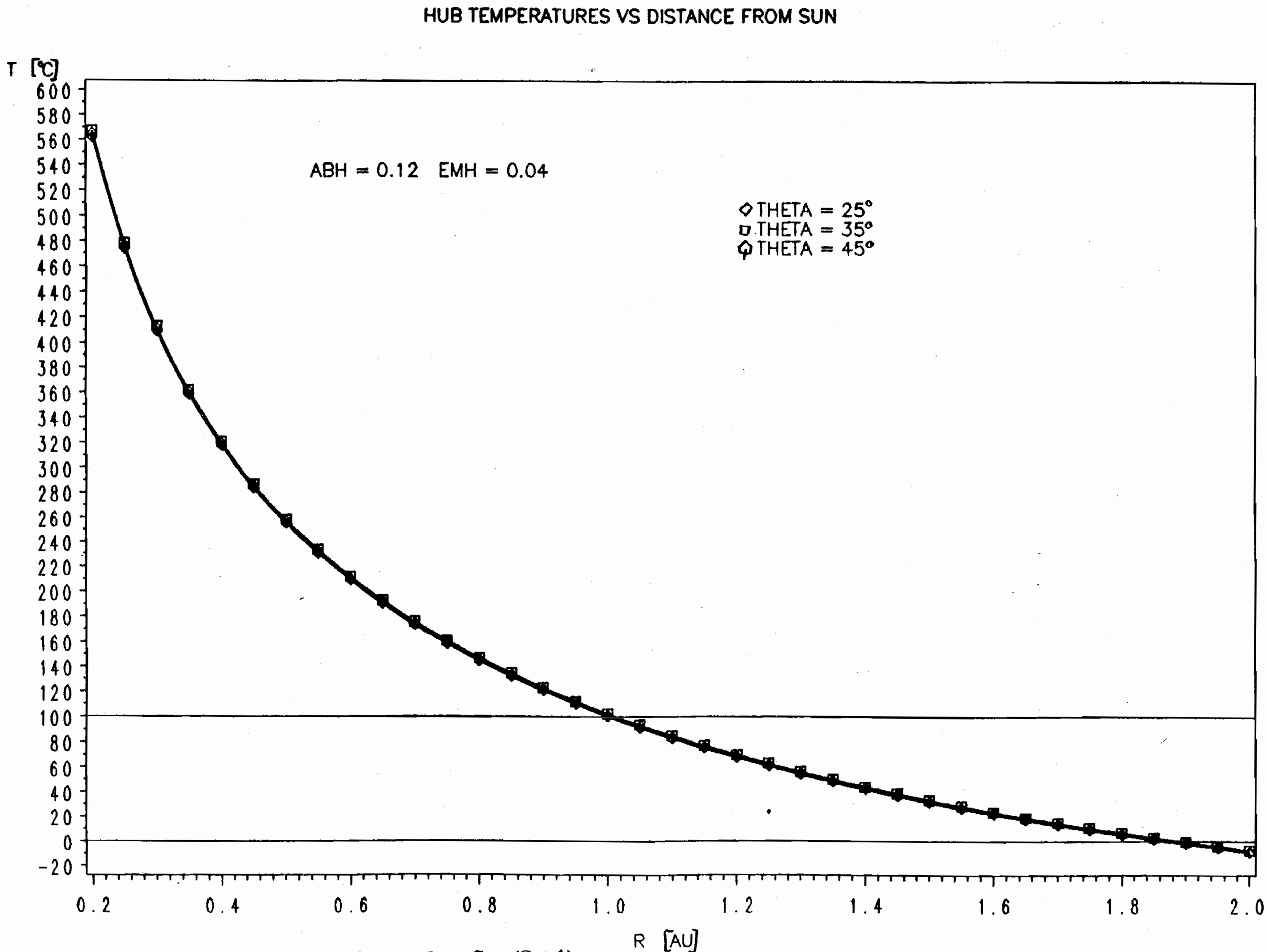


Figure 19. Hub Temperatures vs. Distance from Sun (Set 1)

Table 8. Hub Temperatures during a Heliocentric Transfer (Set 1)

```
SUN BYPASS TEMPERATURES (HUB)

SET 1:
ABH :    0.12     EMH :    0.04

SET 2 (SOLAR SAIL): ABAL  : 0.15    EMAL  : 0.05   ABCR  : 0.47   EMCR  : 0.24

 R    | THETA  |   ARPER    |     IS      |    T (K)    |    T (C)
============================================================================
0.20  |  20.0  |        7.0 |  34425.00   |    830.21   |    557.05
0.20  |  25.0  |        7.0 |  34425.00   |    835.09   |    561.93
0.20  |  30.0  |        7.0 |  34425.00   |    838.33   |    565.17
0.20  |  35.0  |        6.9 |  34425.00   |    839.95   |    566.79
0.20  |  40.0  |        6.7 |  34425.00   |    839.97   |    566.81
0.20  |  45.0  |        6.5 |  34425.00   |    838.38   |    565.22
0.20  |  50.0  |        6.3 |  34425.00   |    835.18   |    562.02

0.40  |  20.0  |        7.0 |   8606.25   |    587.04   |    313.88
0.40  |  25.0  |        7.0 |   8606.25   |    590.50   |    317.34
0.40  |  30.0  |        7.0 |   8606.25   |    592.79   |    319.63
0.40  |  35.0  |        6.9 |   8606.25   |    593.94   |    320.78
0.40  |  40.0  |        6.7 |   8606.25   |    593.95   |    320.79
0.40  |  45.0  |        6.5 |   8606.25   |    592.83   |    319.67
0.40  |  50.0  |        6.3 |   8606.25   |    590.56   |    317.40

0.60  |  20.0  |        7.0 |   3825.00   |    479.32   |    206.16
0.60  |  25.0  |        7.0 |   3825.00   |    482.14   |    208.98
0.60  |  30.0  |        7.0 |   3825.00   |    484.01   |    210.85
0.60  |  35.0  |        6.9 |   3825.00   |    484.95   |    211.79
0.60  |  40.0  |        6.7 |   3825.00   |    484.96   |    211.80
0.60  |  45.0  |        6.5 |   3825.00   |    484.04   |    210.88
0.60  |  50.0  |        6.3 |   3825.00   |    482.19   |    209.03

0.80  |  20.0  |        7.0 |   2151.56   |    415.10   |    141.94
0.80  |  25.0  |        7.0 |   2151.56   |    417.55   |    144.39
0.80  |  30.0  |        7.0 |   2151.56   |    419.17   |    146.01
0.80  |  35.0  |        6.9 |   2151.56   |    419.98   |    146.82
0.80  |  40.0  |        6.7 |   2151.56   |    419.98   |    146.82
0.80  |  45.0  |        6.5 |   2151.56   |    419.19   |    146.03
0.80  |  50.0  |        6.3 |   2151.56   |    417.59   |    144.43

1.00  |  20.0  |        7.0 |   1377.00   |    371.28   |     98.12
1.00  |  25.0  |        7.0 |   1377.00   |    373.47   |    100.31
1.00  |  30.0  |        7.0 |   1377.00   |    374.91   |    101.75
1.00  |  35.0  |        6.9 |   1377.00   |    375.64   |    102.48
1.00  |  40.0  |        6.7 |   1377.00   |    375.65   |    102.49
1.00  |  45.0  |        6.5 |   1377.00   |    374.94   |    101.78
1.00  |  50.0  |        6.3 |   1377.00   |    373.50   |    100.34
```

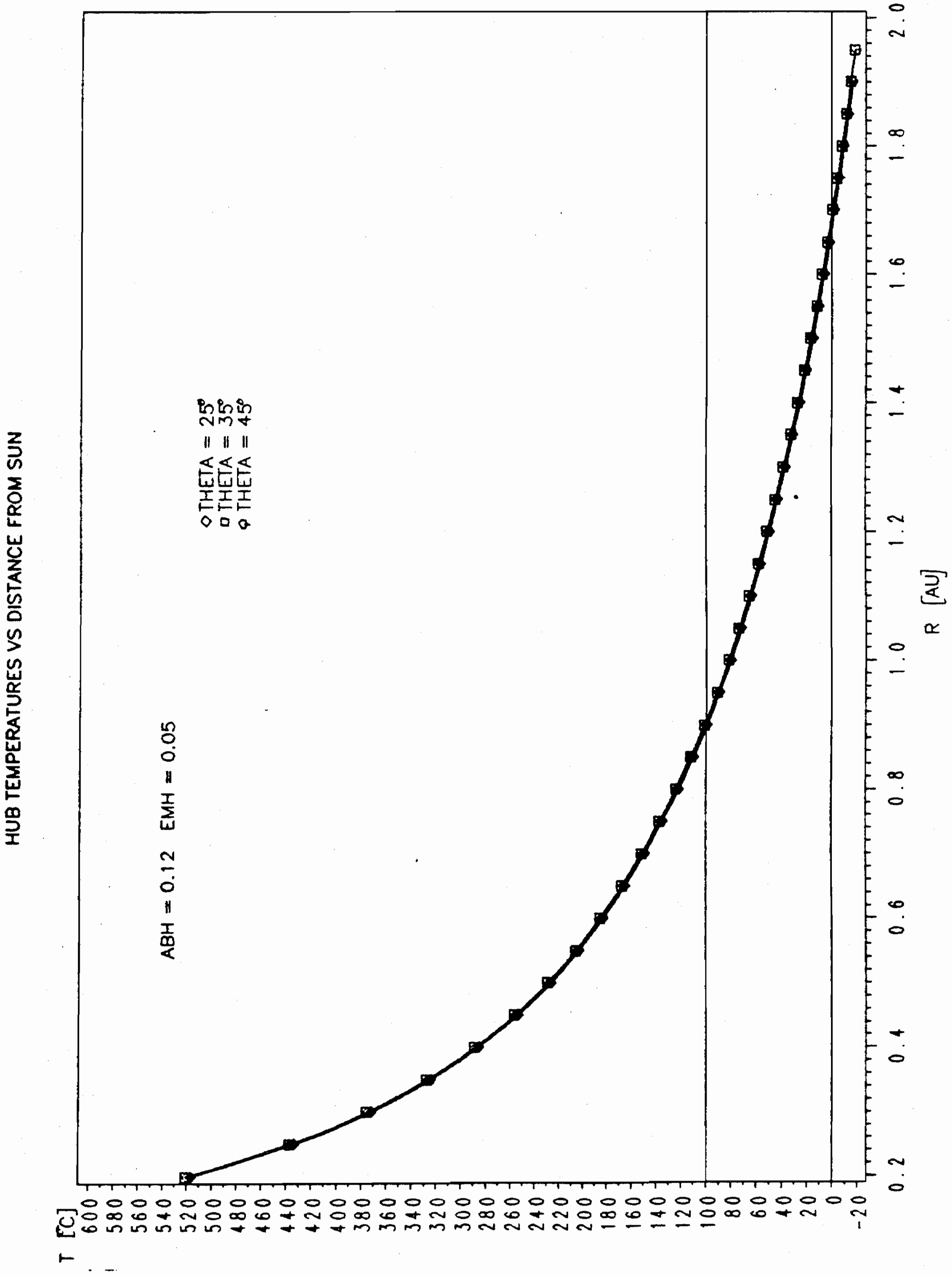


Figure 20. Hub Temperatures vs. Distance from Sun (Set 2)

Table 9. Hub Temperatures during a Heliocentric Transfer (Set 2)

```
SUN BYPASS TEMPERATURES (HUB)

SET 2:
ABH :   0.12    EMH :   0.05

SET 2 (SOLAR SAIL): ABAL : 0.15   EMAL : 0.05  ABCR : 0.47  EMCR : 0.24

 R   | THETA  |   ARPER   |    IS     |   T (K)   |   T (C)
===============================================================
0.20 |   20.0 |       7.0 |  34425.00 |    785.16 |    512.00
0.20 |   25.0 |       7.0 |  34425.00 |    789.78 |    516.62
0.20 |   30.0 |       7.0 |  34425.00 |    792.85 |    519.69
0.20 |   35.0 |       6.9 |  34425.00 |    794.38 |    521.22
0.20 |   40.0 |       6.7 |  34425.00 |    794.39 |    521.23
0.20 |   45.0 |       6.5 |  34425.00 |    792.89 |    519.73
0.20 |   50.0 |       6.3 |  34425.00 |    789.86 |    516.70
---------------------------------------------------------------
0.40 |   20.0 |       7.0 |   8606.25 |    555.19 |    282.03
0.40 |   25.0 |       7.0 |   8606.25 |    558.46 |    285.30
0.40 |   30.0 |       7.0 |   8606.25 |    560.63 |    287.47
0.40 |   35.0 |       6.9 |   8606.25 |    561.71 |    288.55
0.40 |   40.0 |       6.7 |   8606.25 |    561.72 |    288.56
0.40 |   45.0 |       6.5 |   8606.25 |    560.66 |    287.50
0.40 |   50.0 |       6.3 |   8606.25 |    558.52 |    285.36
---------------------------------------------------------------
0.60 |   20.0 |       7.0 |   3825.00 |    453.31 |    180.15
0.60 |   25.0 |       7.0 |   3825.00 |    455.98 |    182.82
0.60 |   30.0 |       7.0 |   3825.00 |    457.75 |    184.59
0.60 |   35.0 |       6.9 |   3825.00 |    458.63 |    185.47
0.60 |   40.0 |       6.7 |   3825.00 |    458.64 |    185.48
0.60 |   45.0 |       6.5 |   3825.00 |    457.78 |    184.62
0.60 |   50.0 |       6.3 |   3825.00 |    456.03 |    182.87
---------------------------------------------------------------
0.80 |   20.0 |       7.0 |   2151.56 |    392.58 |    119.42
0.80 |   25.0 |       7.0 |   2151.56 |    394.89 |    121.73
0.80 |   30.0 |       7.0 |   2151.56 |    396.42 |    123.26
0.80 |   35.0 |       6.9 |   2151.56 |    397.19 |    124.03
0.80 |   40.0 |       6.7 |   2151.56 |    397.20 |    124.04
0.80 |   45.0 |       6.5 |   2151.56 |    396.45 |    123.29
0.80 |   50.0 |       6.3 |   2151.56 |    394.93 |    121.77
---------------------------------------------------------------
1.00 |   20.0 |       7.0 |   1377.00 |    351.13 |     77.97
1.00 |   25.0 |       7.0 |   1377.00 |    353.20 |     80.04
1.00 |   30.0 |       7.0 |   1377.00 |    354.57 |     81.41
1.00 |   35.0 |       6.9 |   1377.00 |    355.26 |     82.10
1.00 |   40.0 |       6.7 |   1377.00 |    355.26 |     82.10
1.00 |   45.0 |       6.5 |   1377.00 |    354.59 |     81.43
1.00 |   50.0 |       6.3 |   1377.00 |    353.24 |     80.08
```

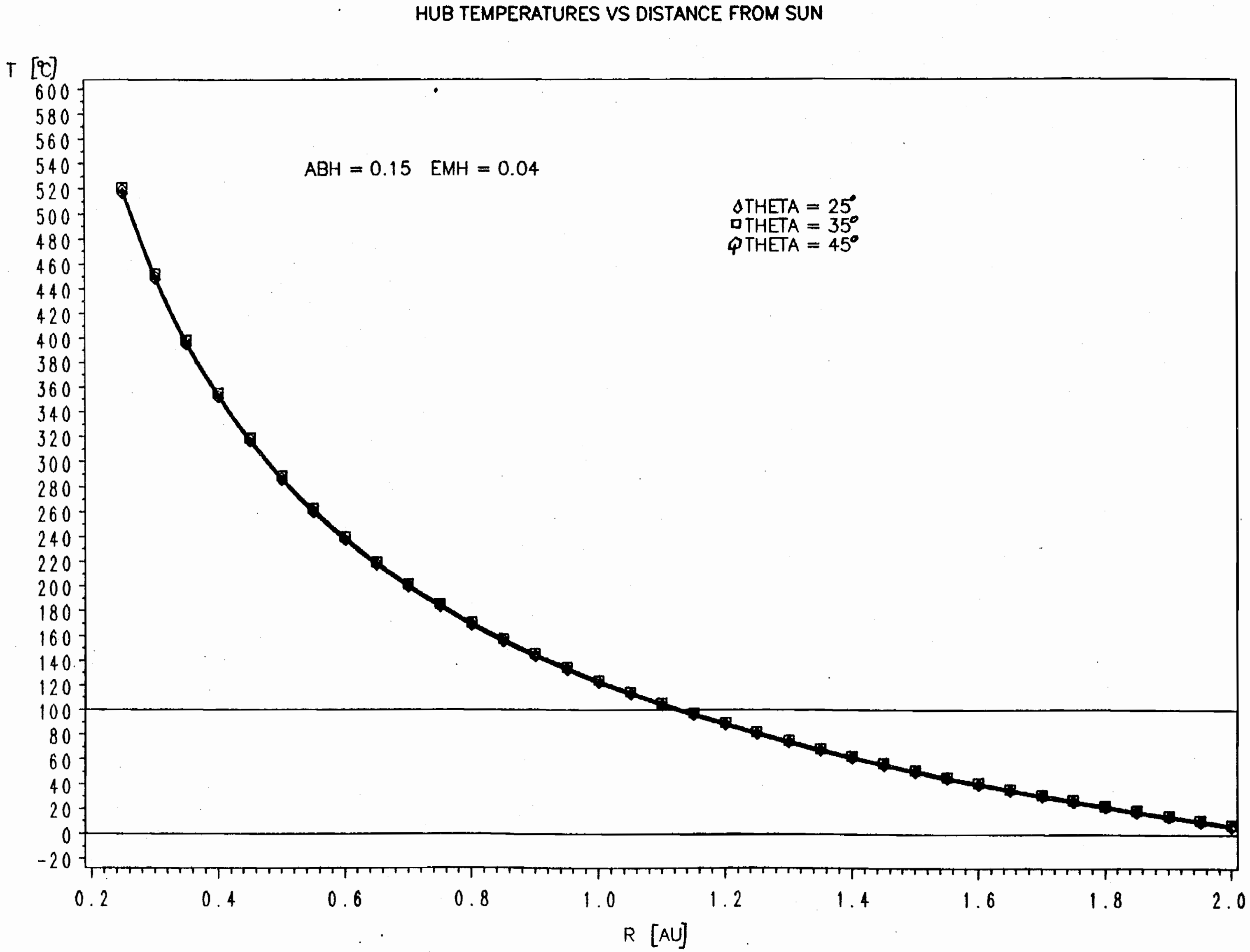


Figure 21. Hub Temperatures vs. Distance from Sun (Set 3)

Table 10. Hub Temperatures during a Heliocentric Transfer (Set 3)

```
SUN BYPASS TEMPERATURES (HUB)

SET 3:
ABH :    0.15     EMH :     0.04

SET 2 (SOLAR SAIL): ABAL  : 0.15   EMAL  : 0.05  ABCR  : 0.47  EMCR  : 0.24

 R    | THETA  |   ARPER   |     IS      |   T (K)    |   T (C)
==============================================================
0.20 |  20.0 |       7.0 | 34425.00 |   877.83 |    604.68
0.20 |  25.0 |       7.0 | 34425.00 |   883.00 |    609.84
0.20 |  30.0 |       7.0 | 34425.00 |   886.43 |    613.27
0.20 |  35.0 |       6.9 | 34425.00 |   888.14 |    614.98
0.20 |  40.0 |       6.7 | 34425.00 |   888.16 |    615.00
0.20 |  45.0 |       6.5 | 34425.00 |   886.48 |    613.32
0.20 |  50.0 |       6.3 | 34425.00 |   883.10 |    609.94
--------------------------------------------------------------
0.40 |  20.0 |       7.0 |  8606.25 |   620.72 |    347.56
0.40 |  25.0 |       7.0 |  8606.25 |   624.38 |    351.22
0.40 |  30.0 |       7.0 |  8606.25 |   626.80 |    353.64
0.40 |  35.0 |       6.9 |  8606.25 |   628.01 |    354.85
0.40 |  40.0 |       6.7 |  8606.25 |   628.02 |    354.86
0.40 |  45.0 |       6.5 |  8606.25 |   626.84 |    353.68
0.40 |  50.0 |       6.3 |  8606.25 |   624.44 |    351.28
--------------------------------------------------------------
0.60 |  20.0 |       7.0 |  3825.00 |   506.82 |    233.66
0.60 |  25.0 |       7.0 |  3825.00 |   509.80 |    236.64
0.60 |  30.0 |       7.0 |  3825.00 |   511.78 |    238.62
0.60 |  35.0 |       6.9 |  3825.00 |   512.77 |    239.61
0.60 |  40.0 |       6.7 |  3825.00 |   512.78 |    239.62
0.60 |  45.0 |       6.5 |  3825.00 |   511.81 |    238.65
0.60 |  50.0 |       6.3 |  3825.00 |   509.86 |    236.70
--------------------------------------------------------------
0.80 |  20.0 |       7.0 |  2151.56 |   438.92 |    165.76
0.80 |  25.0 |       7.0 |  2151.56 |   441.50 |    168.34
0.80 |  30.0 |       7.0 |  2151.56 |   443.21 |    170.05
0.80 |  35.0 |       6.9 |  2151.56 |   444.07 |    170.91
0.80 |  40.0 |       6.7 |  2151.56 |   444.08 |    170.92
0.80 |  45.0 |       6.5 |  2151.56 |   443.24 |    170.08
0.80 |  50.0 |       6.3 |  2151.56 |   441.55 |    168.39
--------------------------------------------------------------
1.00 |  20.0 |       7.0 |  1377.00 |   392.58 |    119.42
1.00 |  25.0 |       7.0 |  1377.00 |   394.89 |    121.73
1.00 |  30.0 |       7.0 |  1377.00 |   396.42 |    123.26
1.00 |  35.0 |       6.9 |  1377.00 |   397.19 |    124.03
1.00 |  40.0 |       6.7 |  1377.00 |   397.20 |    124.04
1.00 |  45.0 |       6.5 |  1377.00 |   396.45 |    123.29
1.00 |  50.0 |       6.3 |  1377.00 |   394.93 |    121.77
```

Chapter 3

3. Thermal Control System Requirements

3.1. Thermal Control Of The Sail

To design a control system for the sail is not feasible. Therefore, thermal control for this part of the spacecraft means to define suitable ranges of material properties and to avoid a trajectory too close to the Sun.

Attitude control calculations [5] showed that the flip over maneuver requires approximately two hours. Thus, the backside of the sail, the so called non-reflective side, is exposed to direct sun radiation for a significant period (approximately 30 minutes). Since the equilibrium is reached after approximately 12 s, this means that this part of the trajectory results in the highest sail temperatures during spiral out operations. Because the non-reflective side has a much higher absorption coefficient than the reflective side, the temperature might be appreciably higher in this case.

The operational temperature range of the mylar-sail is from −70°C to 160°C. Below −70°C Mylar becomes brittle and above 160°C it becomes soft. To obtain maximum force, the absorption of the reflective side should be as low as possible. The best way to achieve this goal is to use aluminum for the top side of the sail. However, if we stay with our preliminary design and cover the back side with chromium, the temperature in the case 9 might exceed the temperature limit. The material properties of interest, absorptivity and emissivity, are dependent upon temperatures, wavelengths, and surface roughness. For this reason, there is a great variance in the values of these properties in the literature. Thus, the actual values will have to be measured, using a sample of the sail material. In this study we give only suitable sets of parameters for the sail, using aluminum as reflective material.

According to Ref.[1] and [6] the properties of aluminum are : 0.12 - 0.15 for the absorptivity and 0.04 - 0.09 for the emissivity. In order to provide maximum power and therefore minimum absorptivity, the absorptivity range was chosen as : 0.12 - 0.13. The ranges for the four properties and the steps which were used in the range procedure of "Tempest" are listed in Table 11.

Table 11. Material Properties

Prop.	Range	Step
ABAL	0.12 - 0.13	0.005
EMAL	0.04 - 0.09	0.005
ABCR	0.1 - 0.4	0.05
EMCR	0.1 - 0.4	0.05

The results of the calculations are shown in Table 12 on page 52 assuming that case 7 occurs and in Table 13 on page 53 without the Mars shadow case. The last columns in these tables give the minimum possible distance to Sun for the heliocentric travel in AU. Again, these calculations were made assuming aluminum as front covering and any kind of material that has the properties of the second material, whatever this material is. It is not even sure that all these materials exist. The backside materials which might fit into these sets are copper, cadmium, bronze, and cobalt. However, cadmium evaporates in vacuum at about 100°C. To verify suitability, a sample piece of sail should be manufactured and the properties should be measured.

Table 12. Suitable Property Sets (with Case 7)

```
TEMPERATURE ESTIMATION  (SAIL RANGE)

RPE :    7378.00 KM          RAE :  42378.00 KM          EA : 0.340

RPM :    4890.00 KM          RAM :   5186.47 KM          MA : 0.150

AREA :    17100.00 M**2       HHGT :      1.88 M     HDIA :      2.88 M

THETA :    35.00

| ABAL  | EMAL  | ABCR  | EMCR  | TMIN (C) | TMAX (C) | RMIN (AU) |
====================================================================
| 0.120 | 0.040 | 0.150 | 0.100 |   -69.55 |   128.47 |      0.72 |
| 0.120 | 0.040 | 0.200 | 0.100 |   -69.55 |   158.42 |      0.72 |
| 0.125 | 0.040 | 0.150 | 0.100 |   -67.46 |   128.47 |      0.74 |
| 0.125 | 0.040 | 0.200 | 0.100 |   -67.46 |   158.42 |      0.74 |
| 0.125 | 0.045 | 0.150 | 0.100 |   -69.26 |   124.96 |      0.72 |
| 0.125 | 0.045 | 0.200 | 0.100 |   -69.26 |   154.65 |      0.72 |
| 0.130 | 0.040 | 0.150 | 0.100 |   -65.43 |   128.47 |      0.75 |
| 0.130 | 0.040 | 0.200 | 0.100 |   -65.43 |   158.42 |      0.75 |
| 0.130 | 0.045 | 0.150 | 0.100 |   -67.25 |   124.96 |      0.74 |
| 0.130 | 0.045 | 0.200 | 0.100 |   -67.25 |   154.65 |      0.74 |
| 0.130 | 0.050 | 0.150 | 0.100 |   -68.99 |   121.60 |      0.72 |
| 0.130 | 0.050 | 0.200 | 0.100 |   -68.99 |   151.04 |      0.72 |
```

Table 13. Suitable Property Sets (without Case 7)

```
TEMPERATURE ESTIMATION  W/O CASE 7 (SAIL RANGE)


RPE :    7378.00 KM          RAE :  42378.00 KM          EA : 0.340

RPM :    4890.00 KM          RAM :    5186.47 KM         MA : 0.150

AREA :    17100.00 M**2       HHGT :     1.88 M     HDIA :      2.88 M

THETA :    35.00


| ABAL   | EMAL   | ABCR   | EMCR   | TMIN (C) | TMAX (C) | RMIN (AU) |
======================================================================
| 0.120  | 0.040  | 0.150  | 0.100  |   -50.49 |   128.47 |      0.72 |
| 0.120  | 0.040  | 0.150  | 0.150  |   -66.86 |    98.95 |      0.62 |
| 0.120  | 0.040  | 0.200  | 0.100  |   -50.04 |   158.42 |      0.72 |
| 0.120  | 0.040  | 0.200  | 0.150  |   -66.44 |   126.70 |      0.62 |
| 0.120  | 0.040  | 0.250  | 0.150  |   -66.03 |   149.64 |      0.62 |
| 0.120  | 0.045  | 0.150  | 0.100  |   -52.43 |   124.96 |      0.71 |
| 0.120  | 0.045  | 0.150  | 0.150  |   -68.19 |    96.54 |      0.61 |
| 0.120  | 0.045  | 0.200  | 0.100  |   -51.99 |   154.65 |      0.71 |
| 0.120  | 0.045  | 0.200  | 0.150  |   -67.78 |   124.11 |      0.61 |
| 0.120  | 0.045  | 0.250  | 0.150  |   -67.37 |   146.90 |      0.61 |
| 0.120  | 0.050  | 0.150  | 0.100  |   -54.30 |   121.60 |      0.70 |
| 0.120  | 0.050  | 0.150  | 0.150  |   -69.49 |    94.21 |      0.60 |
| 0.120  | 0.050  | 0.200  | 0.100  |   -53.86 |   151.04 |      0.70 |
| 0.120  | 0.050  | 0.200  | 0.150  |   -69.08 |   121.60 |      0.60 |
| 0.120  | 0.050  | 0.250  | 0.150  |   -68.67 |   144.25 |      0.60 |
| 0.120  | 0.055  | 0.150  | 0.100  |   -56.08 |   118.38 |      0.69 |
| 0.120  | 0.055  | 0.200  | 0.100  |   -55.65 |   147.58 |      0.69 |
| 0.120  | 0.055  | 0.250  | 0.150  |   -69.93 |   141.68 |      0.60 |
| 0.120  | 0.060  | 0.150  | 0.100  |   -57.80 |   115.29 |      0.67 |
| 0.120  | 0.060  | 0.200  | 0.100  |   -57.37 |   144.25 |      0.67 |
| 0.120  | 0.065  | 0.150  | 0.100  |   -59.45 |   112.31 |      0.66 |
| 0.120  | 0.065  | 0.200  | 0.100  |   -59.02 |   141.05 |      0.66 |
| 0.120  | 0.070  | 0.150  | 0.100  |   -61.04 |   109.44 |      0.65 |
| 0.120  | 0.070  | 0.200  | 0.100  |   -60.61 |   137.97 |      0.65 |
| 0.120  | 0.075  | 0.150  | 0.100  |   -62.57 |   106.68 |      0.65 |
| 0.120  | 0.075  | 0.200  | 0.100  |   -62.15 |   135.00 |      0.65 |
| 0.120  | 0.075  | 0.250  | 0.100  |   -61.73 |   158.42 |      0.65 |
| 0.120  | 0.080  | 0.150  | 0.100  |   -64.05 |   104.01 |      0.64 |
| 0.120  | 0.080  | 0.200  | 0.100  |   -63.63 |   132.14 |      0.64 |
| 0.120  | 0.080  | 0.250  | 0.100  |   -63.21 |   155.39 |      0.64 |
| 0.120  | 0.085  | 0.150  | 0.100  |   -65.48 |   101.44 |      0.63 |
| 0.120  | 0.085  | 0.200  | 0.100  |   -65.06 |   129.37 |      0.63 |
| 0.120  | 0.085  | 0.250  | 0.100  |   -64.64 |   152.47 |      0.63 |
| 0.120  | 0.090  | 0.150  | 0.100  |   -66.86 |    98.95 |      0.62 |
| 0.120  | 0.090  | 0.200  | 0.100  |   -66.44 |   126.70 |      0.62 |
| 0.120  | 0.090  | 0.250  | 0.100  |   -66.03 |   149.64 |      0.62 |
| 0.125  | 0.040  | 0.150  | 0.100  |   -48.26 |   128.47 |      0.74 |
| 0.125  | 0.040  | 0.150  | 0.150  |   -64.79 |    98.95 |      0.63 |
| 0.125  | 0.040  | 0.200  | 0.100  |   -47.83 |   158.42 |      0.74 |
| 0.125  | 0.040  | 0.200  | 0.150  |   -64.39 |   126.70 |      0.63 |
| 0.125  | 0.040  | 0.250  | 0.150  |   -63.99 |   149.64 |      0.63 |
| 0.125  | 0.045  | 0.150  | 0.100  |   -50.22 |   124.96 |      0.72 |
| 0.125  | 0.045  | 0.150  | 0.150  |   -66.14 |    96.54 |      0.62 |
| 0.125  | 0.045  | 0.200  | 0.100  |   -49.79 |   154.65 |      0.72 |
| 0.125  | 0.045  | 0.200  | 0.150  |   -65.74 |   124.11 |      0.62 |
| 0.125  | 0.045  | 0.250  | 0.150  |   -65.34 |   146.90 |      0.62 |
```

0.125	0.050	0.150	0.100	-52.11	121.60	0.71
0.125	0.050	0.150	0.150	-67.45	94.21	0.62
0.125	0.050	0.200	0.100	-51.68	151.04	0.71
0.125	0.050	0.200	0.150	-67.05	121.60	0.62
0.125	0.050	0.250	0.150	-66.65	144.25	0.62
0.125	0.055	0.150	0.100	-53.91	118.38	0.70
0.125	0.055	0.150	0.150	-68.71	91.95	0.61
0.125	0.055	0.200	0.100	-53.49	147.58	0.70
0.125	0.055	0.200	0.150	-68.32	119.17	0.61
0.125	0.055	0.250	0.150	-67.92	141.68	0.61
0.125	0.060	0.150	0.100	-55.64	115.29	0.69
0.125	0.060	0.150	0.150	-69.94	89.76	0.60
0.125	0.060	0.200	0.100	-55.22	144.25	0.69
0.125	0.060	0.200	0.150	-69.55	116.82	0.60
0.125	0.060	0.250	0.150	-69.16	139.19	0.60
0.125	0.060	0.300	0.150	-68.77	158.42	0.60
0.125	0.065	0.150	0.100	-57.31	112.31	0.68
0.125	0.065	0.200	0.100	-56.89	141.05	0.68
0.125	0.065	0.300	0.150	-69.97	155.89	0.59
0.125	0.070	0.150	0.100	-58.92	109.44	0.67
0.125	0.070	0.200	0.100	-58.50	137.97	0.67
0.125	0.075	0.150	0.100	-60.46	106.68	0.66
0.125	0.075	0.200	0.100	-60.05	135.00	0.66
0.125	0.075	0.250	0.100	-59.64	158.42	0.66
0.125	0.080	0.150	0.100	-61.96	104.01	0.65
0.125	0.080	0.200	0.100	-61.55	132.14	0.65
0.125	0.080	0.250	0.100	-61.14	155.39	0.65
0.125	0.085	0.150	0.100	-63.40	101.44	0.64
0.125	0.085	0.200	0.100	-62.99	129.37	0.64
0.125	0.085	0.250	0.100	-62.59	152.47	0.64
0.125	0.090	0.150	0.100	-64.79	98.95	0.63
0.125	0.090	0.200	0.100	-64.39	126.70	0.63
0.125	0.090	0.250	0.100	-63.99	149.64	0.63
0.130	0.040	0.150	0.100	-46.10	128.47	0.75
0.130	0.040	0.150	0.150	-62.79	98.95	0.64
0.130	0.040	0.200	0.100	-45.67	158.42	0.75
0.130	0.040	0.200	0.150	-62.39	126.70	0.64
0.130	0.040	0.250	0.150	-62.01	149.64	0.64
0.130	0.045	0.150	0.100	-48.08	124.96	0.74
0.130	0.045	0.150	0.150	-64.15	96.54	0.64
0.130	0.045	0.200	0.100	-47.66	154.65	0.74
0.130	0.045	0.200	0.150	-63.76	124.11	0.64
0.130	0.045	0.250	0.150	-63.37	146.90	0.64
0.130	0.050	0.150	0.100	-49.98	121.60	0.72
0.130	0.050	0.150	0.150	-65.47	94.21	0.63
0.130	0.050	0.200	0.100	-49.56	151.04	0.72
0.130	0.050	0.200	0.150	-65.08	121.60	0.63
0.130	0.050	0.250	0.150	-64.70	144.25	0.63
0.130	0.055	0.150	0.100	-51.80	118.38	0.71
0.130	0.055	0.150	0.150	-66.74	91.95	0.62
0.130	0.055	0.200	0.100	-51.39	147.58	0.71
0.130	0.055	0.200	0.150	-66.36	119.17	0.62
0.130	0.055	0.250	0.150	-65.98	141.68	0.62
0.130	0.060	0.150	0.100	-53.55	115.29	0.70
0.130	0.060	0.150	0.150	-67.98	89.76	0.61
0.130	0.060	0.200	0.100	-53.14	144.25	0.70
0.130	0.060	0.200	0.150	-67.60	116.82	0.61
0.130	0.060	0.250	0.150	-67.22	139.19	0.61
0.130	0.060	0.300	0.150	-66.85	158.42	0.61
0.130	0.065	0.150	0.100	-55.23	112.31	0.69
0.130	0.065	0.150	0.150	-69.19	87.63	0.61
0.130	0.065	0.200	0.100	-54.83	141.05	0.69
0.130	0.065	0.200	0.150	-68.81	114.53	0.61
0.130	0.065	0.250	0.150	-68.43	136.77	0.61

0.130	0.065	0.300	0.150	-68.06	155.89	0.61
0.130	0.070	0.150	0.100	-56.85	109.44	0.68
0.130	0.070	0.200	0.100	-56.45	137.97	0.68
0.130	0.070	0.200	0.150	-69.98	112.31	0.60
0.130	0.070	0.250	0.150	-69.60	134.42	0.60
0.130	0.070	0.300	0.150	-69.23	153.43	0.60
0.130	0.075	0.150	0.100	-58.42	106.68	0.67
0.130	0.075	0.200	0.100	-58.02	135.00	0.67
0.130	0.075	0.250	0.100	-57.62	158.42	0.67
0.130	0.080	0.150	0.100	-59.92	104.01	0.66
0.130	0.080	0.200	0.100	-59.53	132.14	0.66
0.130	0.080	0.250	0.100	-59.13	155.39	0.66
0.130	0.085	0.150	0.100	-61.38	101.44	0.65
0.130	0.085	0.200	0.100	-60.98	129.37	0.65
0.130	0.085	0.250	0.100	-60.59	152.47	0.65
0.130	0.090	0.150	0.100	-62.79	98.95	0.64
0.130	0.090	0.200	0.100	-62.39	126.70	0.64
0.130	0.090	0.250	0.100	-62.01	149.64	0.64

3.2. Thermal Control Of The Hub

In order to set the requirements for the thermal control system of the hub, we must determine the heat flux needed to maintain the temperature inside the hub within the operating ranges of the equipment. A simple finite element code was developed to calculate the temperature distribution over the hub in cases 1 and 8. Using these distributions the heat fluxes were calculated.

3.2.1. Discretisation Of The Hub

The surface of the hub was divided into 364 plates of equal area plus a top and a bottom disk. Since the problem is symmetrical with respect to the minor axis of the cylinder, only one half of the hub was used for this procedure. The 364 plates are distributed in 14 rows and 26 columns. In addition each plate was divided into an inner an outer part (i.e. the honeycomb was cut midway between the two sheet layers). The half disks on top and bottom of the hub were assumed to have constant temperatures. Furthermore, all of the plates were assumed to have constant temperatures. The last part of the hub is a small cylinder inside the hub, which is wrapped into a thermal blanket. This cylinder contains the equipment which has to be held within a narrow temperature range. Figure 22 on page 57 shows the discretisation of the hub.

The disk areas which are perpendicular to the incident radiation yield :

$$A_{\perp} = \frac{\pi D^2 \cos(\theta)}{8} \tag{23}$$

See Chapter 2 for nomenclature.

The plate areas which are perpendicular to the irradiation only need to be calculated in one row and, due to symmetry, in one quarter of the cylinder. These areas are given by :

$$A_{\perp i} = \frac{D\,(\cos(\alpha_i) - \cos(\alpha_{i-1})) \times H \sin(\theta)}{2 \times 14} \tag{24}$$

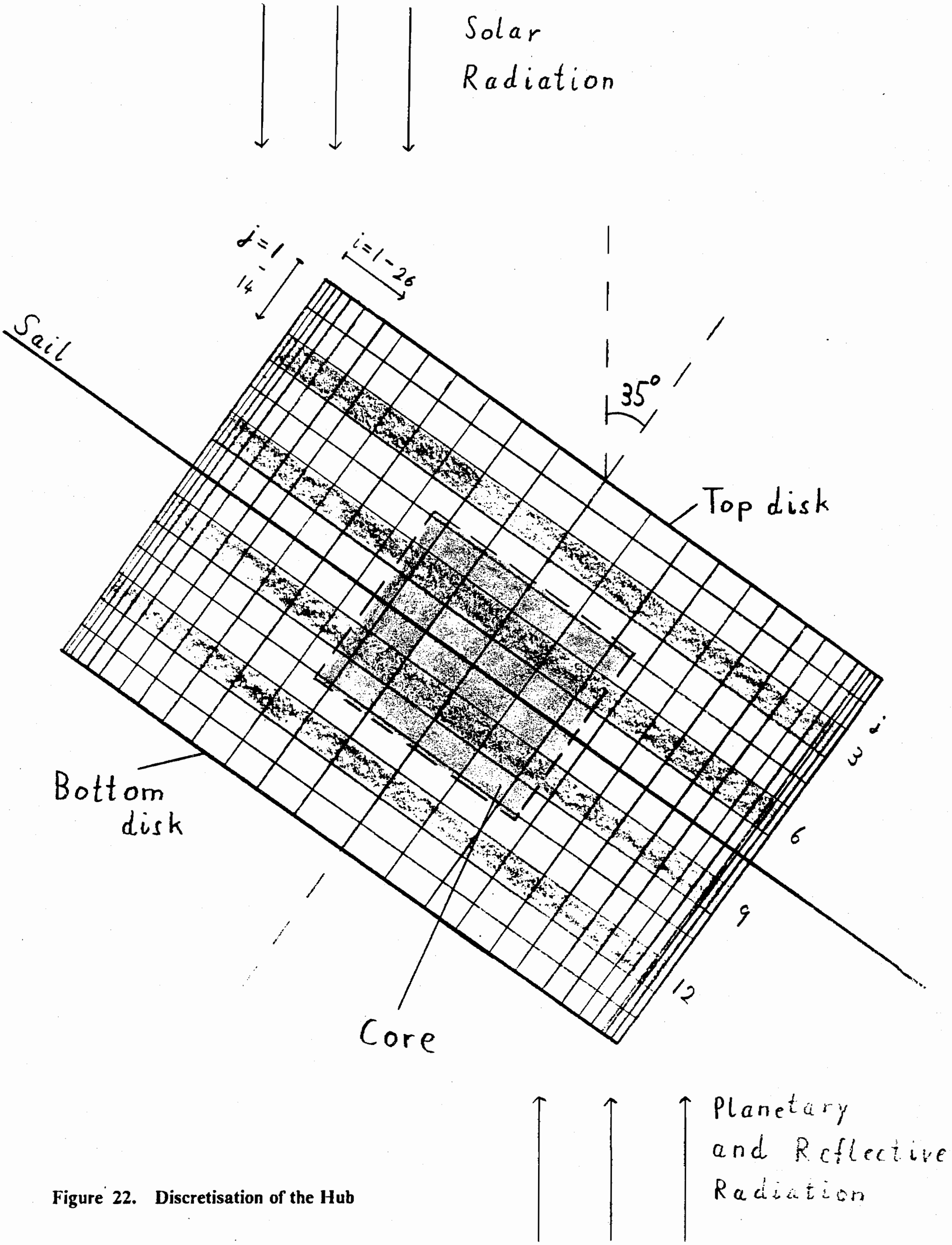


Figure 22. Discretisation of the Hub

The areas perpendicular to the radiation reflected off the sail have the same values. The definition of the angle α is given in the figure below.

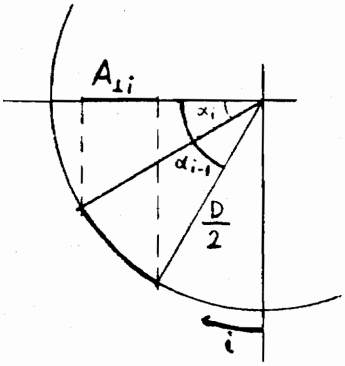


Figure 23. Definition of Angles

The radiating areas are simply the surface areas of the parts. Thus :

$$
\begin{aligned}
A_{r,disk} &= \frac{\pi D^2}{8} \\
A_{r,plate} &= \frac{\pi D H}{2 \times 364}
\end{aligned}
\tag{25}
$$

Additional Constants

In addition to the constants defined in Chapter 2 (orbits, planets, geometry of the spacecraft) we need to define some constants of the material. The geometry of the honeycomb gives us the thickness of the sheet layers d, the length of the honeycomb l_{hc}, and the area perpendicular to the conduction in the radial direction F_{per}. These constants have the following values :

$$
\begin{aligned}
d &= 0.000025\,\text{m} \\
l_{hc} &= 0.01\,\text{m} \\
F_{per} &= 0.03125\text{m}^2
\end{aligned}
$$

The thermal conductivity λ_{Al}, the specific heat capacity of aluminum and the area density of honeycomb are:

$$\lambda_{Al} = 204 \frac{\mathrm{W}}{\mathrm{m\,K}}$$

$$c_p = 879 \frac{\mathrm{J}}{\mathrm{kg\,K}}$$

$$\rho_{\mathrm{hc}} = 0.855 \frac{\mathrm{kg}}{\mathrm{m}^2}$$

The mass of the disks is given by : $m_{disk} = \frac{\rho_{\mathrm{hc}}\, \pi\, D^2}{8}$.

And the mass of each plate yields : $m_{plate} = \frac{\rho_{\mathrm{hc}}\, H\, D\, \pi}{4 \times 26 \times 14}$

The conductive heat flux is given by (Ref. [7]) :

$$\dot{q} = \frac{\lambda_{Al}\, F_{per}}{l} \times \Delta T \tag{26}$$

where F_{per} = Area perpendicular to the heat exchange

l = length between two nodes

Except for ΔT all the terms in (26) are constants; therefore, we may re-arrange (26) :

$$\dot{q} = c\, \Delta T \tag{27}$$

Thus we need three different constants c for the three directions of conduction (angular, axial, radial; see Figure 24 on page 60). Assuming that the conduction mainly takes place in the sheet layers and that the conduction in the honeycomb takes place only in the radial direction, the c's for the angular and axial direction are given by :

$$c_i = \lambda_{Al} \frac{H\, d}{14} \times \frac{2 \times 26}{\pi\, D} \tag{28}$$

$$c_j = \lambda_{Al} \frac{\pi\, D\, d}{2 \times 26} \times \frac{14}{H} \tag{29}$$

For the radial direction we have :

$$c_r = \lambda_{Al} \frac{\pi\, D\, H\, F_{per}}{2 \times 26 \times 14} \times \frac{1}{l_{\mathrm{hc}}} \tag{30}$$

The figure below shows the directions of the conductive heat exchange.

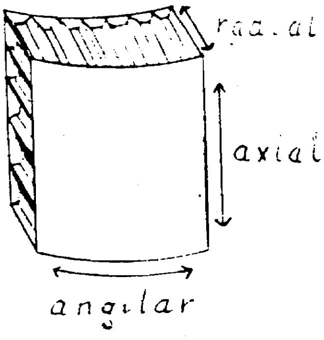


Figure 24. Directions of Conduction

3.2.2. Thermal Equilibrium

There are three types of heat exchange between the top disk and its environment. First of all is the radiative heat exchange between the spacecraft and space, i.e. the incident solar radiation and the outgoing space radiation. Second, there is the radiative heat exchange between the disk and the core part. And finally there is the conductive heat exchange between the disk and the neighboring plates. The same applies for the bottom disk, with reflected and planetary radiation substituted for the solar radiation.

The incident radiation (solar, reflected, planetary) and the space radiation were calculated in the same way as in Chapter 2. The radiative heat exchange between the disks and the core was assumed to be "radiative exchange between two parallel plates". Assuming, that the exchanging area is given by the mean area of the disk and the top disk of the core, we get according to [7] :

$$\dot{q}_{disk,core} = \frac{\sigma}{\frac{1}{\varepsilon_{Al}} + \frac{1}{\varepsilon_{Tb}} - 1} \times \frac{\pi (D^2 + D^2_{core})}{16} \times (T^4_{disk} - T^4_{core}) \qquad (31)$$

where : ε_{Al} = Emissivity of the uncovered part of the hub, assumed to be 0.07

ε_{Tb} = Emissivity of the thermal blanket, assumed to be 0.07

The conductive heat exchange between disk and plate was computed for each plate using :

$$\dot{q}_{disk,plate,i} = 2 \times c_j \, (T_{disk} - T_{platei}) \tag{32}$$

The factor 2 is necessary since the distance between the two nodes is only half as long as the distance between two plate nodes. Adding all 26 conductive exchange distributions up we get the total conductive heat exchange between the disk and the plates. The resulting temperature after a time period Δt is given by :

$$T_{disk,new} = \frac{(\Sigma \dot{q}) \Delta t}{c_p \, m_{disk}} + T_{disk,old} \tag{33}$$

The heat exchange of the outer plates results from the incident radiation of the sun, the planets, and the reflection off the planets atmosphere. In addition there is conductive and radiative exchange between the outer and inner plates. Furthermore, there is conductive heat exchange between each plate and its four neighboring plates. Again, the radiative contributions on the outer side are calculated by the methods explained in Chapter 2. Care must be taken in the evaluation of the incident radiation on a particular plate. Due to shadow, for instance, the plates on the backside of the hub, and the plates on the lower part of the hub will not receive any solar radiation. This problem was taken into account in the development of "TEMPEST". The radiative exchange between the outer and inner plates was computed by :

$$\dot{q}_{r,out,in} = \frac{\sigma}{\frac{1}{\varepsilon_{Al}} + \frac{1}{\varepsilon_{Al}} - 1} \times \frac{\pi \, D \, H}{2 \times 14 \times 26} (T^4_{out} - T^4_{in}) \tag{34}$$

and the conductive exchange between the two parts of the plate is given by :

$$\dot{q}_{c,out,in} = c_r \, (T_{out} - T_{in}) \tag{35}$$

The four in-plane conductive exchanges yield :

$$\begin{aligned}\dot{q}_{i-1,i} &= c_i\,(T_{i-1} - T_i)\\ \dot{q}_{i,i+1} &= c_i\,(T_i - T_{i+1})\\ \dot{q}_{j-1,j} &= c_j\,(T_{j-1} - T_j)\\ \dot{q}_{j,j+1} &= c_j\,(T_j - T_{j+1})\end{aligned} \qquad (36)$$

The new temperatures of the outer plates were calculated by substituting the mass of one plate and the temperatures of the plate in Eq.(33).

The inner plates exchange heat with the outer plates, with the plates next to them (in-plane conduction), and with the core. The heat exchange with the outer plates is explained above. The sign , though, must be changed, because the heat flux is in the opposite direction. The in-plane conductive heat exchange between a plate and its neighbors is explained above. The radiative exchange between the inner plates and the core is, using the assumptions for $\dot{q}_{disk,core}$, given by :

$$\dot{q}_{plate,core} = \frac{\sigma}{\frac{1}{\varepsilon_{Al}} + \frac{1}{\varepsilon_{Tb}} - 1} \times \frac{\pi\,(D\,H + D_{core}\,H_{core})}{4 \times 14 \times 26} \times (T^4_{plate} - T^4_{core}) \qquad (37)$$

Applying (33) we get the new temperatures of the inner plates. The heat flux contributions towards a plate and their assumed directions are shown in Figure 25 on page 63.

3.2.3. Calculation Of The Equilibrium Temperatures

Assumptions

T = const. over the disks

T = const. over the plates

The in-plane conduction takes place only in the sheet layers, not in the honeycomb

All radiative exchanges between plates and core as well as between outer and inner plates are "radiative heat exchanges between two parallel surfaces"

Radiation from plate to plate and from disk to plate is negligible

The core has a constant uniform temperature (perfect conductor)

Internally dissipated heat = 10 W

Equipment is contained in a "core cylinder" of 1 m diameter and 0.8 m height

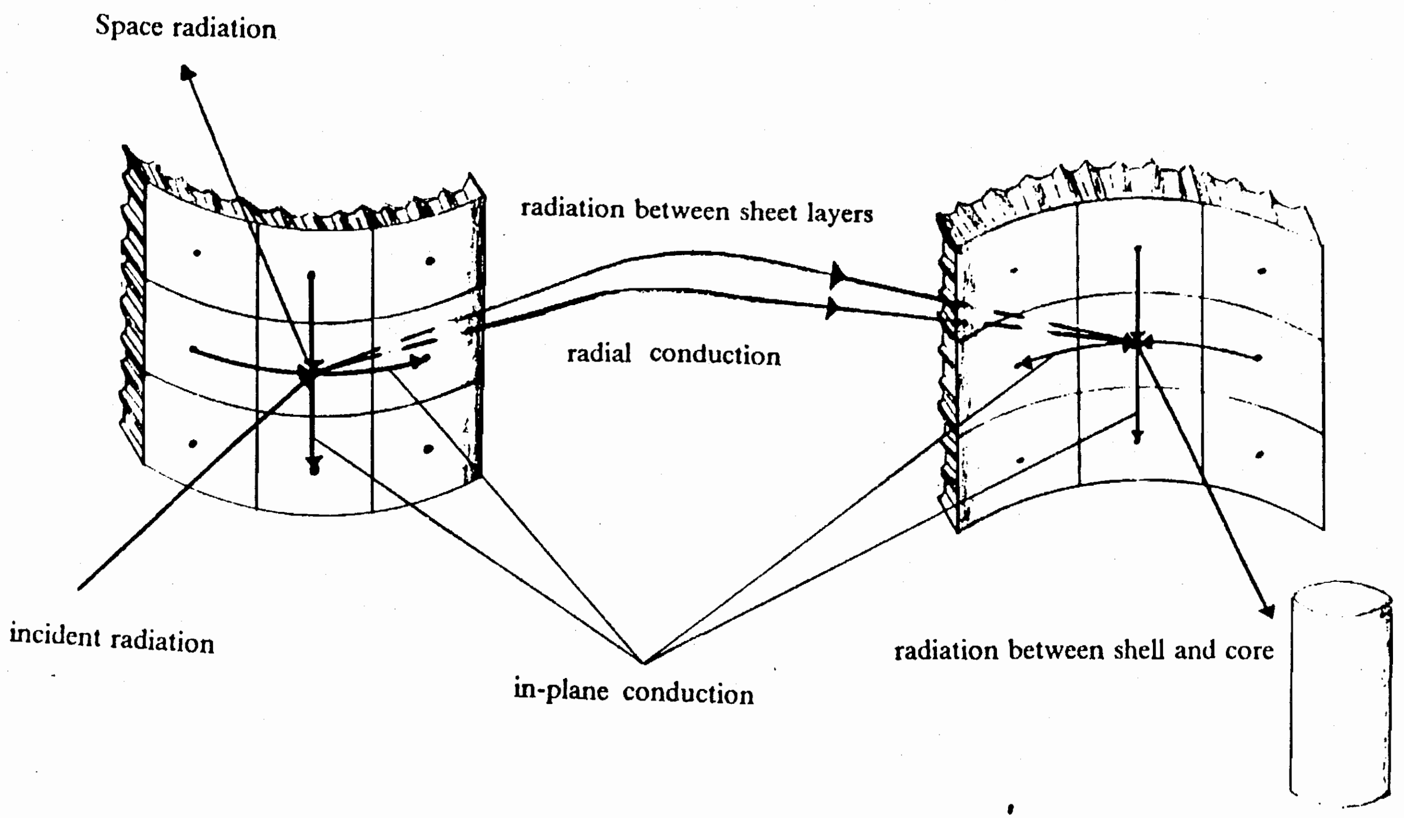


Figure 25. Heat Flux Contributions

Using the above explained procedures, the temperatures for the two disks and the 364 plates were calculated. This was done for four different cases :

A) The spacecraft in the case 1 (in Earth orbit)

B) The spacecraft far away from Earth, at Earth distance from the sun (at Earth distance)

C) The spacecraft far away from Mars, at Mars distance from the sun (at Mars distance)

D) The spacecraft in the case 8 (in Mars orbit)

To avoid an overrun of the thermodynamic equilibrium, the time step was set to 0.5 s. The operational temperature range the spacecraft equipment is approximately 273.16 K - 313.16 K (Ref. [5]). This range was chosen for this study, even though a few components might have slightly different temperature ranges. Obviously, the temperatures will be higher at Earth than at Mars. Therefore, the core was assumed to have a constant temperature of 313.16 K at Earth distance and in Earth orbit, and a constant temperature of 273.16 at Mars distance and in Mars orbit. The initial temperature of the hub (all parts) was set to the same value. To evaluate how long it takes to reach the equilibrium temperatures of each part, a computation of the warm-up and cool-down times was performed. Since the disks have the highest mass, and therefore the highest heat capacity, they need the longest time to change their temperatures significantly. For this reason, the warm-up and cool-down times were calculated for the disks. Due to the lack of incident radiation in cases B and C, the equilibrium temperature of the bottom disk would be 0 K. This is not a very realistic assumption, therefore the calculations were made for the cases A and D, even though the bottom disk equilibrium temperatures are probably lower in cases B and C. The disk equilibrium temperatures were calculated by means of equation (10) and turned out to be :

$$T_{top,earth} = 407.19\,K$$

$$T_{bottom,earth} = 134.92\,K$$

$$T_{top,mars} = 329.34\,K$$

$$T_{bottom,earth} = 144.02\,K$$

The temperature decay plots are shown in Figure 26 on page 66 through Figure 29 on page 69 for the cases A and D.

In order to save cpu time, the time for the evaluation of the hub temperature distribution was chosen to be 4 h = 14400 s. As it can be seen in the plots, the temperatures of the disks are reasonably close to their equilibrium temperatures after this time. Since the time step was 0.5 s, this results in 28800 iterations for each of the four cases. The temperature distribution over four particular rows was plotted and is shown in Figure 30 on page 70 through Figure 33 on page 73 for the four cases. Adding up all radiative heat exchange contributions between core and hub (using Eq.(37) for each plate and Eq.(31) for both disks) we get the total heat exchange between the core and its environment. Due to the fact that we used only half the cylinder for our calculations we have to multiply these values by 2 in order to get the heat flux between the core and the honeycomb cylinder.

Cooling systems are very heavy; therefore we tried to avoid the need for such a system. The hottest calculated case is obviously case A; thus, it would be the case where we would need a cooling system most. The absorptivity and emissivity of the outer surface of the hub were chosen to keep the average temperature of the hub slightly under the 313.16 K margin. This results in a very small outward heat flux and ensures that the core temperature stays below the maximum operating temperature of the equipment. This ensures that we do not need a cooling system, however, a heating system will have to provide more energy than it would have to for a configuration with lower emissivity of the outer surface.

In this study an absorptivity of 0.145 and an emissivity of 0.105 were used. These values may be attainable with aluminum (roughened or anodized). To verify aluminum as suitable for our purpose, however, a sample piece of material must be manufactured and tested. Using the aforementioned values, the maximum heat flux yields 44.25 W. This is the maximum heat flux that is needed to maintain the temperature inside the core within the operating range of the equipment. Assuming an internal heat dissipation of approximately 10 W, the heating system must be able to provide about 35 W of thermal energy near Mars.

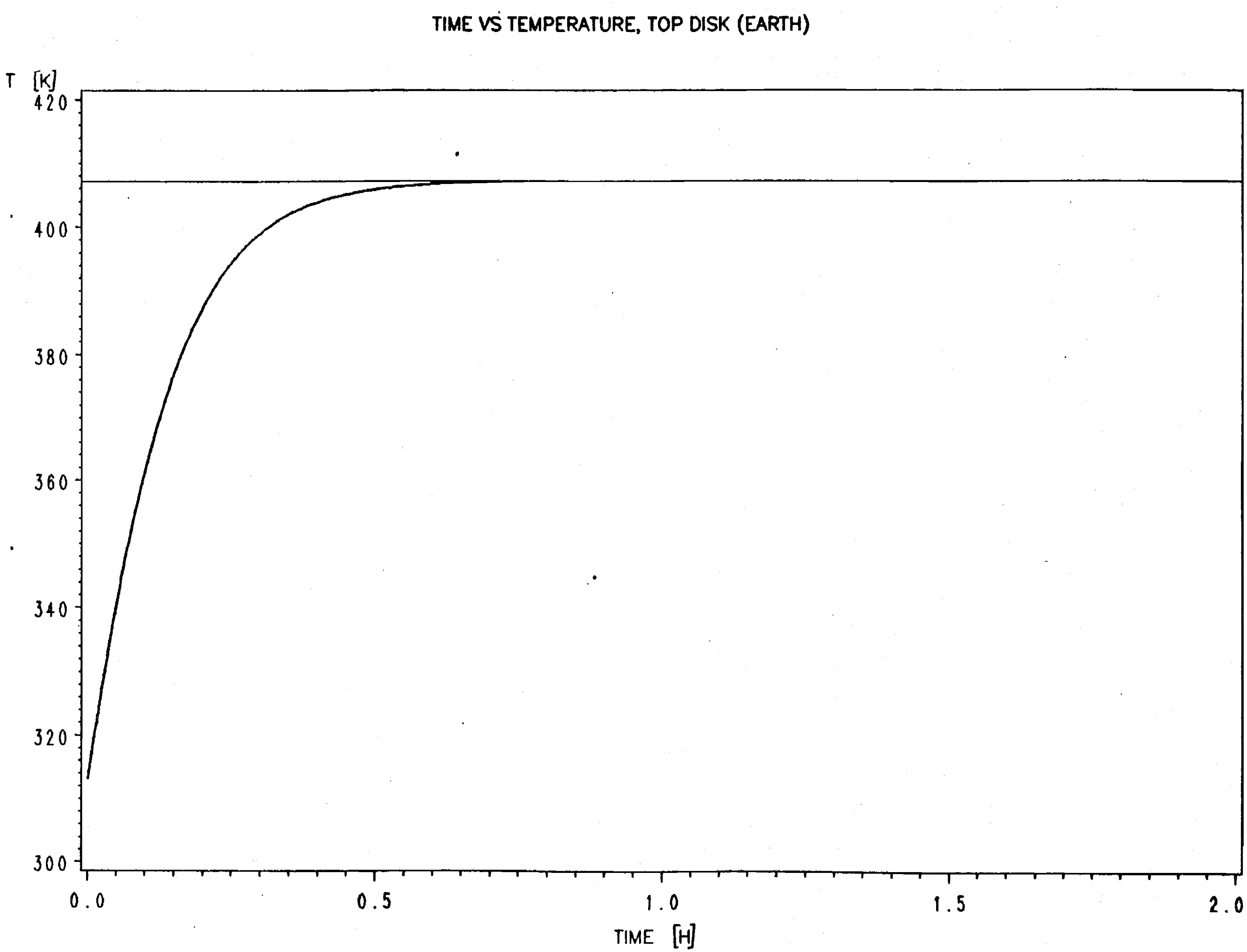


Figure 26. Temperature Variation in Earth Orbit - Top Disk

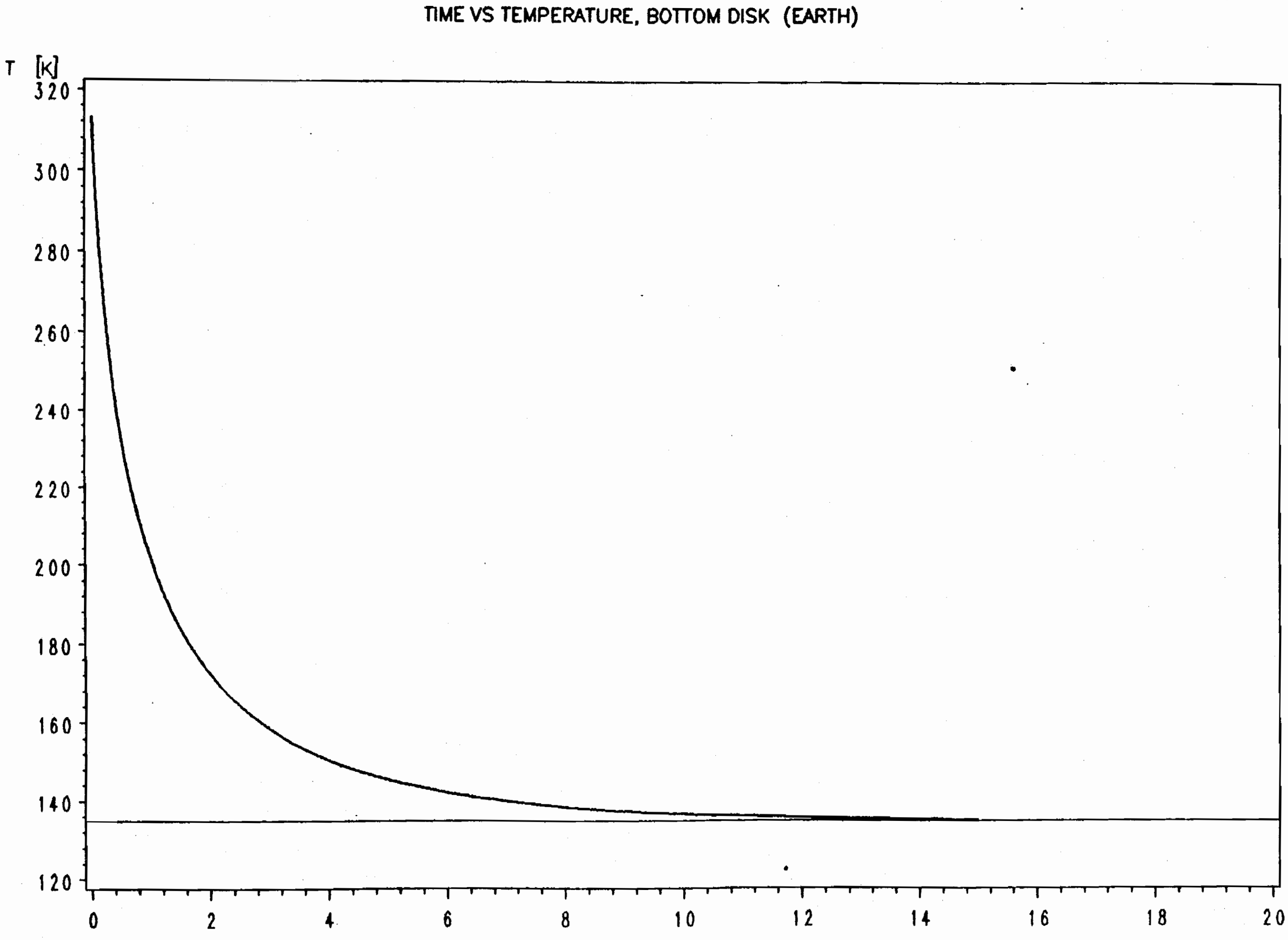


Figure 27. Temperature Variation in Earth Orbit - Bottom Disk

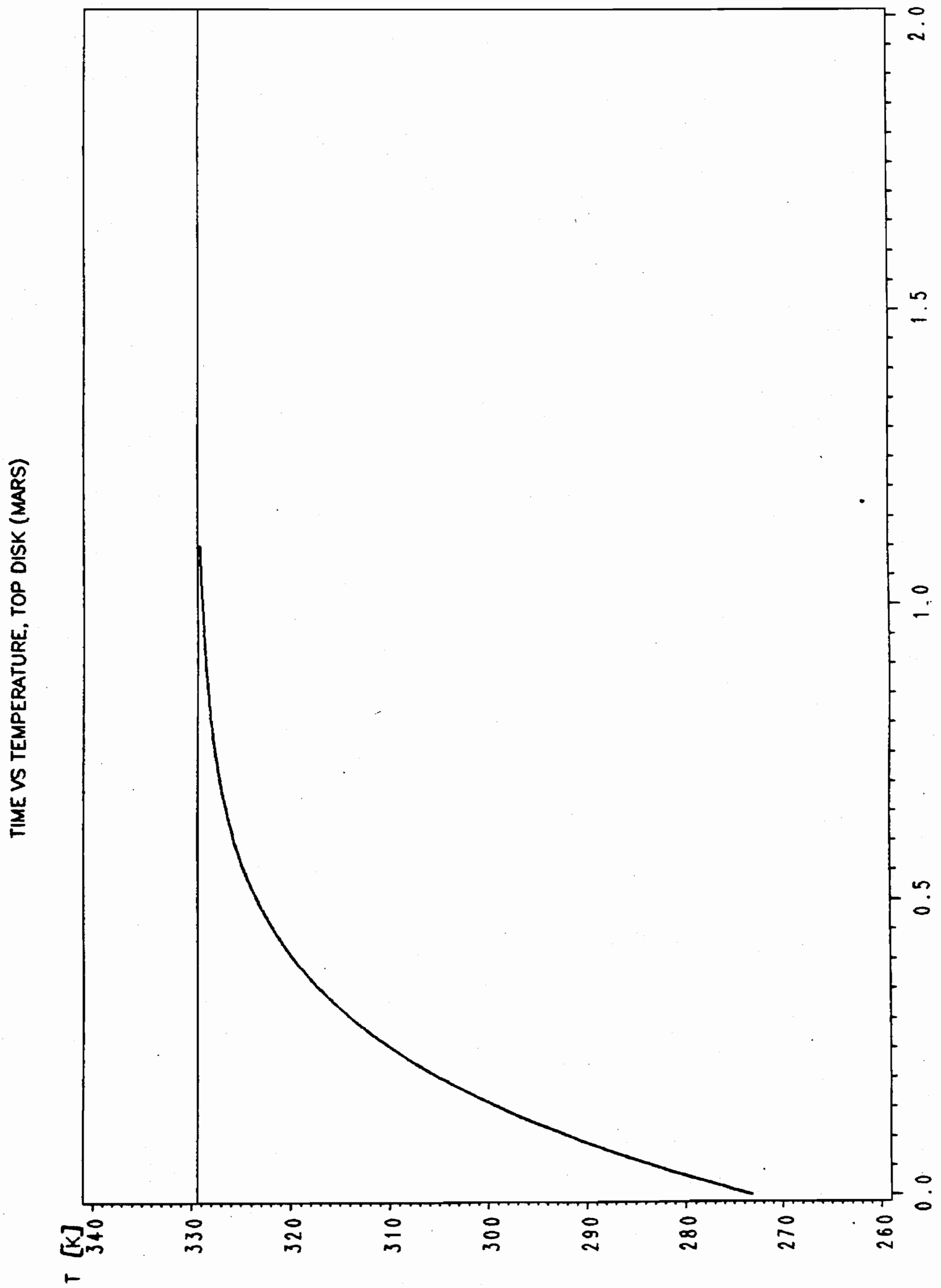


Figure 28. Temperature Variation in Mars Orbit - Top Disk

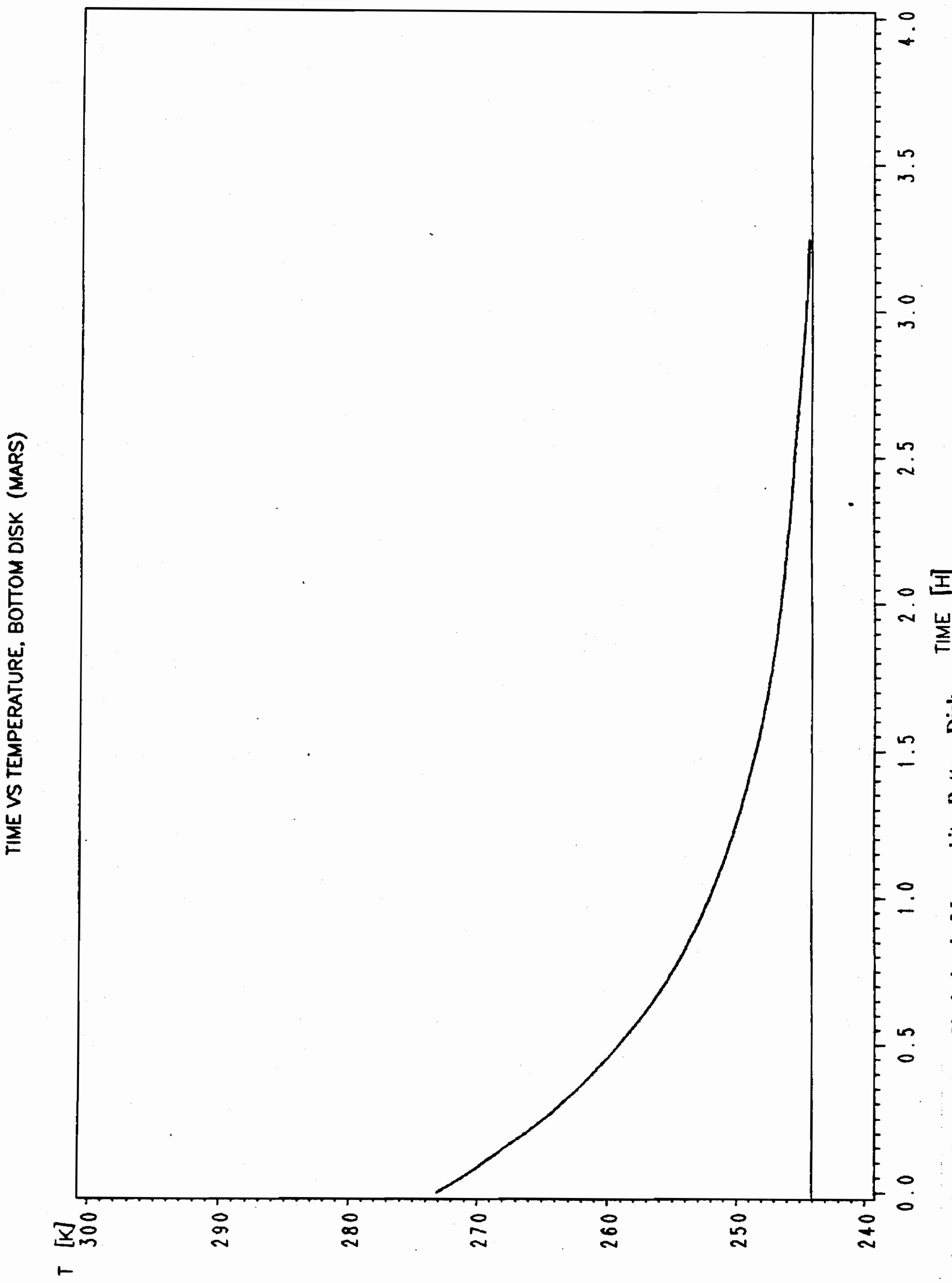
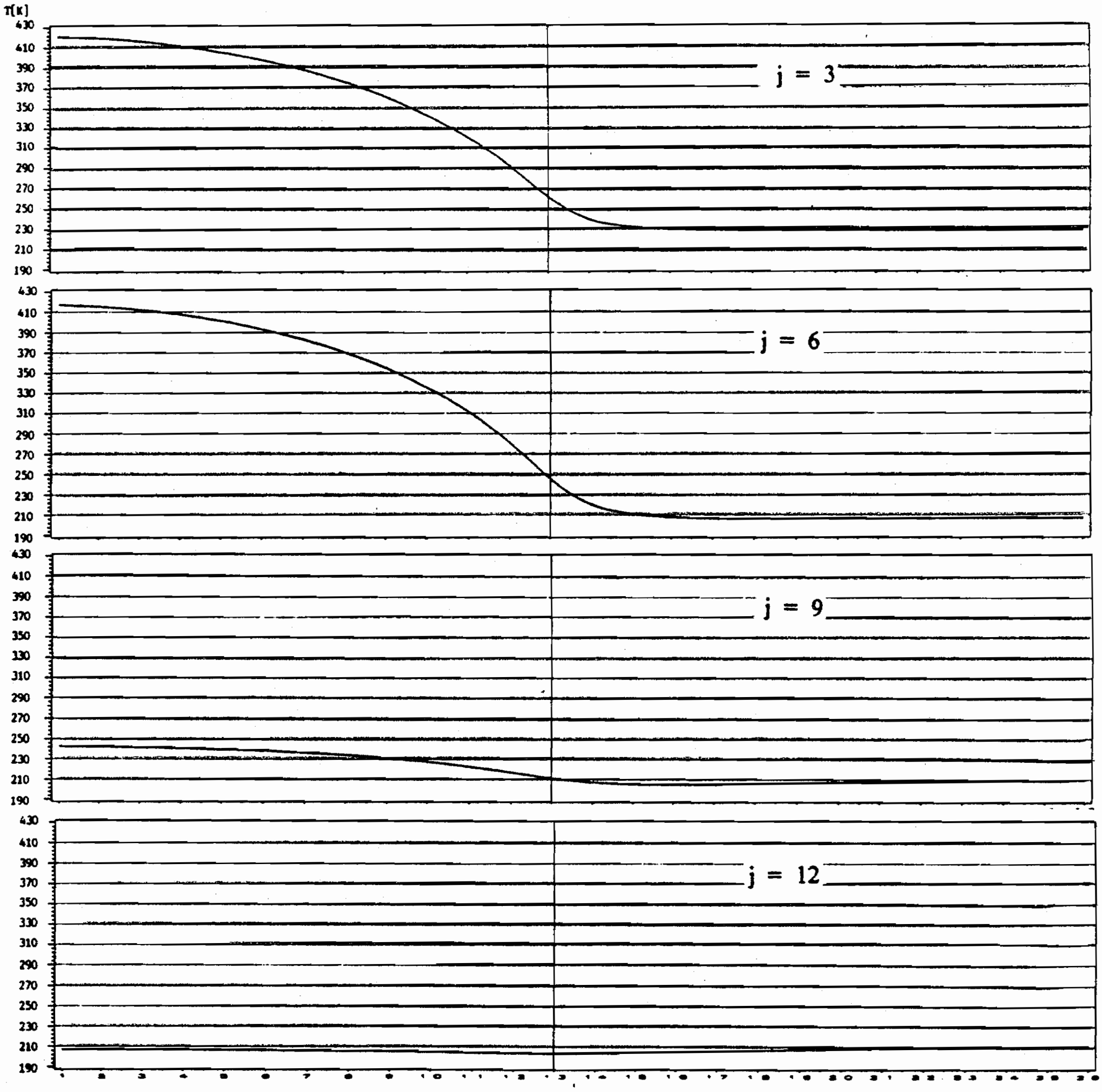


Figure 29. Temperature Variation in Mars orbit - Bottom Disk

$T_{\text{Top disk}} = 393.04 \text{ K}$



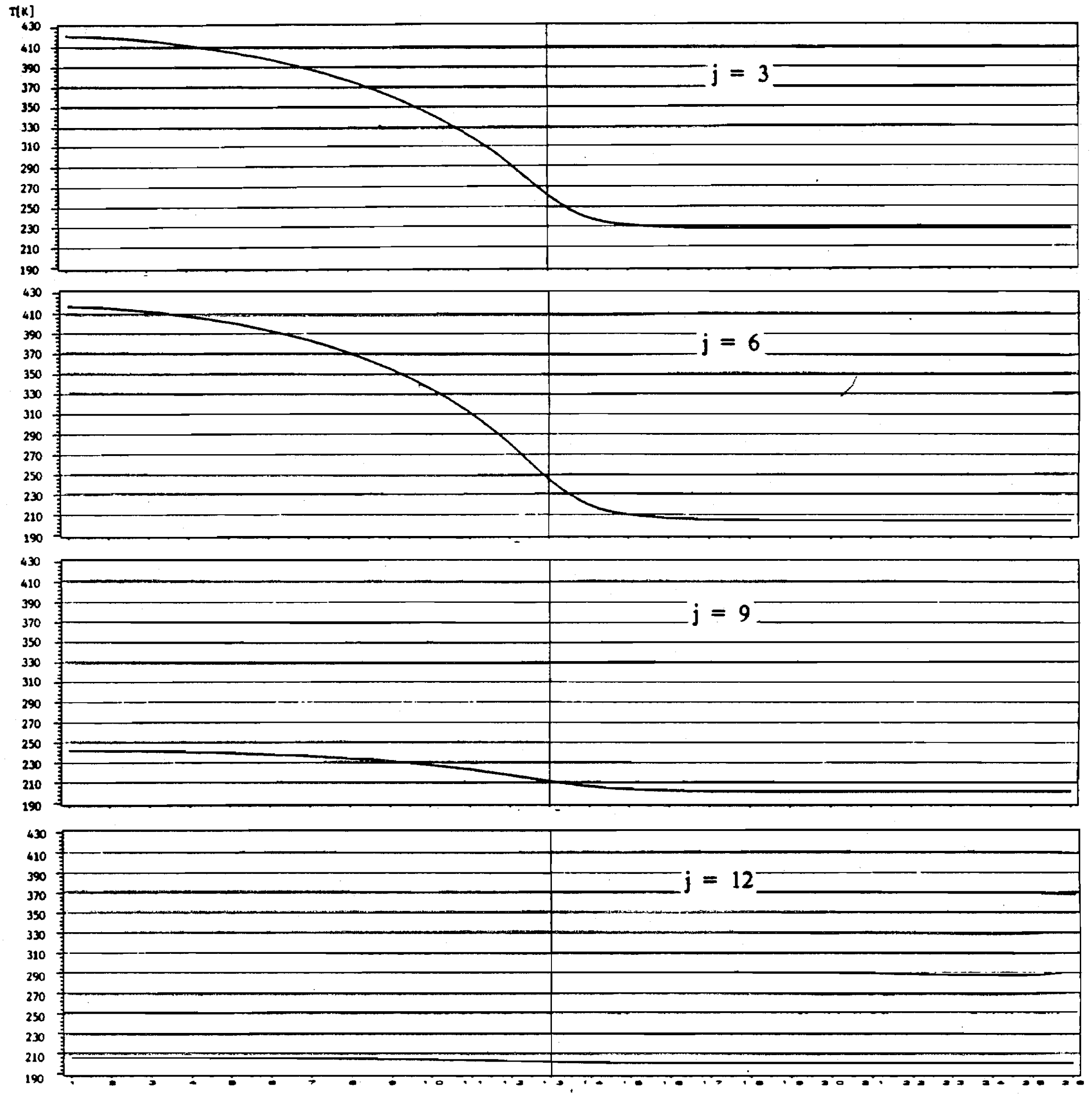
$T_{\text{Bottom disk}} = 207.88 \text{ K}$

$T_{\text{internal}} = 313.16 \text{ K}$

Heat exchange : 3.859 W core to case

Figure 30. Temperature Distribution over the Hub. Spacecraft in Earth Orbit

$T_{\text{Top disk}} = 393.02\ \text{K}$



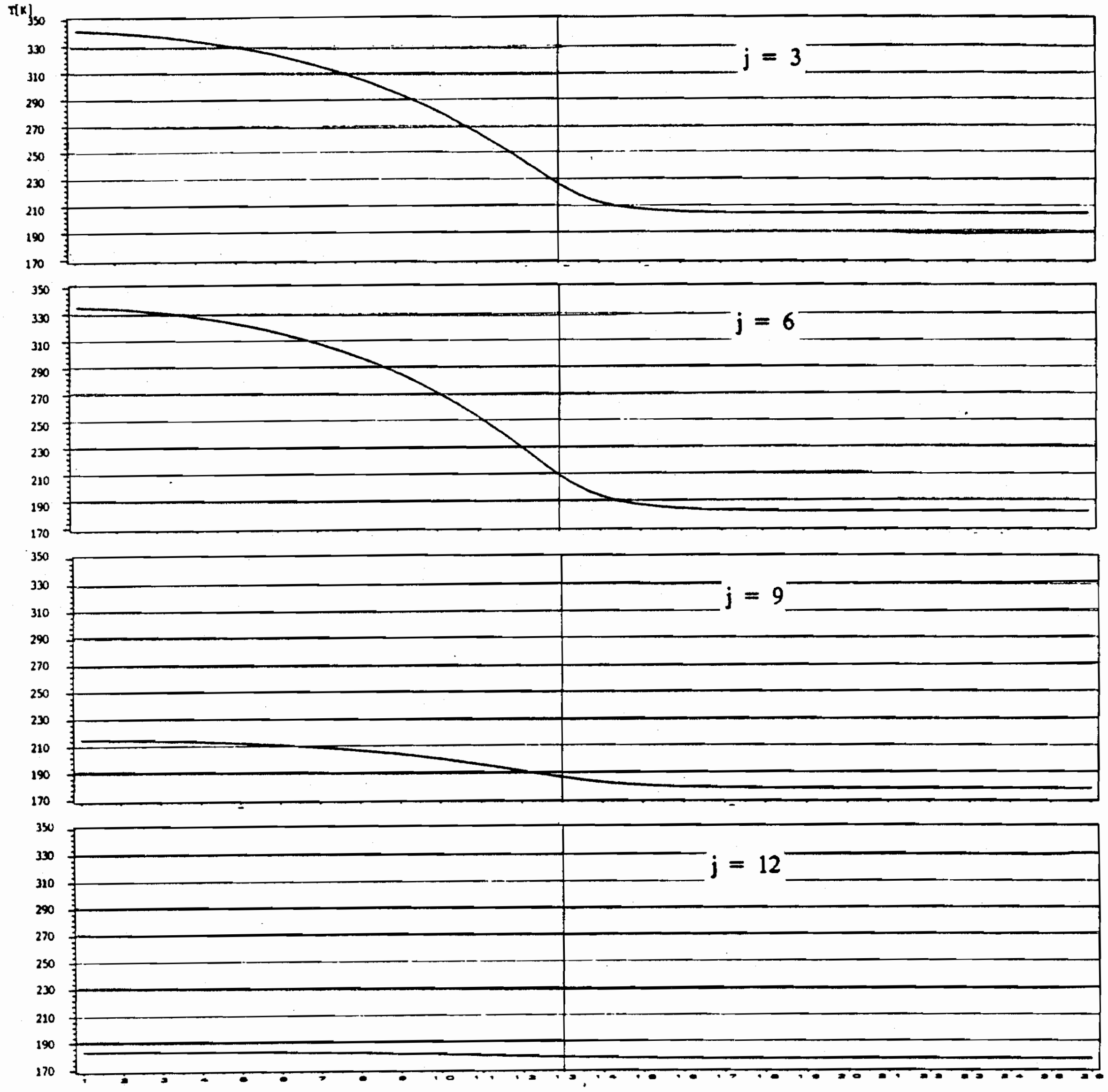
$T_{\text{Bottom disk}} = 199.69\ \text{K}$

$T_{\text{internal}} = 313.16\ \text{K}$

Heat exchange : 7.785 W core to case

Figure 31. Temperature Distribution over the Hub. Spacecraft at Earth Distance

$T_{\text{Top disk}} = 318.65\ \text{K}$



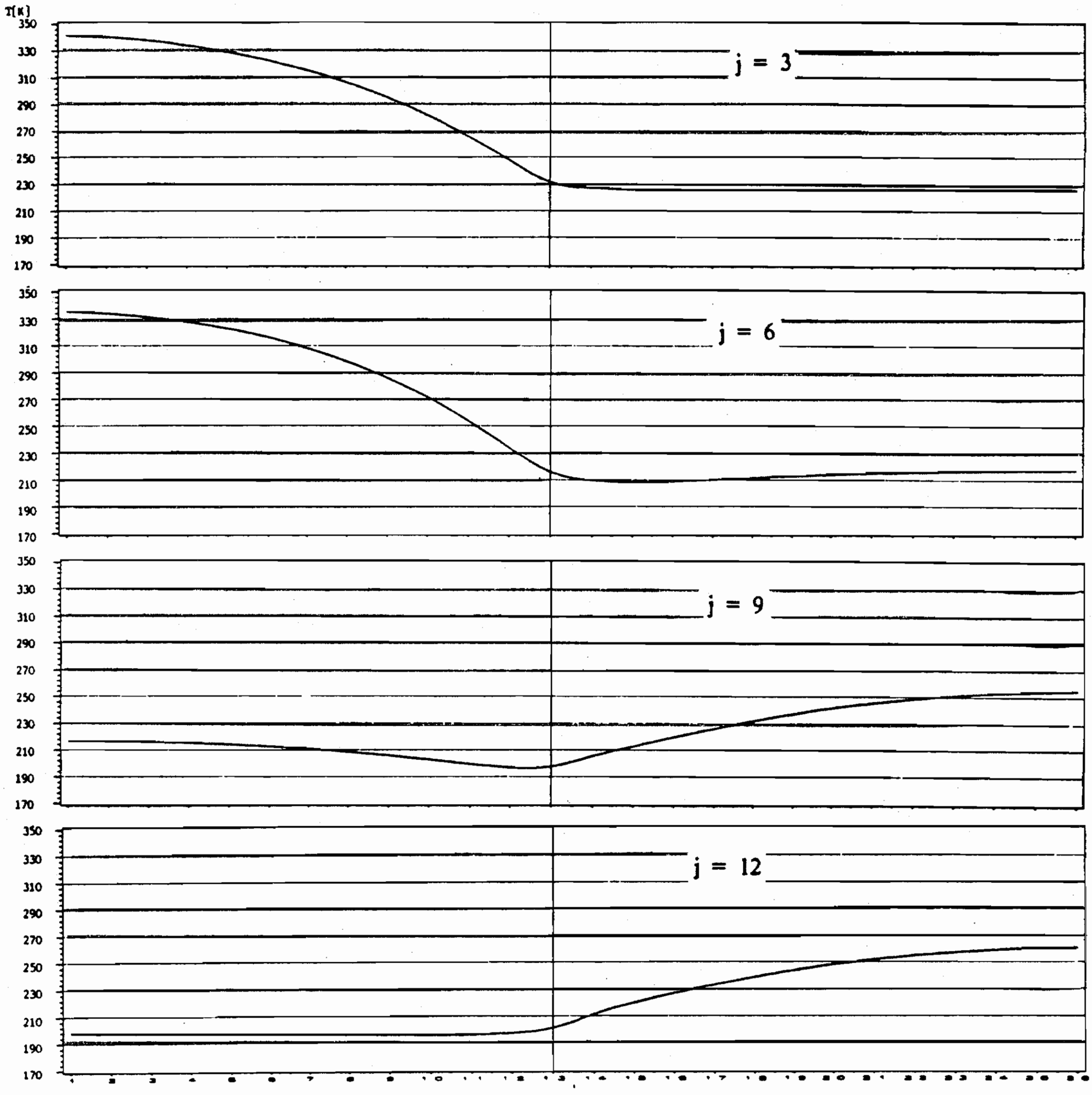
$T_{\text{Bottom disk}} = 176.51\ \text{K}$

$T_{\text{internal}} = 273.16\ \text{K}$

Heat exchange : 44.246 W core to case

Figure 32. Temperature Distribution over the Hub. Spacecraft at Mars Distance

$T_{\text{Top disk}} = 319.26\ \text{K}$



$T_{\text{Bottom disk}} = 248.26\ \text{K}$

$T_{\text{internal}} = 273.16\ \text{K}$

Heat exchange : 3.11 W core to case

Figure 33. Temperature Distribution over the Hub, Spacecraft in Mars Orbit

3.3. Conclusions

The optical properties of the sail covers must lie within the ranges given in section 3.1.. Furthermore, the heliocentric transfer must not bring the spacecraft closer to the sun than the minimum distance given in the tables.

Since the radiation inside the hub (plate to plate and disk to plate) was neglected in this study, the real temperature distribution might be smoother than the plots show. However, the error in the calculation of the maximum heat flux is probably very small; therefore, the requirements for the heating system are probably valid within reasonable margins of error. It was shown that a mission to Mars without a cooling system is possible. The heating system must be able to provide 35 W of thermal energy for operation near Mars. In contrast to the assumption of being a perfect conductor, the core is certainly not a perfect conductor; for this reason, a temperature gradient over the core is likely to exist. This results in the fact that the lower hub might need more heat than the upper hub or vice versa. Thus, the system must be capable of distributing the heat non-uniformly over the hub.

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Appendix A

The Fortran Program ″Tempest″

Program Description

The following code was developed and used throughout this study. It contains the equations and algorithms which are described in this report. The output of each subroutine will be written in different output files. The name and channel number of each output put file appear on the screen when the program has terminated the subroutine. The code contains no file definitions; therefore, these definitions must be included if the program is used on machines other than the VT-Mainframe or equivalent computers. On the VT-Mainframe the program must be started using the ″TEMPRUN″ start batch. The menu point 5 enables the user to read the output files without leaving the program. The input data for ″Tempest″ is given and explained in the file ″Param input″ on channel 8.

Program Listing

```
*     COPYRIGHT BY VPI&SU AEROSPACE DEPARTMENT 1991


      PROGRAM TEMPEST

*     WRITTEN IN VS FORTRAN BY MAIK TIEDEMANN, SOLAR SAIL DESIGN GROUP

*     THIS PROGRAM ESTIMATES THE TEMPERATURES FOR A SOLAR SAIL MARS
*     MISSION. IT IS DIVIDED INTO FOUR PARTS : SAIL AND HUB
*     TEMPERATURES IN 9 PARTICULAR CASES, SHADOW ENTRY TEMPERATURES,
*     TEMPERATURE DISTRIBUTION OF THE CENTRAL HUB,
*     AND TEMPERATURES DURING A SUN BYPASS. ALL TEMPERATURES ARE
*     EQUILIBRIUM TEMPERATURES, EXCEPT FOR THE HUB TEMPERATURE
*     DISTRIBUTION. THE INPUT PARAMETERS ARE WRITTEN IN FILE
*     "PARAM INPUT" AND MUST BE CHANGED BY MEANS OF AN EDITOR,
*     IF NECESSARY. THE OUTPUT DATA APPEARS IN DIFFERENT FILES.
*     THE NAMES OF THESE FILES WILL APPEAR ON THE SCREEN AFTER
*     THE TERMINATION OF EACH PROCEDURE.
*     THE START BATCH "TEMPRUN EXEC" SHOULD BE USED TO ENSURE PROPER
*     EXECUTION OF ALL FUNCTIONS (ON THE VT MAINFRAME)


*     VARIABLES AND PARAMETERS :
*
*     RPE    PERIAPSIS OF EARTH ORBIT (KM)
*     RAE    APOAPSIS OF EARTH ORBIT (KM)
*     RPM    PERIAPSIS OF MARS ORBIT (KM)
*     RAM    APOAPSIS OF MARS ORBIT (KM)
*     EA     ALBEDO FACTOR OF EARTH
*     MA     ALBEDO FACTOR OF MARS
*     ABAL   ABSORPTION COEFFICIENT OF ALUMINUM SIDE
*     EMAL   EMISSION COEFFICIENT OF ALUMINUM SIDE
*     RAL    REFLECTIVITY OF ALUMINUM SIDE
*     RCR    REFLECTIVITY OF CHROMIUM SIDE
*     ABCR   ABSORPTION COEFFICIENT OF CHROMIUM SIDE
*     EMCR   EMISSION COEFFICIENT OF CHROMIUM SIDE
*     EMM    MEAN EMISSION COEFFICIENT
*     ABH    ABSORPTION COEFFICIENT OF HUB
*     EMH    EMISSION COEFFICIENT OF HUB
*     AREA   AREA OF SOLAR SAIL (M**2)
*     ARPER  AREA PERPENDICULAR TO RAYS  (M**2)
*     BETFM  MEAN ANGLE BETWEEN SUNRAYS AND FRONT SIDE OF SAIL
*     BETRM  MEAN ANGLE BETWEEN SUNRAYS AND REAR SIDE OF SAIL
*     APSF   AREA PERPENDICULAR TO SUN RAYS FRONT SIDE CASE 4,5 (M**2)
*     APSR   AREA PERPENDICULAR TO SUN RAYS REAR SIDE CASE 4,5 (M**2)
*     ARPERPAREA PERPENDICULAR TO PLANETARY RAYS
*     HDIA   OUTER DIAMETER OF HUB  (M)
*     HHGT   HEIGHT OF HUB  (M)
*     APH    AREA OF HUB PERPENDICULAR TO RAYS  (M**2)
*     ISE    SOLAR CONSTANT AT EARTH  (W/M**2)
```

```
*    ISM      SOLAR CONSTANT AT MARS  (W/M**2)
*    SIGMA    STEFAN-BOLTZMANN'S CONSTANT  (W/M**2 K**4)
*    AU       ASTRONOMIC UNIT
*    WE       AVERAGE HEAT FLUX OF EARTH / M**2  (W/M**2)
*    WM       AVERAGE HEAT FLUX OF MARS / M**2  (W/M**2)
*    RE       EARTH RADIUS  (KM)
*    RM       MARS RADIUS  (KM)
*    RSUN     SUN RADIUS  (KM)
*    QS       HEAT FLUX RESULTING FROM SUN RADIATION  (W)
*    QR       HEAT FLUX RESULTING FROM REFLECTED SUN RADIATION  (W)
*    QE       HEAT FLUX RESULTING FROM EARTH RADIATION  (W)
*    T        TEMPERATURE OF SOLAR SAIL  (K, C)
*    TH       TEMPERATURE OF HUB  (K, C)
*    FSP      VIEW FACTOR SPACECRAFT TO PLANET (FSE-EARTH, FSM-MARS)
*    FSSP     VIEW FACTOR SPACECRAFT TO SPACE
*    FSSPL    VIEW FACTOR SPACECRAFT TO SUNLIT PLANET
*    THETA    ANGLE BETWEEN RAYS AND VECTOR NORMAL TO AREA  (DEGREE)
*    THET     ANGLE BETWEEN RAYS AND VECTOR NORMAL TO AREA  (RAD)
*    A        MAJOR AXIS/2  (KM)
*    E        ECCENTRICITY
*    P        LATUS RECTUM/2  (KM)
*    E0       DISTANCE FACTOR
*    R        DISTANCE SPACECRAFT SUN  (AU)
*    IS       SOLAR INTENSITY AT SPACECRAFT'S DISTANCE TO SUN  (W/M**2)
*    TMIN     MINIMUM TEMPERATURE OF 9 CASES  (OF SAIL, HUB)
*    TMAX     MAXIMUM TEMPERATURE OF 9 CASES  (OF SAIL, HUB)


     INTEGER CHOI, CH, WWO

     INTEGER MODE
     REAL SIGMA, PI
     REAL RPE, RAE, RPM, RAM
     REAL ISE, ISM, RE, RM, WE, WM, EA, MA, RSUN, AU
     REAL AREA, HHGT, HDIA, THETA, THET
     DOUBLE PRECISION ABAL, EMAL, ABCR, EMCR, ABH, EMH, RAL, RCR, EMM

     COMMON / MAIN / SIGMA, PI, RPE, RAE, RPM, RAM, ISE, ISM, RE, RM,
     #             WE, WM, EA, MA, AREA, HHGT, HDIA, THET,
     #             ABAL, EMAL, ABCR, EMCR, ABH, EMH, RAL, RCR, EMM,
     #             MODE, RSUN, AU

**   CONSTANTS  ****

     PI = 3.141592654
     SIGMA = 5.67E-8
     ISE = 1377.
     ISM =  590.
     WE = 250.
     WM = 150.
     RE = 6370.
     RM = 3390.
     RSUN = 696000.
     AU = 1.495E8

**   INPUT  **********
```

```
      READ (8, *) RPE, RAE, EA
      READ (8, *) RPM, RAM, MA
      READ (8, *) ABAL, EMAL, ABCR, EMCR
      READ (8, *) ABH, EMH
      READ (8, *) AREA, HHGT, HDIA
      READ (8, *) THETA

      THET = THETA*PI/180.
      RAL = 1 - ABAL
      RCR = 1 - ABCR
      MODE = 1

**    MENU  *****************

      PRINT *
      PRINT *
      PRINT *
      PRINT *, '  WELCOME TO "TEMPERATURE ESTIMATION" '
 10   PRINT *
      PRINT *, '  1. TEMPERATURES IN 9 PARTICULAR CASES '
      PRINT *, '  2. TEMPERATURES DURING A SUN BYPASS '
      PRINT *, '  3. SHADOW ENTRY TEMPERATURES '
      PRINT *, '  4. HUB TEMPERATURE DISTRIBUTION '
      PRINT *, '  5. READ OUTPUT FILE '
      PRINT *, '  6. QUIT '
      PRINT *
      PRINT *, '  YOUR CHOICE ?  '
      PRINT *
      PRINT *
      PRINT *
      PRINT *

      READ *, CHOI
      IF (CHOI .EQ. 1) THEN
 20      PRINT *, '  TEMPERATURES IN 9 PARTICULAR CASES '
         PRINT *
         PRINT *,'  1. SAIL AND HUB TEMPERATURES FOR 9 CASES'
         PRINT *,'  2. MIN AND MAX TEMPERATURES FOR DIFFERENT SETS OF
      #PARAMETERS'
         PRINT *,'  3. BACK TO MAIN MENU '
         PRINT *
         PRINT *,'  YOUR CHOICE ? '
         READ *, CH
         IF (CH .EQ. 1) THEN
            PRINT *, '  WITH (1) OR WITHOUT (2) CASE 7 ? '
            READ *, WWO
            CALL SATTEMP (WWO)
            GOTO 10
         ELSE
            iF (CH .EQ. 2) THEN
               CALL RANGE
               GOTO 10
            ELSE
               IF (CH .EQ. 3) THEN
                  GOTO 10
```

```
                  ELSE
                     GOTO 20
                  END IF
               END IF
            END IF
         ELSE
            IF (CHOI .EQ. 2) THEN
               PRINT *,'   TEMPERATURES DURING A SUN BYPASS '
               PRINT *
               CALL SUN
               GOTO 10
            ELSE
               IF (CHOI .EQ. 3) THEN
                  PRINT *,'   SHADOW ENTRY TEMPERATURES '
                  PRINT *
                  CALL SENTRY
                  GOTO 10
               ELSE
                  IF (CHOI .EQ. 4) THEN
                     PRINT *,'   HUB TEMPERATURE DISTRIBUTION '
                     PRINT *
                     CALL TEMPDIS
                     GOTO 10
                  ELSE
                     IF (CHOI .EQ. 5) THEN
                        PRINT *,'   READ OUTPUT FILE '
                        PRINT *
                        CALL REOUT
                        GOTO 10
                     ELSE
                        IF (CHOI .EQ. 6) THEN
                           GOTO 30
                        ELSE
                           GOTO 10
                        END IF
                     END IF
                  END IF
               END IF
            END IF
         END IF
 30      END


         SUBROUTINE RANGE

*        THIS SUBROUTINE COMPUTES THE MINIMUM AND MAXIMUM
*        TEMPERATURES IN THE NINE CASES, FOR EITHER
*        THE SAIL OR THE HUB, FOR
*        RANGES OF PARAMETERS (ABSORPTIVITY AND EMISSITY).
*        THE SAIL PARAMETERS IN THE INPUT FILE ARE USED IN THE HUB
*        TEMPERATURE ESTIMATION.


         INTEGER HS, WWO, CH
         CHARACTER TEX*35
```

```
      REAL ABHS, EMHS, ABALS, EMALS, ABCRS, EMCRS
      DOUBLE PRECISION ABHMIN, ABHMAX, EMHMIN, EMHMAX, STEPA
      DOUBLE PRECISION ABALMIN, ABALMAX, EMALMIN, EMALMAX, STEPAA
      DOUBLE PRECISION ABCRMIN, ABCRMAX, EMCRMIN, EMCRMAX, STEPAC
      DOUBLE PRECISION STEPE, STEPEA, STEPEC

      INTEGER MODE
      REAL SIGMA, PI
      REAL RPE, RAE, RPM, RAM
      REAL ISE, ISM, RE, RM, WE, WM, EA, MA, RSUN, AU
      REAL AREA, HHGT, HDIA, THETA, THET
      DOUBLE PRECISION ABAL, EMAL, ABCR, EMCR, ABH, EMH, RAL, RCR, EMM

      COMMON / MAIN / SIGMA, PI, RPE, RAE, RPM, RAM, ISE, ISM, RE, RM,
      #            WE, WM, EA, MA, AREA, HHGT, HDIA, THET,
      #            ABAL, EMAL, ABCR, EMCR, ABH, EMH, RAL, RCR, EMM,
      #            MODE, RSUN, AU

      COMMON / CONS /  TMINS, TMAXS, TMINH, TMAXH, CMINS, CMAXS, CMINH,
      #             CMAXH

      MODE = 2
      PRINT *, '   FOR THE SAIL (1) OR THE HUB (2) ?'
      READ *, HS
      PRINT *, '   WITH (1) OR WITHOUT (2) CASE 7 ?'
      READ *, WWO

**    SAIL  **********

      IF (HS .EQ. 1) THEN
         IF (WWO .EQ. 1) THEN
            TEX = ' (SAIL RANGE)'
         ELSE
            TEX = ' W/O CASE 7 (SAIL RANGE)'
         END IF
         CALL HEAD (10, TEX)
         WRITE (10, *) ' | ABAL  | EMAL  | ABCR  | EMCR  |',
      #        ' TMIN (C) | TMAX (C) | CMIN | CMAX |'
         WRITE (10, *) ' ==============================',
      #        '============================'
         ABALS = ABAL
         EMALS = EMAL
         ABCRS = ABCR
         EMCRS = EMCR
         PRINT *, '   INPUT ABAL MIN : '
         READ *, ABALMIN
         PRINT *, '   INPUT ABAL MAX : '
         READ *, ABALMAX
         PRINT *, '   INPUT STEP ABAL : '
         READ *, STEPAA
         PRINT *, '   INPUT EMAL MIN : '
         READ *, EMALMIN
         PRINT *, '   INPUT EMAL MAX : '
         READ *, EMALMAX
         PRINT *, '   INPUT STEP EMAL : '
         READ *, STEPEA
```

```
        PRINT *,'   INPUT ABCR MIN :'
        READ *, ABCRMIN
        PRINT *,'   INPUT ABCR MAX :'
        READ *, ABCRMAX
        PRINT *,'   INPUT STEP ABCR :'
        READ *, STEPAC
        PRINT *,'   INPUT EMCR MIN :'
        READ *, EMCRMIN
        PRINT *,'   INPUT EMCR MAX :'
        READ *, EMCRMAX
        PRINT *,'   INPUT STEP EMCR :'
        READ *, STEPEC

        DO 40 ABAL = ABALMIN, ABALMAX+.002, STEPAA
            DO 30 EMAL = EMALMIN, EMALMAX+.002, STEPEA
                DO 20 ABCR = ABCRMIN, ABCRMAX+.002, STEPAC
                    DO 10 EMCR = EMCRMIN, EMCRMAX+.002, STEPEC

                        RAL = 1 - ABAL
                        RCR = 1 - ABCR
                        CALL SATTEMP (WWO)
C                       IF (TMINS-273.16 .GE. -70.00) THEN
C                           IF (TMAXS-273.16 .LE. 160.00) THEN
                                WRITE (10,'(4(A,F5.3),2(A,F8.2),2(A,I3),A)')
    #                            ' |', ABAL, '|', EMAL, '|', ABCR,
    #                            '|', EMCR, '|',  TMINS-273.16,
    #                            '|', TMAXS-273.16, '|', CMINS, ' |', CMAXS,
    #                            ' |'
C                           END IF
C                       END IF
10                  CONTINUE
20              CONTINUE
30          CONTINUE
40      CONTINUE
        ABAL = ABALS
        EMAL = EMALS
        ABCR = ABCRS
        EMCR = EMCRS
        RAL = 1 - ABAL
        RCR = 1 - ABCR
        WRITE (*,'(//A)') '   OUTPUT IN FILE "SAILTAB" ON CHANNEL 10'

**  HUB ***********

    ELSE
        IF (WWO .EQ. 1) THEN
            TEX = '(HUB RANGE)'
        ELSE
            TEX = ' W/O CASE 7 (HUB RANGE)'
        END IF
        CALL HEAD (11, TEX)
        WRITE (11, *) '|  ABH     |  EMH     |',
    #       '  TMIN (C) |  TMAX (C) | CMIN | CMAX |'
        WRITE (11,'(2A)') '  ============================',
    #       '========================'
        ABHS = ABH
```

```
         EMHS = EMH
         PRINT *, '  INPUT ABH MIN : '
         READ *, ABHMIN
         PRINT *, '  INPUT ABH MAX : '
         READ *, ABHMAX
         PRINT *, '  INPUT STEP ABH : '
         READ *, STEPA
         PRINT *, '  INPUT EMH MIN : '
         READ *, EMHMIN
         PRINT *, '  INPUT EMH MAX : '
         READ *, EMHMAX
         PRINT *, '  INPUT STEP EMH : '
         READ *, STEPE
         DO 60 ABH = ABHMIN, ABHMAX + 0.002, STEPA
            DO 50 EMH = EMHMIN, EMHMAX + 0.002, STEPE
               CALL SATTEMP (WWO)
               WRITE (11,'(2(A,F6.3),2(A,F10.2),2(A,I3),A)')
      #           ' | ', ABH, '  | ', EMH, '  | ', TMINH-273.16, ' | ',
      #           TMAXH-273.16, ' | ', CMINH, '  | ', CMAXH, '  |'
50          CONTINUE
60       CONTINUE
         ABH = ABHS
         EMH = EMHS
         WRITE (*,'(//A)') '  OUTPUT IN FILE "HUBTAB" ON CHANNEL 11'
      END IF

      MODE = 1
      END


      SUBROUTINE SATTEMP (WWO)

*     TEMPERATURE ESTIMATION FOR A SOLAR SAIL MARS MISSION.
*     THIS SUBROUTINE ESTIMATES SOLAR SAIL AND HUB TEMPERATURES IN
*     SIX POSITIONS NEAR EARTH AND IN THREE POSITIONS NEAR MARS.
*     THE INPUT PARAMETERS ARE : THE PARAMETERS OF THE ORBITS
*     AROUND EARTH AND MARS, THE ABSORPTION AND EMISSION
*     COEFFICIENTS OF THE BOTTOM AND TOP SIDE OF THE SAIL,
*     THE ABSORPTION AND EMISSION COEFFICIENTS OF THE HUB,
*     AND THE ALBEDO FACTORS OF EARTH AND MARS. (INPUT VIA COMMON
*     'MAIN' FROM 'TEMPEST')

      INTEGER WWO

      CHARACTER TEX*35
      INTEGER MODE
      REAL SIGMA, PI
      REAL RPE, RAE, RPM, RAM
      REAL ISE, ISM, RE, RM, WE, WM, EA, MA, RSUN, AU
      REAL AREA, HHGT, HDIA, THETA, THET
      DOUBLE PRECISION ABAL, EMAL, ABCR, EMCR, ABH, EMH, RAL, RCR, EMM

      INTEGER CMINS, CMMAXS, CMINH, CMAXH
      REAL QS, QR, QE, QM, FSE, FSM, FSSP, FSSPL, ARPER, TMINS, TMAXS, A
      REAL E, P, TMINH, TMAXH, QSH, QRH, QEH, QMH, APH
      REAL BETFM, BETRM, APSF, APSR
```

```
      COMMON / MAIN / SIGMA, PI, RPE, RAE, RPM, RAM, ISE, ISM, RE, RM,
      #          WE, WM, EA, MA, AREA, HHGT, HDIA, THET,
      #          ABAL, EMAL, ABCR, EMCR, ABH, EMH, RAL, RCR, EMM,
      #          MODE, RSUN, AU

      COMMON / CONS / TMINS, TMAXS, TMINH, TMAXH, CMINS, CMAXS, CMINH,
      #          CMAXH

      EMM = (EMAL+EMCR)/2.

      TEX = '                              '
      IF (MODE .EQ. 1) THEN
         CALL HEAD (9, TEX)
         CALL HEAD (6, TEX)
      END IF

      TMINH=0.
      TMAXH=0.
      TMINS=0.
      TMAXS=0.
      CMINS=1.
      CMAXS=1.
      CMINH=1.
      CMAXH=1.

*     CASE 1

      FSE = (RE**2.)/(RAE**2.)
      FSSP = 1.-FSE
      FSSPL = FSE
      ARPER = COS(THET) * AREA
      QS = ABAL * ARPER * ISE
      QR = EA * ABCR * FSSPL * ARPER * ISE
      QE = WE * ABCR * FSE * ARPER
      APH = HDIA*HHGT*SIN(THET)/2. + PI*HDIA**2.*COS(THET)/4.
      QSH = ISE*ABH*(APH + RAL*SIN(THET)*HDIA*HHGT/2.)
      QRH = EA*ABH*ISE*FSSPL*(APH + RCR*SIN(THET)*HDIA*HHGT/2.)
      QEH = WE*ABH*FSE*(APH + RCR*SIN(THET)*HDIA*HHGT/2.)
      CALL TTOFILE ( QS, QR, QE, QSH, QRH, QEH,
      #         FSE, FSSP, FSSPL, 1, 9 )

*     CASE 2

      A = (RPE+RAE)/2.
      E = (RAE-RPE)/(RAE+RPE)
      P = A * (1.-E**2.)
      FSE = RE**2. / P**2.
      FSSP = 1.-FSE
      FSSPL = FSE/2.
      ARPER = AREA
      QS = ABAL * ARPER * ISE
      QR = 0.
      QE = 0.
      APH = PI*HDIA**2./4
      QSH = ABH*ISE*APH
```

```
      QRH = EA*ISE*ABH*FSSPL*HDIA*HHGT
      QEH = WE*ABH*FSE*HDIA*HHGT
      CALL TTOFILE ( QS, QR, QE, QSH, QRH, QEH,
      #    FSE, FSSP, FSSPL, 2, 9 )

*     CASE 3

      FSE = RE**2./RPE**2.
      FSSP = 1- FSE
      FSSPL = 0.
      ARPER = COS(THET) * AREA
      QS = 0
      QR = 0
      QE = WE * ABAL * FSE * ARPER
      APH = HDIA*HHGT*SIN(THET)/2. + PI*HDIA**2.*COS(THET)/4.
      QSH = 0
      QRH = 0
      QEH = WE*ABH*FSE*(APH + RAL*SIN(THET)*HDIA*HHGT/2.)
      CALL TTOFILE ( QS, QR, QE, QSH, QRH, QEH,
      #    FSE, FSSP, FSSPL, 3, 9 )

*     CASE 4 & 5

      FSE = RE**2./P**2.
      FSSP = 1 - FSE
      FSSPL = FSE/2
      ARPER = AREA
      BETFM = (ATAN ((RSUN+P)/AU))/2.
      BETRM = (ATAN ((RSUN-P)/AU))/2.
      APSF = AREA*SIN(BETFM)
      APSR = AREA*SIN(BETRM)
      QS = ABAL*ISE*APSF + ABCR*ISE*APSR
      QR = ABAL * EA * FSSPL * ARPER * ISE
      QE = WE * ABAL * FSE * ARPER
      APH = HDIA*HHGT
      QSH = ISE*ABH*APH
      QRH = EA*ISE*ABH*FSSPL*PI*HDIA**2./4.
      QEH = WE*ABH*FSE*PI*HDIA**2./4.
      CALL TTOFILE ( QS, QR, QE, QSH, QRH, QEH,
      #    FSE, FSSP, FSSPL, 4, 9 )
      QS = ABCR*ISE*APSF + ABAL*ISE*APSR
      QR = ABCR * EA * FSSPL * ARPER * ISE
      QE = WE * ABCR * ARPER * FSE
      CALL TTOFILE ( QS, QR, QE, QSH, QRH, QEH,
      #    FSE, FSSP, FSSPL, 5, 9 )

*     CASE 6

      A = (RPM+RAM)/2.
      E = (RAM-RPM)/(RAM+RPM)
      P = A * (1.-E**2.)
      FSM = RM**2. / P**2.
      FSSP = 1.-FSM
      FSSPL = FSM/2.
      ARPER = AREA
      QS = ABAL * ARPER * ISM
```

```
      QR = 0.
      QM = 0.
      APH = PI*HDIA**2./4
      QSH = ABH*ISM*APH
      QRH = MA*ISM*ABH*FSSPL*HDIA*HHGT
      QMH = WM*ABH*FSM*HDIA*HHGT
      CALL TTOFILE ( QS, QR, QM, QSH, QRH, QMH,
      #    FSM, FSSP, FSSPL, 6, 9 )

      IF (WWO .EQ. 1) THEN
*     CASE 7

         FSM = RM**2./RPM**2.
         FSSP = 1- FSM
         FSSPL = 0.
         ARPER = COS(THET) * AREA
         QS = 0
         QR = 0
         QM = WM * ABAL * FSM * ARPER
         APH = HDIA*HHGT*SIN(THET)/2. + PI*HDIA**2.*COS(THET)/4.
         QSH = 0
         QRH = 0
         QMH = WM*ABH*FSM*(APH + RAL*SIN(THET)*HDIA*HHGT/2.)
         CALL TTOFILE ( QS, QR, QM, QSH, QRH, QMH,
      #        FSM, FSSP, FSSPL, 7, 9 )
      END IF

*     CASE 8

      FSM = (RM**2.)/(RAM**2.)
      FSSP = 1.-FSM
      FSSPL = FSM
      ARPER = COS(THET) * AREA
      QS = ABAL * ARPER * ISM
      QR = MA * ABCR * FSM * ARPER * ISM
      QM = WM * ABCR * FSM * ARPER
      APH = HDIA*HHGT*SIN(THET)/2. + PI*HDIA**2.*COS(THET)/4.
      QSH = ISM*ABH*(APH + RAL*SIN(THET)*HDIA*HHGT/2.)
      QRH = MA*ABH*ISM*FSSPL*(APH + RCR*SIN(THET)*HDIA*HHGT/2.)
      QMH = WM*ABH*FSM*(APH + RCR*SIN(THET)*HDIA*HHGT/2.)
      CALL TTOFILE ( QS, QR, QM, QSH, QRH, QMH,
      #           FSM, FSSP, FSSPL, 8, 9 )

*     CASE 9

      A = (RPE+RAE)/2.
      E = (RAE-RPE)/(RAE+RPE)
      P = A * (1.-E**2.)
      FSE = RE**2. / P**2.
      FSSP = 1.-FSE
      FSSPL = FSE/2.
      ARPER = AREA
      QS = ABCR * ARPER * ISE
      QR = 0.
      QE = 0.
      APH = PI*HDIA**2./4
```

```
      QSH = ABH*ISE*APH
      QRH = EA*ISE*ABH*FSSPL*HDIA*HHGT
      QEH = WE*ABH*FSE*HDIA*HHGT
      CALL TTOFILE ( QS, QR, QE, QSH, QRH, QEH,
      #    FSE, FSSP, FSSPL, 9, 9 )


      IF (MODE .EQ. 1) THEN
         WRITE(9,'(//2(A,F7.2),2(A,I2))') ' SAIL :   TMIN = ',
      #        TMINS - 273.16, ' C    TMAX = ', TMAXS - 273.16,
      #        ' C    CMINS = ', CMINS, '    CMAXS = ', CMAXS
         WRITE(9,'(2(A,F7.2),2(A,I2)//)') ' HUB  :   TMIN = ',
      #        TMINH - 273.16, ' C    TMAX = ', TMAXH - 273.16,
      #        ' C    CMINH = ', CMINH, '    CMAXH = ', CMAXH
         WRITE(*,'(//2(A,F7.2),2(A,I2))') ' SAIL :   TMIN = ',
      #        TMINS - 273.16, ' C    TMAX = ', TMAXS - 273.16,
      #        ' C    CMINH = ', CMINS, '    CMAXS = ', CMAXS
         WRITE(*,'(2(A,F7.2),2(A,I2)//)') ' HUB  :   TMIN = ',
      #        TMINH - 273.16, ' C    TMAX = ', TMAXH - 273.16,
      #        ' C    CMINH = ', CMINH, '    CMAXH = ', CMAXH
         PRINT *, '   OUTPUT IN FILE "TEMPOUT" ON CHANNEL 9'
      END IF

      END


      SUBROUTINE SENTRY

*     TEMPERATURE ESTIMATION FOR A SOLAR SAIL MARS MISSION
*     THIS SUBROUTINE ESTIMATES SHADOW ENTRY TEMPERATURES AT
*     THE SHADOW ENTRY POINTS OF EARTH AND MARS SHADOW.
*     THE INPUT PARAMETERS ARE : THE ABSORPTION AND EMISSION
*     COEFFICIENTS OF THE SAIL AND THE HUB,
*     AND THE SHADOW ENTRY ANGLES AND RADII

      INTEGER MODE
      REAL SIGMA, PI
      REAL RPE, RAE, RPM, RAM
      REAL ISE, ISM, RE, RM, WE, WM, EA, MA, RSUN, AU
      REAL AREA, HHGT, HDIA, THETA, THET
      DOUBLE PRECISION ABAL, EMAL, ABCR, EMCR, ABH, EMH, RAL, RCR, EMM

      CHARACTER TEX*35
      INTEGER CHOI
      REAL SEA, SA, SER, FSE, FSSP, FSSPL, ARPER, QS, QR, QE, QM, QSH
      REAL QRH, QEH, QMH, APH, APHP, FSM

      COMMON / MAIN / SIGMA, PI, RPE, RAE, RPM, RAM, ISE, ISM, RE, RM,
      #           WE, WM, EA, MA, AREA, HHGT, HDIA, THET,
      #           ABAL, EMAL, ABCR, EMCR, ABH, EMH, RAL, RCR, EMM,
      #           MODE, RSUN, AU


      EMM = (EMAL+EMCR)/2.
      PRINT *, '   SHADOW ENTRY TEMPERATURES FOR EARTH SHADOW (1) OR'
```

```
PRINT *, '   MARS SHADOW (2) ?'
READ *, CHOI
PRINT *, '   INPUT SHADOW ENTRY ANGLE (DEGREE) : '
READ *, SEA
PRINT *, '   INPUT SHADOW ENTRY RADIUS (KM) : '
READ *, SER
SA = SEA*PI/180.
IF (CHOI .EQ. 1) THEN
    TEX = ' (SHADOW ENTRY, EARTH)            '
    CALL HEAD (12, TEX)
    CALL HEAD (6, TEX)
    FSE = RE**2/SER**2
    FSSP = 1-FSE
    FSSPL = 0.
    ARPER = AREA * COS(THET)
    ARPERP = AREA * COS(THET+SA)
    QS = ABAL * ARPER * ISE
    QR = 0.
    QE = WE * ABAL * FSE * ARPERP
    APH = HDIA*HHGT*SIN(THET)/2. + PI*HDIA**2.*COS(THET)/4.
    APHP = HDIA*HHGT*SIN(THET+SA)/2. + PI*HDIA**2.*COS(THET+SA)/4.
    QSH = ABH*ISE*(APH + RAL*SIN(THET)*HDIA*HHGT/2.)
    QRH = 0.
    QEH = WE*ABH*FSE*(APHP + RAL*SIN(THET+SA)*HDIA*HHGT/2.)
    CALL  TTOFILE ( QS, QR, QE, QSH, QRH, QEH,
#       FSE, FSSP, FSSPL, 0, 12)
    PRINT *, '   OUTPUT IN FILE "SEEARTH" ON CHANNEL 12'

ELSE
    TEX = ' (SHADOW ENTRY, MARS)             '
    CALL HEAD (13, TEX)
    CALL HEAD (6, TEX)
    FSM = RM**2/SER**2
    FSSP = 1-FSM
    FSSPL = 0.
    ARPER = AREA * COS(THET)
    ARPERP = AREA * COS(THET+SA)
    QS = ABAL * ARPER * ISM
    QR = 0.
    QM = WM * ABAL * FSM * ARPERP
    APH = HDIA*HHGT*SIN(THET)/2. + PI*HDIA**2.*COS(THET)/4.
    APHP = HDIA*HHGT*SIN(THET+SA)/2. + PI*HDIA**2.*COS(THET+SA)/4.
    QSH = ABH*ISM*(APH + RAL*SIN(THET)*HDIA*HHGT/2.)
    QRH = 0.
    QMH = WM*ABH*FSM*(APHP + RAL*SIN(THET+SA)*HDIA*HHGT/2.)
    CALL  TTOFILE ( QS, QR, QM, QSH, QRH, QMH,
#       FSM, FSSP, FSSPL, 0, 13)
    PRINT *, '   OUTPUT IN FILE "SEMARS" ON CHANNEL 13'

END IF
END


SUBROUTINE TTOFILE ( QS, QR, QP, QSH, QRH, QPH,
#       FSP, FSSP, FSSPL, CASE, CH )
```

```
      INTEGER MODE
      REAL SIGMA, PI
      REAL RPE, RAE, RPM, RAM
      REAL ISE, ISM, RE, RM, WE, WM, EA, MA, RSUN, AU
      REAL AREA, HHGT, HDIA, THETA, THET
      DOUBLE PRECISION ABAL, EMAL, ABCR, EMCR, ABH, EMH, RAL, RCR, EMM

      REAL QS, QR, QP, FSP, FSSP, FSSPL, T2, T3
      REAL TH, T, QSH, QRH, QPH, TMINH, TMAXH, TMINS, TMAXS
      INTEGER CASE, CH, CMINS, CMAXS, CMINH, CMAXH

      COMMON / MAIN / SIGMA, PI, RPE, RAE, RPM, RAM, ISE, ISM, RE, RM,
     #           WE, WM, EA, MA, AREA, HHGT, HDIA, THET,
     #           ABAL, EMAL, ABCR, EMCR, ABH, EMH, RAL, RCR, EMM,
     #           MODE, RSUN, AU

      COMMON / CONS / TMINS ,TMAXS, TMINH, TMAXH, CMINS, CMAXS, CMINH,
     #           CMAXH

      T2 = QR / (1-FSSPL)
      T3 = QP /  FSSP
      T = ( (QS+T2+T3) / (SIGMA * EMM * 2. * AREA) )**.25

      T2 = QRH / (1-FSSPL)
      T3 = QPH / FSSP
      TH = ( (QSH+T2+T3) / (SIGMA*EMH*PI*HDIA*(HHGT+HDIA/2.)) )**.25

      IF (CASE .EQ. 1) THEN
         TMINS = T
         TMAXS = T
         TMINH = TH
         TMAXH = TH
      ELSE
         IF (T .LT. TMINS) THEN
            TMINS = T
            CMINS = CASE
         ELSE
            IF (T .GT. TMAXS) THEN
               TMAXS = T
               CMAXS = CASE
            END IF
         END IF
         IF (TH .LT. TMINH) THEN
            TMINH = TH
            CMINH = CASE
         ELSE
            IF (TH .GT. TMAXH) THEN
               TMAXH = TH
               CMAXH = CASE
            END IF
         END IF
      END IF

      IF (MODE .EQ.1) THEN
         WRITE (CH, '(A, I3)') ' CASE ', CASE
         WRITE (CH, '(3(A,F6.4)/)') ' FSP : ', FSP, '    FSSP : ',
```

```
     #          FSSP, '    FSSPL : ', FSSPL
          WRITE (CH, *) '     |       QS [W]       QR [W]',
     #          '       QP [W]       T[K]       T[C]'
          WRITE (CH, *) '--------------------------------',
     #          '----------------------------------'
          WRITE (CH, '(2(A,3F13.1, 2F11.2/))')
     #          ' SAIL  |', QS, QR, QP, T, T-273.16,
     #          ' HUB   |', QSH, QRH, QPH, TH, TH-273.16
          WRITE (CH, '(/2A/)') '= = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = =',
     #          '= = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = ='
          WRITE (*, '(A, I3)') ' CASE ', CASE
          WRITE (*, '(3(A,F6.4)/)') ' FSP : ', FSP, '    FSSP : ',
     #          FSSP, '    FSSPL : ', FSSPL
          WRITE (*, *) '     |       QS [W]       QR [W]',
     #          '       QP [W]       T[K]       T[C]'
          WRITE (*, *) '--------------------------------',
     #          '----------------------------------'
          WRITE (*, '(2(A,3F13.1, 2F11.2/))')
     #          ' SAIL  |', QS, QR, QP, T, T-273.16,
     #          ' HUB   |', QSH, QRH, QPH, TH, TH-273.16
          WRITE (*, '(/2A/)') '= = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = =',
     #          '= = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = ='
     END IF

     END


     SUBROUTINE SUN

*    THIS SUBROUTINE COMPUTES THE SPACECRAFT TEMPERATURES FOR A
*    HELIOCENTRIC TRAVEL DEPENDING ON THE DISTANCE R (AU) AND THE
*    ANGLE THETA (DEG) BETWEEN THE SAIL NORMAL AND THE SUNRAYS.
*    PLANETARY RADIATION AND REFLECTIVE RADIATION ARE NEGLECTED.
*    THE THREE ANGLES THE1 TO THE3 ARE THE ANGLES FOR WHICH
*    ADDITIONAL OUTPUT IS PROVIDED TO THE PLOTFILE.


     INTEGER MODE
     REAL SIGMA, PI
     REAL RPE, RAE, RPM, RAM
     REAL ISE, ISM, RE, RM, WE, WM, EA, MA, RSUN, AU
     REAL AREA, HHGT, HDIA, THETA, THET
     DOUBLE PRECISION ABAL, EMAL, ABCR, EMCR, ABH, EMH, RAL, RCR, EMM

     CHARACTER TEX*35
     INTEGER HS
     DOUBLE PRECISION R, THE, RMIN, RMAX, THEMIN, THEMAX, THE1, THE2,
     #            THE3, STEPR
     REAL E0, IS
     PARAMETER ( RMIN = 0.2, RMAX = 2.0, THEMIN = 20, THEMAX = 50 )
     PARAMETER ( THE1 = 25., THE2 = 35., THE3 = 45. )

     COMMON / MAIN / SIGMA, PI, RPE, RAE, RPM, RAM, ISE, ISM, RE, RM,
     #           WE, WM, EA, MA, AREA, HHGT, HDIA, THET,
     #           ABAL, EMAL, ABCR, EMCR, ABH, EMH, RAL, RCR, EMM,
     #           MODE, RSUN, AU
```

```
      PRINT *, '   FOR THE SAIL (1) OR THE HUB (2) ?'
      READ *, HS
      PRINT *
      PRINT *, '   INPUT STEP OF RADIUS : '
      READ *, STEPR
      PRINT *

**    SAIL  ********

      IF (HS .EQ. 1) THEN
         TEX = ' (SUN BYPASS, SAIL)              '
         CALL HEAD (14, TEX)
         CALL HEAD (6, TEX)
         EMM = (EMAL+EMCR)/2
         WRITE (14, '(2A)') '   R   | THETA |   ARPER   |    IS     |',
     #       '   T (K)   |   T (C) '
         WRITE(14, '(2A)') ' = = = = = = = = = = = = = = = = = = = = = = = = = = = =',
     #       '= = = = = = = = = = = = = = = = = = = = = = ='
         WRITE (*, '(2A)') '   R   | THETA |   ARPER   |    IS     |',
     #       '   T (K)   |   T (C) '
         WRITE(*, '(2A)') ' = = = = = = = = = = = = = = = = = = = = = = = = = = = =',
     #       '= = = = = = = = = = = = = = = = = = = = = = ='

         DO 20 R = RMIN, RMAX, STEPR
            E0 = (1/R)**2
            IS = E0 * ISE
            DO 10 THE = THEMIN, THEMAX, 5
               ARPER = AREA * COS (THE*PI/180)
               T = ( (IS*ABAL*COS(THE*PI/180)) / (2*SIGMA*EMM)) **.25
               WRITE(14,'(F6.2,A,F6.1,A,F9.1,A,F9.2,A,F9.2,A,F9.2)')
     #            R,' | ',THE,' | ',ARPER,' | ',IS,' | ',
     #            T,' | ', T-273.16
               IF (THE .EQ. THE1) THEN
                  WRITE (16, '(I5, F15.2, F15.2)') 1, R, T-273.16
               ELSE
                  IF (THE .EQ. THE2) THEN
                     WRITE (16, '(I5, F15.2, F15.2)') 2, R, T-273.16
                  ELSE
                     IF (THE .EQ. THE3) THEN
                        WRITE (16, '(I5, F15.2, F15.2)') 3, R, T-273.16
                     END IF
                  END IF
               END IF
               WRITE(*,'(F6.2,A,F6.1,A,F9.1,A,F9.2,A,F9.2,A,F9.2)')
     #            R,' | ',THE,' | ',ARPER,' | ',IS,' | ',
     #            T,' | ', T-273.16
10          CONTINUE
            WRITE(14, '(2A)') ' ____________________________________',
     #         '_______________________'
            WRITE(*, '(2A//)') ' ____________________________________',
     #         '_______________________'
20       CONTINUE
         PRINT *, '   OUTPUT IN FILE "SUNSAIL" ON CHANNEL 14'
         PRINT *, '   PLOTFILE : "SSAILPL" ON CHANNEL 16'
```

```
**   HUB **************

     ELSE

        TEX = ' (SUN BYPASS, HUB)           '
        CALL HEAD (15, TEX)
        CALL HEAD (6, TEX)
        WRITE (15, '(2A)') '   R   | THETA  |   ARPER   |   IS    |',
     #     '  T (K)   |  T (C) '
        WRITE(15, '(2A)') ' =================================',
     #     '=========================='
        WRITE (*, '(2A)') '   R   | THETA  |   ARPER   |   IS    |',
     #     '  T (K)   |  T (C) '
        WRITE(*, '(2A)') ' ================================',
     #     '=========================='

        DO 40 R = RMIN, RMAX, STEPR
           E0 = (1/R)**2
           IS = E0 * ISE
           DO 30 THE = THEMIN, THEMAX, 5
              APH = HDIA*HHGT*SIN(THE*PI/180.)/2. + PI*HDIA**2.*COS
     #           (THE*PI/180.)/4.
              T = ( (IS*ABH*(APH+RAL*SIN(THE*PI/180.)*HDIA*HHGT/2.))
     #           /(SIGMA*EMH*PI*HDIA*(HHGT+HDIA/2.)))**.25
              WRITE(15,'(F6.2,A,F6.1,A,F9.1,A,F9.2,A,F9.2,A,F9.2)')
     #           R,' | ',THE,' | ',APH,' | ',IS,' | ',
     #           T,' | ', T-273.16
              IF (THE .EQ. THE1) THEN
                 WRITE (17, '(I5, F15.2, F15.2)') 1, R, T-273.16
              ELSE
                 IF (THE .EQ. THE2) THEN
                    WRITE (17, '(I5, F15.2, F15.2)') 2, R, T-273.16
                 ELSE
                    IF (THE .EQ. THE3) THEN
                       WRITE (17, '(I5, F15.2, F15.2)') 3, R, T-273.16
                    END IF
                 END IF
              END IF
              WRITE(*,'(F6.2,A,F6.1,A,F9.1,A,F9.2,A,F9.2,A,F9.2)')
     #           R,' | ',THE,' | ',APH,' | ',IS,' | ',
     #           T,' | ', T-273.16
30         CONTINUE
           WRITE(15, '(2A)') ' ______________________________',
     #     '____________________'
           WRITE(*, '(2A//)') ' ______________________________',
     #     '____________________'
40      CONTINUE
        PRINT *, '   OUTPUT IN FILE "SUNHUB" ON CHANNEL 15'
        PRINT *, '   PLOTFILE : "SHUBPL" ON CHANNEL 17'

     END IF

     END
```

```
      SUBROUTINE TEMPDIS

*     TEMPDIS DETERMINES THE TEMPERATURE DISTRIBUTION OVER THE
*     HUB. IT DISCRETIZES THE HUB INTO TWO DISKS (BOTTOM AND TOP) AND
*     NSA*NSR PLATES. IN ADDITION, IT COMPUTES THE HEAT EXCHANGE
*     BETWEEN CASE AND CORE OF THE HUB. THUS IT DETERMINES THE
*     THERMAL CONTROL SYSTEM REQUIREMENTS IN THE GIVEN CASES.


*     VARIABLES AND CONSTANTS :

*     QI, QJ   CONDUCTION IN I AND J DIRECTION   (W)
*     APD      AREA PERPEND IRRADIATION, DISK   (M**2)
*     ARD      AREA RADIATING, DISK  (M**2)
*     CI, CJ   CONDUCTION CONSTANT  (W/K)
*     AR       AREA RADIATING PLATES   (M**2)
*     NSR      # OF SEGMENTS ANGULAR
*     NSA      # OF SEGMENTS AXIAL
*     DT       TIME STEP FOR CONDUCTION MODEL  (S)
*     TI       INITIAL TEMPERATURE OF ALL PARTS  (K)
*     QSD      SOLAR RADIATION ON DISK  (W)
*     QED      PLANETARY RADIATION ON DISK  (W)
*     QRD      REFLECTED RADIATION ON DISK  (W)
*     QSPD     SPACE RADIATION, DISK  (W)
*     QC       CONDUCTION TO/FROM DISK  (W)
*     QIRR     IRRADIATION ON PLATES  (W)
*     QSP      SPACE RADIATION, PLATE  (W)
*     CDIA     DIAMETER OF WRAPPED CORE PART  (M)
*     CHGT     HEIGHT OF WRAPPED CORE PART  (M)
*     MD       MASS OF DISK   (KG)
*     MSEG     MASS OF PLATE   (KG)
*     APIR     AREA OF PLATES PERPEND TO QIRR  (M**2)
*     TH       TEMPERATURE OF HUB  (K)
*     LAMAL LAMBDA OF HUB MATERIAL  (W/(K*M))
*     DSHEETTHICKNESS OF SHEET LAYERS OF HONEYCOMB  (M)
*     LHC      LENGTH OF HONEYCOMB  (M)
*     FPER     AREA PERPEND TO CONDUCTION BETWEEN SHEET LAYERS  (M**2)
*     DENSHCAREA DENSITY OF HONEYCOMB  (KG/M**2)
*     TIN      TEMPERATURE ON INSIDE OF HUB  (K)
*     ETB      EMMISSIVITY OF THERMAL BLANKET
*     EAL      EMMISSIVITY OF HONEYCOMB WITHOUT COATING

      INTEGER  I, J, IW, JW, FIELD, K, S, P
      REAL QS, QI1(2), QI2(2), QJ1(2), QJ2(2), APD, ARD, CI, CJ, CR
      REAL AR, AI, AIM1, NSA, NSR, TI, FSE, QSD, QED, QRD, QSPDT
      REAL QSPDB, QCT, QCB, QIRR, MD, MSEG, Z, TI2, QRDTB, TR2I
      REAL QRDIT, QRDIB, FSM, QR2I

      PARAMETER (IW = 50, JW = 50, TI1 = 313, FIELD = (IW+2)*(JW+2)*2)

      REAL APIR(1:IW+1), TH(1:2, 0:IW+1, 0:JW+1), TT, EAL, LHC
      REAL LAMAL, DSHEET, FPER, CP, DT, DENSHC, TIN, ETB, CDIA, CHGT

      PARAMETER ( LAMAL=204., DSHEET=0.000025, CDIA=1.00, CHGT=0.8 )
      PARAMETER ( FPER = 0.03125, CP = 879, DENSHC = 0.855 )
      PARAMETER ( ETB = 0.07, TI2 = 273.16, EAL =0.07, LHC = 0.01 )
```

```
      INTEGER MODE
      REAL SIGMA, PI
      REAL RPE, RAE, RPM, RAM
      REAL ISE, ISM, RE, RM, WE, WM, EA, MA, RSUN, AU
      REAL AREA, HHGT, HDIA, THETA, THET
      DOUBLE PRECISION ABAL, EMAL, ABCR, EMCR, ABH, EMH, RAL, RCR, EMM

      DATA   TH / FIELD*TI1 /

      COMMON / MAIN / SIGMA, PI, RPE, RAE, RPM, RAM, ISE, ISM, RE, RM,
     #            WE, WM, EA, MA, AREA, HHGT, HDIA, THET,
     #            ABAL, EMAL, ABCR, EMCR, ABH, EMH, RAL, RCR, EMM,
     #            MODE, RSUN, AU

      PRINT *, '  NUMBER OF SEGMENTS : '
      PRINT *
      PRINT *, '  RADIAL, PER HALF CYLINDER (EVEN NUMBER) :  '
      READ *, NSR
      PRINT *, '  AXIAL, PER CYLINDER LENGTH (EVEN NUMBER) : '
      READ *, NSA
      PRINT *, '  HOW MANY SECONDS ? : '
      READ *, S
      P=500.
      DT=0.5

***   AREAS PERPENDICULAR ******

      APD = PI * HDIA**2./8. * COS(THET)

      AIM1 = PI/2.
      DO 10 I = 1, NSR/2.
         AI = AIM1 - PI/NSR
         APIR(I) = HDIA/2.*(COS(AI)-COS(AIM1)) * HHGT/NSA*SIN(THET)
         APIR(NSR-I+1) = APIR(I)
         AIM1 = AI
10    CONTINUE

***   RADIATING AREAS **********

      AR = PI*HDIA*HHGT / (2.*NSR*NSA)
      ARD = PI*HDIA**2./8.

***   CONSTANTS ****************

      CI = LAMAL*HHGT/NSA*DSHEET / (PI*HDIA/2./NSR)
      CJ = LAMAL*PI*HDIA/(2.*NSR)*DSHEET / (HHGT/NSA)
      CR = LAMAL*PI*HDIA/2./NSR*HHGT/NSA*FPER / LHC
      MD = DENSHC*PI*HDIA**2./8.
      MSEG = DENSHC * HDIA*PI/2./NSR * HHGT/NSA/2.

****  CASE 1 *****************

      TIN = 313.16
```

```
      FSE = (RE**2.)/(RAE**2.)
C     FSE = 0.
      QSD = ABH*ISE*APD
      QED = WE*ABH*FSE*APD
      QRD = EA*ABH*ISE*FSE*APD

      DO 70 Z=0.5, S, DT

          IF (Z .EQ. P) THEN
              WRITE (*, '(A, F10.2)') '    SEC : ', Z
              P=P+500.
          END IF

          QCT = 0.
          QCB = 0.
          QSPDT = SIGMA*EMH*ARD*(TH(1, 1, 0))**4.
          QSPDB = SIGMA*EMH*ARD*(TH(1, 1, NSA+1))**4.*(1.-FSE)
          DO 20 I=1, NSR
              QCT = QCT + 2.*CJ*(TH(1, I, 1)-TH(1, I, 0))
              QCB = QCB + 2.*CJ*(TH(1, I, NSA)-TH(1, I, NSA+1))
20        CONTINUE

          QRDIT = SIGMA*(PI*(HDIA**2.+CDIA**2.)/16.)/(1./EAL+1./ETB-1.) *
     #        ((TH(2, 1, 0))**4.-TIN**4.)
          QRDIB = SIGMA*(PI*(HDIA**2.+CDIA**2.)/16.)/(1./EAL+1./ETB-1.) *
     #        ((TH(2, 1, NSA+1))**4.-TIN**4.)

          TR2I = 0.
          DO 50 J=1, NSA
              DO 40 I=1, NSR
                  IF (I .LE. NSR/2) THEN
                      QSP = SIGMA*EMH*AR*(TH(1, I, J))**4.
                      IF (J .LE. NSA/2) THEN
                          QIRR = ABH*ISE*(1+RAL)*APIR(I)
                      ELSE
                          QIRR = 0
                      END IF
                  ELSE
                      QSP = SIGMA*EMH*AR*(1-FSE)*(TH(1, I, J))**4.
                      IF (J .GT. NSA/2) THEN
                          QIRR = ABH*FSE*(1+RCR)*APIR(I)*(EA*ISE+WE)
                      ELSE
                          QIRR = 0
                      END IF
                  END IF

                  DO 60 K=1, 2
                      QI1(K) = CI*(TH(K, I-1, J)-TH(K, I, J))
                      QI2(K) = CI*(TH(K, I, J)-TH(K, I+1, J))
                      QJ1(K) = CJ*(TH(K, I, J-1)-TH(K, I, J))
                      IF (J .EQ. 1) QJ1(K) = 2.*QJ1(K)
                      QJ2(K) = CJ*(TH(K, I, J)-TH(K, I, J+1))
                      IF (J .EQ. NSA) QJ2(K) = 2.*QJ2(K)
60                CONTINUE

                  QCR = CR*(TH(1, I, J)-TH(2, I, J))
```

```
              QR12 = SIGMA*EAL/(2-EAL)*(TH(1, I, J)**4.-TH(2, I, J)**4.)
     #             *PI*HDIA*HHGT/(2.*NSR*NSA)
              QR2I = SIGMA/(1./EAL+1./ETB-1.) * (PI*HDIA*HHGT+PI*CDIA
     #             * CHGT)/(4.*NSA*NSR) * (TH(2, I, J)**4. - TIN**4.)
              TR2I = TR2I + QR2I

              TH(1, I, J) = (QI1(1)-QI2(1)+QJ1(1)-QJ2(1)+QIRR-QSP
     #             -QR12-QCR) * DT / (CP*MSEG) + TH(1, I, J)
              TH(2, I, J) = (QI1(2)-QI2(2)+QJ1(2)-QJ2(2)+QR12
     #             +QCR-QR2I) * DT / (CP*MSEG) + TH(2, I, J)

              IF (I .EQ. 1) THEN
                   TH(1, 0, J) = TH(1, 1, J)
                   TH(2, 0, J) = TH(2, 1, J)
              END IF
              IF (I .EQ. NSR) THEN
                   TH(1, NSR+1, J) = TH(1, NSR, J)
                   TH(2, NSR+1, J) = TH(2, NSR, J)
              END IF

40           CONTINUE
50        CONTINUE

          TH(1, 0, 0) = (QSD-QSPDT+QCT-QRDIT)*DT / (CP*MD)
     #        + TH(1, 0, 0)
          TH(1, 0, NSA+1) = (QRD+QED+QCB-QSPDB-QRDIB)*DT/(CP*MD)
     #        + TH(1, 0, NSA+1)

          DO 30 I=0, NSR+1
               TH(1, I, 0) = TH(1, 0, 0)
               TH(1, I, NSA+1) = TH(1, 0, NSA+1)
               TH(2, I, 0) = TH(1, I, 0)
               TH(2, I, NSA+1) = TH(1, I, NSA+1)
30        CONTINUE

70   CONTINUE

     CALL HEAD ( 18, ': HUB TEMPER. DISTRIBUTION  (EARTH)')
     WRITE (18, '(A, I15, A/)') ' T = ', S, ' SEC'
     WRITE (18, '(2I5, 2F10.4)') 0, 0, TH(1, 0, 0), TH(2, 0, 0)
     DO 90 J = 1, NSA
          DO 80 I=1, NSR
               WRITE(18, '(2I5, 2F10.4)') I, J, TH(1, I, J), TH(2,I,J)
80        CONTINUE
90   CONTINUE
     J = NSA+1
     WRITE (18, '(2I5, 2F10.4)') 0, J, TH(1,0,NSA+1), TH(2,0,NSA+1)
     WRITE (18, '(/A)') ' + = CASE TO CORE '
     WRITE (18, '(A, F10.3)') ' HEAT EXCHANGE : ', 2.*(TR2I+
     #    QRDIT+QRDIB)
     PRINT *
     PRINT *, '   OUTPUT IN FILE "THUBDISE" ON CHANNEL 18  (CASE 1)'
     PRINT *

****CASE 8 *****************
```

```
      DO 110 J = 0, NSA+1
         DO 100 I = 0, NSR+1
            TH(1, I, J) = TI2
            TH(2, I, J) = TI2
100      CONTINUE
110   CONTINUE

      TIN = 273.16
      P = 500.
C     FSM = 0.
      FSM = (RM**2.)/(RAM**2.)
      QSD = ABH*ISM*APD
      QMD = WM*ABH*FSM*APD
      QRD = MA*ABH*ISM*FSM*APD

      DO 180 Z=0.5, S, DT

         IF (Z .EQ. P) THEN
            WRITE (*, '(A, F10.2)') '    SEC : ', Z
            P=P+500.
         END IF

         QCT = 0.
         QCB = 0.
         QSPDT = SIGMA*EMH*ARD*(TH(1, 1, 0))**4.
         QSPDB = SIGMA*EMH*ARD*(TH(1, 1, NSA+1))**4.*(1.-FSM)
         DO 120 I=1, NSR
            QCT = QCT + 2.*CJ*(TH(1, I, 1)-TH(1, I, 0))
            QCB = QCB + 2.*CJ*(TH(1, I, NSA)-TH(1, I, NSA+1))
120      CONTINUE

         QRDIT = SIGMA*(PI*(HDIA**2.+CDIA**2.)/16.)/(1./EAL+1./ETB-1.) *
     #      ((TH(2, 1, 0))**4.-TIN**4.)
         QRDIB = SIGMA*(PI*(HDIA**2.+CDIA**2.)/16.)/(1./EAL+1./ETB-1.) *
     #      ((TH(2, 1, NSA+1))**4.-TIN**4.)

         TR2I = 0.
         DO 140 J=1, NSA
            DO 130 I=1, NSR
               IF (I .LE. NSR/2) THEN
                  QSP = SIGMA*EMH*AR*(TH(1, I, J))**4.
                  IF (J .LE. NSA/2) THEN
                     QIRR = ABH*ISM*(1+RAL)*APIR(I)
                  ELSE
                     QIRR = 0
                  END IF
               ELSE
                  QSP = SIGMA*EMH*AR*(1-FSM)*(TH(1, I, J))**4.
                  IF (J .GT. NSA/2) THEN
                     QIRR = ABH*FSM*(1+RCR)*APIR(I)*(MA*ISM+WM)
                  ELSE
                     QIRR = 0
                  END IF
               END IF

               DO 150 K=1, 2
```

```
                     QI1(K) = CI*(TH(K, I-1, J)-TH(K, I, J))
                     QI2(K) = CI*(TH(K, I, J)-TH(K, I+1, J))
                     QJ1(K) = CJ*(TH(K, I, J-1)-TH(K, I, J))
                     IF (J .EQ. 1) QJ1(K) = 2.*QJ1(K)
                     QJ2(K) = CJ*(TH(K, I, J)-TH(K, I, J+1))
                     IF (J .EQ. NSA) QJ2(K) = 2.*QJ2(K)
150              CONTINUE

                 QCR = CR*(TH(1, I, J)-TH(2, I, J))
                 QR12 = SIGMA*EAL/(2-EAL)*(TH(1, I, J)**4.-TH(2, I, J)**4.)
  #                  *PI*HDIA*HHGT/(2.*NSR*NSA)
                 QR2I = SIGMA/(1./EAL+1./ETB-1.) * (PI*HDIA*HHGT+PI*CDIA
  #                  * CHGT)/(4.*NSA*NSR) * (TH(2, I, J)**4. - TIN**4.)
                 TR2I = TR2I + QR2I

                 TH(1, I, J) = (QI1(1)-QI2(1)+QJ1(1)-QJ2(1)+QIRR-QSP
  #                  -QR12-QCR) * DT / (CP*MSEG) + TH(1, I, J)
                 TH(2, I, J) = (QI1(2)-QI2(2)+QJ1(2)-QJ2(2)+QR12
  #                  +QCR-QR2I) * DT / (CP*MSEG) + TH(2, I, J)

                 IF (I .EQ. 1) THEN
                     TH(1, 0, J) = TH(1, 1, J)
                     TH(2, 0, J) = TH(2, 1, J)
                 END IF
                 IF (I .EQ. NSR) THEN
                     TH(1, NSR+1, J) = TH(1, NSR, J)
                     TH(2, NSR+1, J) = TH(2, NSR, J)
                 END IF

130          CONTINUE
140      CONTINUE

         TH(1, 0, 0) = (QSD-QSPDT+QCT-QRDIT)*DT / (CP*MD) + TH(1, 0, 0)
         TH(1, 0, NSA+1) = (QRD+QMD+QCB-QSPDB-QRDIB)*DT/(CP*MD)
  #          + TH(1, 0, NSA+1)

         DO 160 I=0, NSR+1
             TH(1, I, 0) = TH(1, 0, 0)
             TH(1, I, NSA+1) = TH(1, 0, NSA+1)
             TH(2, I, 0) = TH(1, I, 0)
             TH(2, I, NSA+1) = TH(1, I, NSA+1)
160      CONTINUE

180  CONTINUE

     CALL HEAD ( 19, ': HUB TEMPERAT. DISTRIBUTION (MARS)')
     WRITE (19, '(A, I15, A/)') ' T = ', S, ' SEC'
     WRITE(19, '(2I5, 2F10.4)') 0, 0, TH(1, 0, 0), TH(2, 0, 0)
     DO 200 J = 1, NSA
         DO 190 I=1, NSR
             WRITE(19, '(2I5, 2F10.4)') I, J, TH(1, I, J), TH(2, I, J)
190      CONTINUE
200  CONTINUE
     J = NSA+1
     WRITE(19, '(2I5, 2F10.4)') 0, J, TH(1,0,NSA+1), TH(2,0,NSA+1)
     WRITE (19, '(/A)') ' + = CASE TO CORE '
```

```
WRITE (19, '(A, F13.3)') ' HEAT EXCHANGE : ', 2.*(TR2I+
#    QRDIT+QRDIB)
PRINT *
PRINT *, '   OUTPUT IN FILE "THUBDISM" ON CHANNEL 19  (CASE 8)'

END


SUBROUTINE HEAD (CH, TEX)

INTEGER CH
CHARACTER TEX*35

INTEGER MODE
REAL SIGMA, PI
REAL RPE, RAE, RPM, RAM
REAL ISE, ISM, RE, RM, WE, WM, EA, MA, RSUN, AU
REAL AREA, HHGT, HDIA, THET
DOUBLE PRECISION ABAL, EMAL, ABCR, EMCR, ABH, EMH, RAL, RCR, EMM

COMMON / MAIN / SIGMA, PI, RPE, RAE, RPM, RAM, ISE, ISM, RE, RM,
#            WE, WM, EA, MA, AREA, HHGT, HDIA, THET,
#            ABAL, EMAL, ABCR, EMCR, ABH, EMH, RAL, RCR, EMM,
#            MODE, RSUN, AU

WRITE (CH, '(//2A///)') ' TEMPERATURE ESTIMATION ', TEX
WRITE (CH, '(2(A, F9.2), A, F5.3/)') ' RPE : ', RPE,
#    ' KM       RAE : ', RAE, ' KM       EA : ', EA
WRITE (CH, '(2(A, F9.2), A, F5.3/)') ' RPM : ', RPM,
#    ' KM       RAM : ', RAM, ' KM       MA : ', MA
IF (CH .NE. 10) THEN
     IF (CH .NE.11) THEN
          WRITE (CH, '(4(A, F6.3)/)') ' ABAL : ', ABAL, '     EMAL : ',
#              EMAL, '     ABCR : ', ABCR, '     EMCR : ', EMCR
          WRITE (CH, '(2(A,F6.3)/)') ' ABH  : ', ABH, '     EMH  : ', EMH
     END IF
END IF
WRITE (CH, '(A, F10.2, 2(A, F7.2), A/)') ' AREA : ', AREA,
#    ' M**2    HHGT : ', HHGT, ' M    HDIA : ', HDIA, ' M'
IF (CH .NE. 14) THEN
     IF (CH .NE.15) THEN
          WRITE (CH, '(A, F7.2///)') ' THETA : ', THET*180./PI
     ELSE
          WRITE (CH, '(///)')
     END IF
ELSE
     WRITE (CH, '(///)')
END IF

END


SUBROUTINE REOUT

INTEGER CH, I
CHARACTER LIN*79
```

```
      PRINT *,'    CHANNEL # : '
      READ *, CH
      REWIND CH

      DO 10, I=1, 5000
         READ (CH, '(A)', END = 20) LIN
         WRITE (*, '(A)') LIN
10    CONTINUE

20    END
```

Appendix B

The Fortran Program "QDOT"

Program Description

"QDOT" was used to determine the cool-down times of the spacecraft and the times needed to reach the equilibrium temperature of the disks for the hub temperature distribution calculations. Furthermore, it was used to compute the outgoing heat flux. The following listing is only one example of the different versions which were used during this study.

Program Listing

```
PROGRAM QDOT

REAL WPL, M, AS, FSP, FSSP, SIGMA, AR, ARPER, CP, ISE, EA, QOUT
DOUBLE PRECISION TI, DT, TE, TEQ

PARAMETER ( SIGMA = 5.67E-8, WPL = 150, FSP = 0.4272 )
PARAMETER ( FSSP = 0.5728, ARPER = 2.668, CP = 879, M = 2.2813)
PARAMETER ( TE = 273.16, TEQ = 329.38, AS = 0.145 , EMM = .105 )
```

```
      PARAMETER ( ISE = 590, EA = 0.15 )

      AR=3.2572
      T=0.
      DT=1.0

C     QT = (WPL+EA*ISE)*AS*FSP*ARPER
      QT = AS*ISE*ARPER
      WRITE (9, '(2F10.2)') 0, TE

      DO 10 TI = TE, TEQ+.1, DT
         DTI = 2.*CP*(DT)*M / (2.* QT
      #       - SIGMA*EMM*AR*((TI+DT)**4. + TI**4.))
         T = T+DTI
         QOUT = QT  - SIGMA*AR*EMM*TI**4.
         WRITE (9, '(2F15.5)') T/3600, TI+DT
         WRITE (10, '(2F15.2)') TI, QOUT
10    CONTINUE

      END
```

Vita

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Personal

Born March 3, 1965; in Hamburg, Federal Republic of Germany

Single

No Children

Education

Vordiplom - 1988	Technische Universitaet Braunschweig Major Maschinenbau
Internships	1986 MBB Flugzeugbau, Hamburg 11 Weeks 1990 mtu maintenance, Hannover 5 Weeks 1990 mtu, Muenchen 6 Weeks
Abitur - 1984	Albrecht Thaer Gymnasium

Military Service

Mandatory Military Service - 1984	15 Months, Bundeswehr Service as assistant instructor in a communications battalion

Maik Tiedem