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Estimating Payload Internal Temperatures and Radiator Size for Multimegawatt Space Platforms

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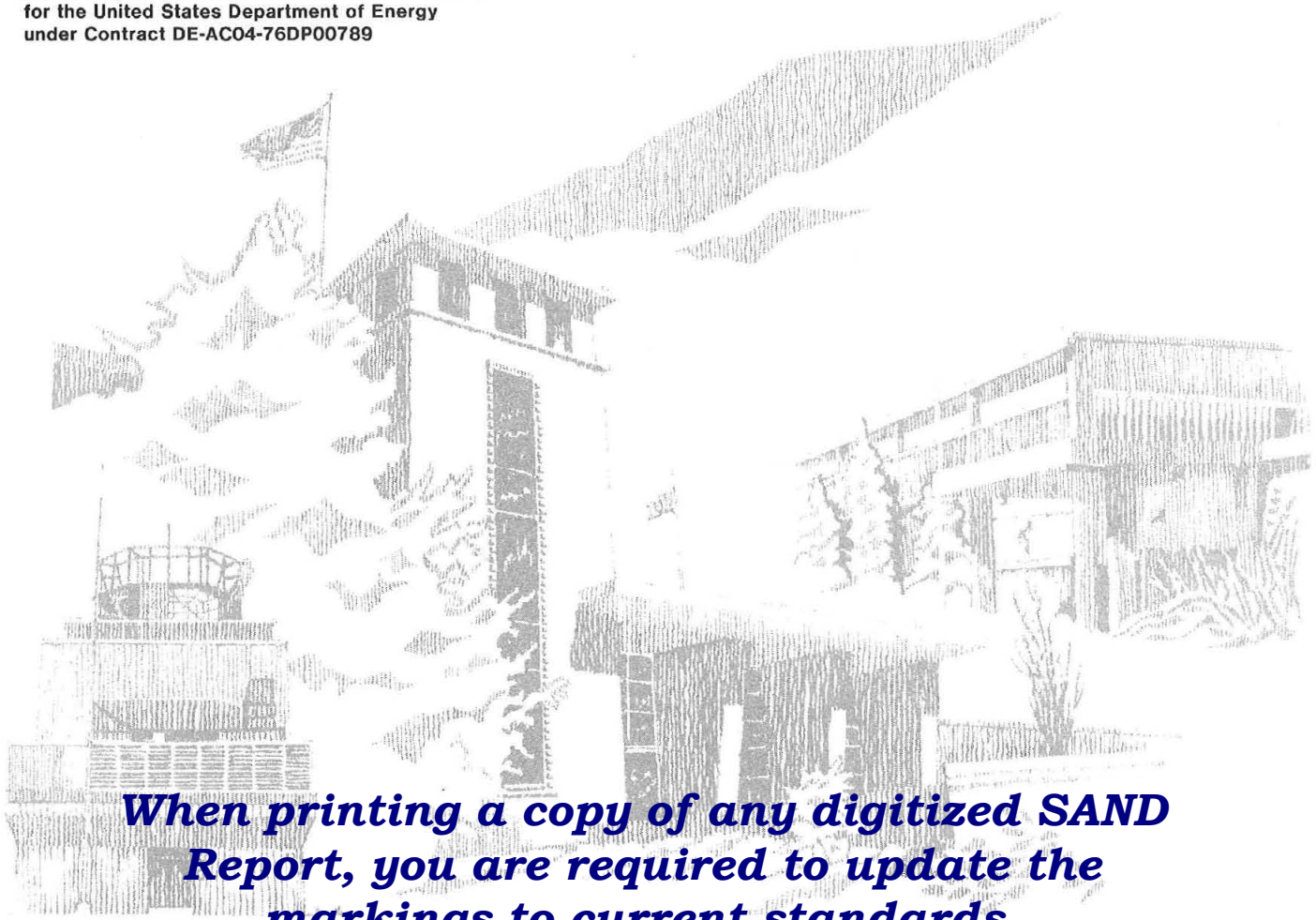

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ABSTRACT

A conceptual space platform consists of a payload, a power conditioning unit (PCU), and two radiators: the main radiator and a secondary radiator. A computer program was written to determine the required size of the two radiators and the temperatures of the PCU and payload for a given platform power level. An iterative approach is necessary because the required size of the main radiator depends on the size of the secondary radiator and vice versa. Also, the temperatures of the payload and PCU depend on the size of the radiators. The program user can subdivide the two radiators into any number of nodes to increase the accuracy of the radiant heat transfer solution. The use of more nodes also allows better prediction of the nonlinear temperature drop that occurs across the radiators as the working fluid deposits the platform's waste heat in the radiator. View factor expressions are automatically calculated for different choices of the number of nodes. The user can also select different separation distances between the various platform structures. A model is included to couple the radiant and conduction heat transfer that occurs between the payload and its meteoroid shell and between the PCU and its shell. Also, the program allows the use of a refrigerator to cool the payload. If a refrigerator is used, the program determines the amount of additional thermal power needed to run the refrigerator. The results of parametric calculations are included to demonstrate the use of the program.

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1.0 INTRODUCTION

Proposed multimegawatt (MMW) space-based platforms containing payloads of electronic equipment will require large amounts of electrical power for operation. The consumption of electrical power by the payload will result in the generation of waste heat which must be rejected to space, via radiant heat transfer, to keep the operating temperatures of the equipment within acceptable limits. An active cooling system can be used to cool the electronic equipment whereby a working fluid is pumped through a heat exchanger within the payload and then to an external (secondary) radiator. The size of the required secondary radiator will depend on several factors including the amount of waste heat to be rejected, the operation temperature of the radiator, and the proximity of the radiator to other platform components such as the payload and the power supply (main) radiator.

Determining the size of the secondary radiator is not straightforward because the presence of all of the major platform structures must be considered when performing the radiant heat transfer calculations. Figure 1.1 provides a schematic diagram of the four major structures comprising the platform. The four structures are (1) the main radiator, (2) the secondary radiator, (3) the power conditioning unit (PCU) and its shell, and (4) the payload and its shell.

The main and secondary radiators are represented as disks facing each other and separated by some specified distance. A disk radiating from both sides represents the most effective use of heat transfer area for a single radiator. However, if more than one radiator along with other relatively hot components are included on the platform, this configuration will not provide the most effective use of radiating area. Besides the relative radiator orientation, the optimum radiator configuration depends on other factors such as platform stability, maneuverability, survivability, and structural considerations. (The design of such a platform will certainly be a complicated and challenging endeavor.) The platform configuration used for the analyses described in this report was chosen for modeling simplicity and to demonstrate that the position of the platform components relative to each other strongly affects the radiant heat transfer calculations. These effects are demonstrated by varying the component separation distances in the radiant heat transfer calculations.

The main radiator must reject the waste heat associated with the primary power source of the platform. Most likely, a Brayton or Rankine thermodynamic cycle will be used for the thermal-to-electric conversion. The thermal-to-electric conversion efficiency will therefore be on the order of 20% to 30% and most of the primary power will be converted to waste heat. For a Brayton cycle, the temperature at which power is rejected to space is not constant, thereby further complicating the task of determining the radiator sizes.

The secondary radiator, as already mentioned, is required to remove the waste heat associated with the cooling of the electronic components comprising the PCU and payload. The fluid inlet temperature to this radiator is equal to the outlet temperature of the heat exchanger cooling the electronic components. Likewise, the fluid outlet temperature of the radiator is equal to the inlet temperature of the heat exchanger. For cooling of the electronic components, the temperature of the secondary radiator working fluid can not exceed the temperature of the components being cooled (unless a refrigerator is used). Thus, operation of the components at higher temperatures allows reduction of the secondary radiator area in two ways. First, less waste heat needs to be rejected actively to maintain a higher payload temperature, and second, the inlet and outlet temperatures of the secondary radiator can be higher.

The PCU and PCU shell are both modeled as cylinders with the outer cylinder representing the shell. The PCU consists of the electronic components required to convert the platform electrical power into a form which the payload can use. These components typically are about 95% efficient and thus a relatively small amount of waste heat will be generated within the PCU.

The payload and its shell are geometrically modeled the same way as the PCU and its shell. The payload consists of electronic equipment required for the operation of the platform such as computers, radars, radios, and guidance systems. Essentially all the electrical power consumed by these components will be converted to waste heat (with the possible exception of the radars). Active cooling of these components will therefore be essential.

Modeling all the electrical equipment as a single payload is based on the simplification that the different electronic components operate at the same temperature. In reality, each component will have different temperature limitations and may even require its own radiator.

Surrounding the PCU and payload will be shells. These shells serve two purposes: (1) to provide protection of the internal components from meteoroids, and (2) to provide additional surface area for radiation of waste heat to space. Thus, the PCU and payload each have a "shell radiator" surrounding them. Transfer of heat from the internals to the shell will occur by radiation and via conduction through any support structure. Also, heat pipes (which have very high effective conductivities) may be connected between the shell and the internals to take maximum advantage of the additional shell surface area.

A computer program has been written to model the heat transfer between the major structures of this conceptual space platform. Because the heat flux across the radiators will vary

with position, the program allows the user to divide the radiators into any number of nodes. Because view factors for all the surfaces of the platform cannot be determined until the sizes of the radiators are known, an iterative approach is used to solve for the radiator dimensions. Also, the maximum temperature at which the secondary radiator can operate depends on the temperatures of the PCU and payload. Again, an iterative scheme is used to determine this temperature. If a refrigerator is used to cool the payload, the program determines the additional thermal power required to run the refrigerator along with the resulting increase in the main radiator size. Finally, heat transfer from the PCU or payload to the PCU or payload shell will occur both by radiation and by conduction. Coupling of the two modes of heat transfer is accomplished by using the Modified Regula Falsi method for finding roots of a function.

This report contains a description of the models used in the program to determine the radiator sizes and the PCU and payload temperatures. Also, the results of parametric calculations are presented to demonstrate the heat transfer dependence on various input parameters such as the number of nodes, the separation distances between the various structures, the conduction parameters, and the use of a refrigerator.

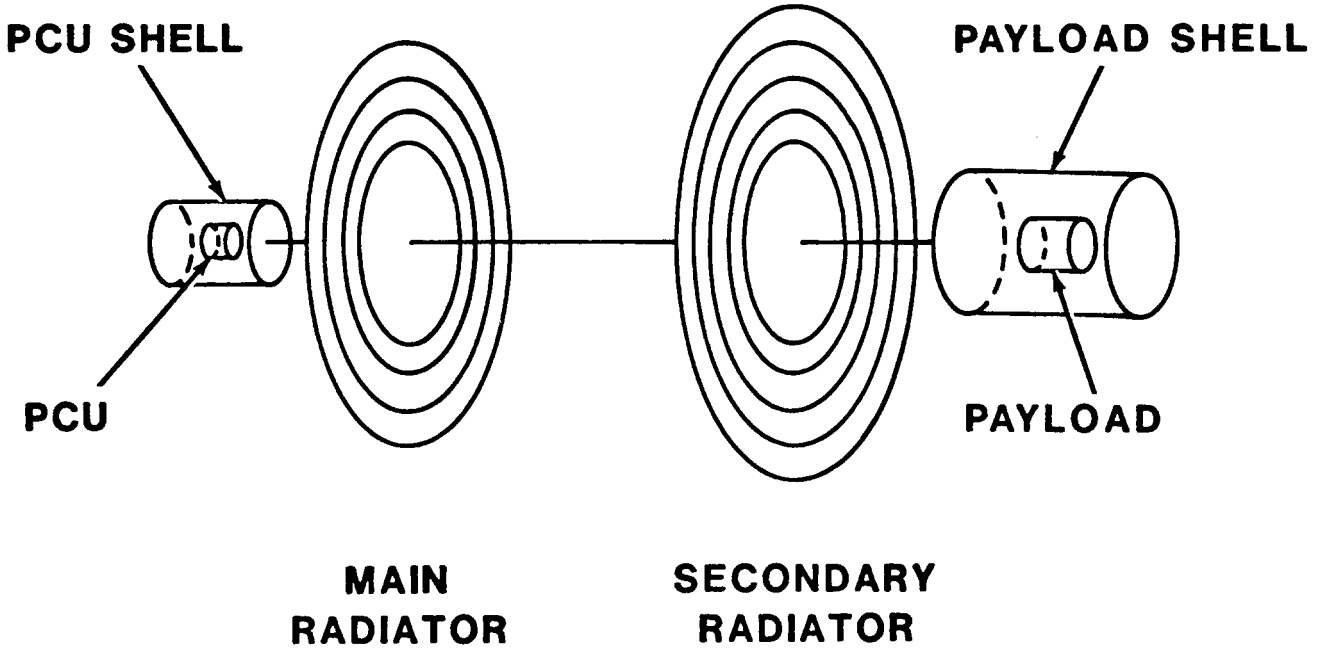


Figure 1.1 Schematic Diagram of Platform Structures

2.0 MATHEMATICAL MODELS

2.1 Radiosity Equations

The first step toward determination of the radiator sizes and the payload and PCU temperatures is the development of a model to calculate the radiant heat transfer between multiple surfaces. For this model, the assumption has been made that all the surfaces are gray and diffuse. A gray surface is one whose radiative properties (i.e., emissivity) are not a function of wavelength. A diffuse surface is one that emits and reflects radiation with equal intensity in all directions. The first assumption is reasonable for this model because most of the radiation will be emitted at relatively long wavelengths. The radiation properties for the surfaces of interest do not vary much at these long wavelengths. The second assumption is adopted because the directional characteristics of the surfaces simply are not known. The use of these two assumptions offers considerable simplification of the radiant heat transfer equations and is consistent with the level of accuracy required keeping in mind the conceptual nature of the space platform. (Such a platform has never been built or designed.)

To model the radiant heat transfer between the surfaces, a method known as the radiosity method [1] was used. This method, common in the literature, allows the calculation of radiant heat transfer between any number of surfaces. The radiosity of a surface is defined as the rate at which radiation leaves a surface by both emission and reflection. For N surfaces, a linear set of N equations with N unknowns is solved to determine the radiosity for each surface. From the radiosities, the heat flux or temperature can be determined for the surfaces.

Three types of surfaces are considered in the radiosity method: (1) surfaces for which the temperature is known, (2) surfaces for which the net heat flux is known, and (3) "two-sided" surfaces. A two-sided surface is one in which the temperatures of both sides of the surface are equal, although unknown. Also, the sum of the heat fluxes from both sides of the surface is known; however, the heat flux for each side is unknown. An example of a two-sided surface is a structure radiating to space (a radiator) with the sun shining on only one side. Thus, the heat flux leaving each side of the radiator is unknown even though the total heat produced by the radiator is known. If heat conduction from one side of the radiator to the other is very large (i.e., low thermal resistance), the two sides will have the same temperature; however, this temperature is unknown.

The equations relating the radiosity for one surface to the radiosity of all the other surfaces are derived in reference 1 for surface types 1 and 2; i.e., surfaces with either known temperature or net heat flux. These equations are given below.

$$\sigma T_i^4 = \frac{J_i}{\epsilon_i} - \left(\frac{1-\epsilon_i}{\epsilon_i}\right) \sum_j F_{ij} J_j \qquad (1)$$

$$\frac{q_i}{A_i} = J_i - \sum_j F_{ij} J_j \qquad (2)$$

where: J_i = radiosity for surface i,
T_i = temperature for surface i,
q_i/A_i = heat flux for surface i,
ϵ_i = emissivity for surface i,
F_{ij} = view factor from surface i to surface j, and
σ = Stefan-Boltzmann constant.

The equations for surface type 3, a two-sided surface, are derived below starting with equations (1) and (2) along with the additional constraints that:

$$T_i = T_k \qquad (3)$$

and,

$$Q = q_i + q_k \qquad (4)$$

The subscripts i and k refer to the two sides of the surface. In the matrix of radiosity equations, each side of a two-sided surface is represented as a separate surface. Therefore, information indicating what surfaces are "connected" to form a two-sided surface must be provided within the program.

First, equation (1) is written for both sides of the two-sided surface, i and k. These two equations can then be combined, using the first constraint given above (equation 3), to eliminate the unknown temperatures. Thus,

$$\frac{J_i}{\epsilon_i} - \left(\frac{1-\epsilon_i}{\epsilon_i}\right) \sum_j F_{ij} J_j = \frac{J_k}{\epsilon_k} - \left(\frac{1-\epsilon_k}{\epsilon_k}\right) \sum_j F_{kj} J_j \qquad (5)$$

Now, equation (2) is written for both sides of the surface and the second constraint (equation 4) is used to eliminate the unknown heat fluxes. Also note that the areas of both sides are equal and recall that Q is the total heat produced by the two-sided surface. Thus,

$$\frac{Q}{A} = J_i - \sum_j F_{ij} J_j + J_k - \sum_j F_{kj} J_j \qquad (6)$$

Equations (5) and (6) are now rewritten such that the radiosity for the i^{th} surface is isolated on the left side of the equal sign and all other terms are placed on the right. (This is done to place the equations in a form suitable for use with a Gauss-Siedel iterative scheme and to simplify the derivation.) The new equations are:

$$J_i = B\left[\frac{J_k}{\varepsilon_k} + \left(\frac{1}{\varepsilon_i} - 1\right) \sum_{j \neq i} F_{ij} J_j - \left(\frac{1}{\varepsilon_k} - 1\right) \sum_{j \neq i} F_{kj} J_j\right] \qquad (5')$$

$$J_i = G\left[\frac{Q}{A_i} - J_k + \sum_{j \neq i} \left(F_{ij} + F_{kj}\right) J_j\right] \qquad (6')$$

These summations are over all surfaces except the i^{th} surface because this term has been factored out. It is necessary to satisfy both the temperature and the heat flux constraints simultaneously for both sides of the two-sided surface. Therefore, equation (6′) is written for the k^{th} surface and then substituted into equation (5′) to yield a single equation for the radiosity of the i^{th} surface. After simplification and rearrangement:

$$J_i = B\left[\left(\frac{1}{\varepsilon_i} - 1\right) \sum_{j=i} F_{ij} J_j - \left(\frac{1}{\varepsilon_k} - 1\right) \sum_{j \neq i} F_{kj} J_j + \frac{G}{\varepsilon_k} \frac{Q_i}{A_i} + \frac{G}{\varepsilon_k} \sum_{j=k} \left(F_{ij} + F_{kj}\right) J_j\right] \Bigg/ \left[1 + \frac{B\,G}{\varepsilon_k}\right] \qquad (7)$$

where:

$$B = 1 \Bigg/ \left[\frac{1}{\varepsilon_i} - F_{ii}\left(\frac{1}{\varepsilon_i} - 1\right)\right], \quad G = 1 \Big/ \left(1 - F_{kk}\right)$$

Thus, equations (1), (2), and (7) can be used to determine the radiosities for surfaces within an enclosure containing surface types 1, 2, and 3, respectively. As already mentioned, a Gauss-Siedel iterative technique was chosen to solve these equations. In this technique, the initial radiosities for all surfaces are guessed. Using these initial values, new values are

calculated for each surface with the updated value used for each successive radiosity calculation. With this technique, any desired accuracy (which should be consistent with the accuracy of the radiation properties) can be chosen for the desired convergence criteria.

These equations were programmed for computer application in a subroutine called RADHT. Because of the generality with which the equations are written, it is possible to use this subroutine to solve for the radiation heat transfer within any enclosure simply by changing the input to the subroutine. To lend some confidence in the use of this subroutine, several assessment calculations were performed. The problems for these calculations were taken from various textbooks and are presented in Appendix A. Very good agreement with the textbook solutions was achieved for all cases.

2.2 Radiator Sizing Equations

The platform radiators have been assumed to be contact heat exchangers as discussed in reference 2. In a contact heat exchanger, a working fluid flowing in conduits transfers waste heat to heat pipes which are "plugged into" the conduit. The heat pipes then radiate the waste heat to space. For the disk radiators in this study, the conduits are like the spokes of a wheel and the heat pipes are connected circumferentially to form the disk. In a contact radiator, the contact resistance between the conduit and the heat pipes can be made very small such that the temperature drop across the contact can be considered insignificant. Also, the temperature drop from the working fluid to the conduit wall is typically less than 5 K [2]. Thus, very efficient use of the heat transfer area can be achieved. For the purposes of determining radiator size, the temperature drop from the fluid to the heat pipes was assumed to be zero. Because this temperature drop is really nonzero, the actual radiator size would be somewhat larger.

The input to subroutine RADHT, discussed in the previous section, includes the view factors between all the different surfaces of the enclosure. The problem arises that the view factors can not be determined until the dimensions of the radiators are known. To further complicate this problem is the fact that the temperature distribution from the inside edge to the outside edge of each disk radiator is also not known. This section includes a discussion of an iterative approach to solve this problem.

First, consider a radiator in the shape of a disk. Assuming $T = T_1 = T_2$, an energy balance on a differential area element, dA, of the radiator yields:

$$\dot{m} C_p dT = \left[\sigma \varepsilon_1 \left(T_1^4 - T_{s1}^4 \right) + \sigma \varepsilon_2 \left(T_2^4 - T_{s2}^4 \right) \right] dA \qquad (8)$$

where: ε_1 = surface emissivity of side 1,
ε_2 = surface emissivity of side 2,
T_1 = surface temperature of side 1,
T_2 = surface temperature of side 2,
T_{s1} = effective background temperature, side 1,
T_{s2} = effective background temperature, side 2,
σ = Stefan-Boltzmann constant.
$\dot{m}$ = working fluid mass flow rate, and
c_p = working fluid specific heat.

The boundary conditions for this differential equation are the radiator inlet and outlet temperatures which are program input values. The required value for the quantity $\dot{m}c_p$ can thus be determined as the heat to be rejected divided by the inlet to outlet temperature difference.

Therefore, for steady-state operation, the energy deposited in the differential area element by the radiator working fluid must equal the energy radiated from both sides of the radiator. The solution of this equation yields the temperature distribution across the radiator. The key to solving this equation is in finding an effective background temperature, T_s, that accounts for the presence of all the structures of the platform.

This equation can be simplified by making some algebraic substitutions. First, for the disk:

$$dA = 2\pi\, r\, dr$$

where r is the radius.

Also,

$$\bar{\varepsilon} = (\varepsilon_1 + \varepsilon_2)/2.0$$

$$C = -\dot{m}c_p/4\pi\bar{\varepsilon}\sigma$$

$$T_s^4 = (\varepsilon_1 T_{s1}^4 + \varepsilon_2 T_{s2}^4)/(\varepsilon_1 + \varepsilon_2)$$

This last substitution allows the replacement of two variables by a single variable. This implies that it is possible to determine a single effective background temperature for both sides of the element; i.e., it is not necessary to determine the effective background temperature for each side separately. This substitution considerably simplifies the solution because fewer variables are required and less computation per iteration is needed. Also, an analytical solution to the integral can be found. Without this substitution, the integration would have to be performed numerically.

These substitutions result in the following equation:

$$rdr = \left(\frac{C}{T_s^4 - T^4} \right) dT \qquad (9)$$

The solution to this differential equation can be determined by the integration of each side of the equation over the appropriate intervals. Thus,

$$\int_{R_I}^{R_O} rdr = \int_{T_I}^{T_O} \left(\frac{C}{T_s^4 - T^4} \right) dT \qquad (10)$$

where: R_I = the disk inner radius,
R_O = the disk outer radius,
T_I = the temperature at the inner radius, and
T_O = the temperature at the outer radius.

Performing the integration yields:

$$\frac{r_{i+1}^2}{2} = \frac{r_i^2}{2} + \frac{C}{4T_{si}^3} \left[\ln \left\{ \frac{(T_{si} + T_{i+1})}{(T_{si} - T_{i+1})} \frac{(T_{si} - T_i)}{(T_{si} + T_i)} \right\} + 2 \left\{ \arctan \left(\frac{T_{i+1}}{T_{si}} \right) - \arctan \left(\frac{T_i}{T_{si}} \right) \right\} \right] \qquad (11)$$

If the disk is subdivided into N nodes, equation (11) can be applied to each node where the subscripts i and i+1 refer to the inner and outer boundary of the node, respectively.

At this point, two different solution approaches could be used. The first approach is to use equation (11) to determine the outer radius of the radiator for a given value of T_s. (The inner radius, inside temperature, and outside temperature are known.) Now the radiator can be divided into N nodes of any arbitrary width. Equation (11) can then be used to solve for the temperatures at the boundaries of the nodes. These temperatures must be solved iteratively due to the transcendental nature of the equation. A simpler approach (the approach used in the program) is to assume that the node widths will be such that the temperature drop across all nodes is equal. Thus,

$$T_{i+1} = T_i + (T_I - T_O)/N$$

Now, equation (11) can be used to solve for the node radii directly. This approach has the additional benefit of automatically placing more nodes in the region of the largest temperature gradient.

With the node radii and end temperatures thus computed, it is necessary to determine an "average" temperature for each node. This average is not the algebraic average of the node end temperatures because of the fourth power temperature dependance for radiant heat transfer. To determine the average node temperature, consider an energy balance on the node.

$$\dot{m} c_p \left(T_i - T_{i+1}\right) = 2\sigma\bar{\varepsilon}\pi \left(r_{i+1}^2 - r_i^2\right)\left(\bar{T}_i^4 - T_{si}^4\right) \qquad (12)$$

where $\bar{T}_i$ is the average temperature that satisfies this equation. Rearranging this equation yields:

$$\bar{T}_i = \left[\frac{2C\left(T_{i+1} - T_i\right)}{r_{i+1}^2 - r_i^2} + T_{si}^4\right]^{1/4} \qquad (12')$$

Now equation (10) can be used to determine the radius at which the average temperature occurs. To do this, perform the integration with r_i as the upper limit of integration for r and T_i as the upper limit of integration for T.

Thus, equations (11) and (12′) can be used to determine the dimensions and temperature distribution of the radiator for a given effective background temperature, $T_{s,i}$, for each node. The task now is to determine the T_s values for both radiators. The following iterative procedure is used to accomplish this task.

STEP 1: Use the effective temperature of space as a first guess to T_s for each node.

STEP 2: Use equations (11) and (12′) to determine the node radii and temperatures.

STEP 3: Now that values for the radiator dimensions exist, view factors for all the surfaces of the platform can be calculated. Also, values for the average node temperatures exist. Therefore, the subroutine RADHT can be used to determine the heat fluxes and temperatures for all surfaces.

STEP 4: Now calculate the power radiated away by both sides of each node using the RADHT calculated values of heat flux. Thus,

$$P_i = q_i + q_k \qquad (13)$$

where the q's are the product of the node heat flux and area. The i and k subscripts indicate the two sides of the node. Now, for each node,

$$P_i = 2A_i \sigma\bar{\varepsilon} \left(\bar{T}_i^4 - T_{s,i}^4\right) \qquad (14)$$

Rearranging yields an expression for updating the values of T_s,

$$T_{s,i}' = (\bar{T}_i^4 - P_i/A_i 2\,\sigma\bar{\epsilon}\,)^{1/4} \qquad (14')$$

STEP 5: Now, the updated values of T_s can be compared to the previous values. Steps 1 through 4 can then be repeated until these values converge or when the P_i values converge to the desired degree of accuracy.

Use of the Gauss-Siedel iterative technique for solving the radiosity equations fits in well with this procedure because the radiosities from the previous iteration can be used for the initial guess for the current iteration.

Subroutine RADSIZE contains the logic to perform the radiator-sizing calculations. The subroutine has been written to allow the radiator inlet temperature to be at either the inside or outside radius of the radiator. As will be discussed later, it may be advantageous (with respect to minimizing required radiator area) to deliver the hot working fluid to the outside of the radiator first, via insulated conduits, and to then collect the cooler fluid at the inner radius.

If the radiator is to reject heat at a constant temperature (as would be the case for a Rankine cycle main power supply), the radiator inlet and outlet temperatures are equal and thus the temperature distribution across the radiator is known. For this case, the preceding procedure is simplified. Now, equation (14) can be used to solve for the node areas directly because the node temperatures are known. However, the effective background node temperatures remain as unknowns and the iterative approach is still required.

2.3 View Factors

It is necessary to calculate view factors between all surfaces of the platform. This is done in subroutines VIEW1 and VIEW2. Subroutine VIEW1 determines the view factors between the payload and PCU and their shells. The view factors between these structures need to be calculated only once because the dimensions for these structures are fixed. Subroutine VIEW2 determines the view factors between all the nodes of the two radiators and all other surfaces. Because the dimensions of the radiators are determined iteratively, it is necessary to recalculate these view factors for each iteration.

Both view factor subroutines make use of only two basic view factor expressions. All other view factors are determined by view factor algebra or by using the fact that the sum of the view factors from one surface to all the others must equal 1.0.

The two basic view factor expressions are for a disk-to-disk and a cylinder-to-concentric-cylinder. The expressions for the two view factors are taken from reference 3. A considerable amount of view factor algebra is required to arrive at expressions for view factors between cylinders and rings and between rings and other rings. Figure 2.3.1 provides schematic diagrams of the different geometries for which view factors are calculated. Subroutines VIEW1 and VIEW2 make use of other subroutines and functions to calculate all the required view factors. The following is a list of these subroutines and functions.

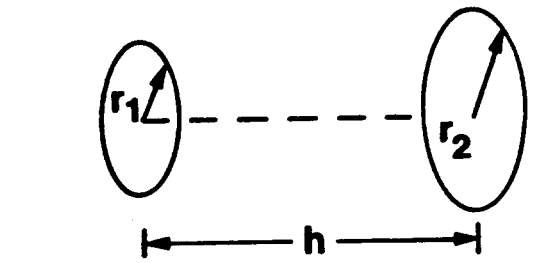
FUNCTION DTOD - determines the view factor between a disk of radius r_1 to another disk of radius r_2 separated by distance h. (See reference 3, page 826, #21.)

FUNCTION CTOD - determines the view factor between a cylinder of radius r_1 and an adjacent and perpendicular disk of radius r_2. Some view factor algebra is included starting with the view factor between two concentric cylinders. (See reference 3, page 828, #28.)

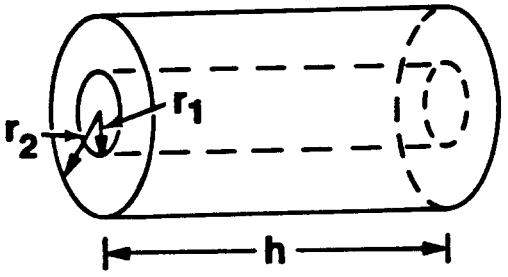
SUBROUTINE FRINGS - uses function DTOD and view factor algebra to determine ring-to-ring view factors. The rings are separated by distance h.

SUBROUTINE CTORING - uses function CTOD and view factor algebra to determine cylinder-to-ring view factors. The cylinder and ring are separated by distance h.

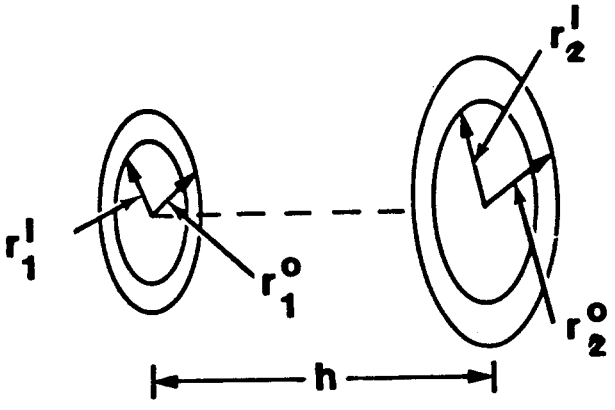
Because the radiators can be divided into any number of nodes, the view factor subroutines must be written with the number of nodes as a parameter. The details of the bookkeeping and the view factor algebra used to arrive at all the view factors will not be explained in any further detail. However, Appendix B, which contains a computer listing of the entire program, can be examined for the appropriate FORTRAN expressions.



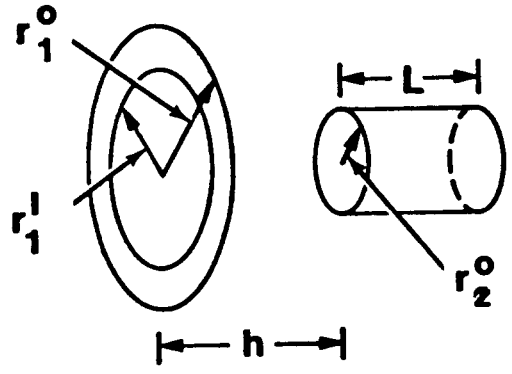
Disk-to-Disk



Cylinder-to
-Concentric
Cylinder



Ring-to-Ring



Cylinder-to-
Ring

Figure 2.3.1 View Factor Geometries

2.4 Coupled Heat Transfer Modes

The radiator-sizing equations discussed in the previous sections can be solved without considering conduction between the payload (or PCU) internals and the shell because only the total heat flux leaving the shell is of consequence for radiator sizing. In other words, it doesn't matter if the waste heat generated in the internals is transferred to the shell by conduction or radiation; it is the total heat transferred that determines the shell temperature and heat flux. Therefore, the radiator-sizing calculations can be performed assuming that all the waste heat is transferred from the internals to the shell by radiation and that none of the waste heat is transferred to the shell by conduction. However, determining the temperature of the internals does depend on the amount of waste heat removed by conduction and radiation.

Waste heat generated in the PCU and payload internals will be transferred from the internals to the shell by both radiation and conduction. The conduction will occur along the support structure used to support the shell. Also, heat pipes may be connected between the internals and shell to greatly improve this heat transfer mechanism. Heat pipes have very large effective thermal conductivities and essentially can transfer heat isothermally. The coupling of the conduction and radiation heat transfer modes is nonlinear because conduction is proportional to the first power of temperature; whereas, radiation is proportional to the fourth power. To accomplish this coupling, use was made of the Modified Regula Falsi [4] method for finding roots of a function. This coupling approach is discussed in this section.

An energy balance on the internals can be written as:

$$q - q_v - q_d - q_r = 0.0 \qquad (15)$$

where: q = total waste heat generated,
q_v = waste heat removed by convection,
q_d = waste heat removed by conduction, and
q_r = waste heat removed by radiation.

The expression for the convection term depends on the type of heat exchanger used to cool the internals; i.e., the number of fluid passes, the size and type of fins, etc. Given the conceptual nature of the platform, convection heat transfer is not modeled in detail. Instead, the convection term is treated parametrically such that q_v is assumed to be a known quantity. (The convection term will be discussed in more detail later in this section.) Thus, two terms in equation (15) are unknown, namely, q_d and q_r. Equation (15) can be rewritten in the form of a function as:

$$f(q_r) = q - q_v - q_d - q_r \qquad (15')$$

Finding the values of q_r and q_d that make this function equal to zero is desired. This is equivalent to finding the root of an equation for which the Modified Regula Falsi method is applicable.

To evaluate the radiation term, the radiosity equations of Section 2.1 can be used for the internals and shell surfaces. Solution of the equations yields the shell and internal temperatures from which the conduction term can be calculated using:

$$q_d = (kA/x)\ \Delta T$$

where: k = effective thermal conductivity,
A = heat transfer area for conduction,
x = conduction path length, and
ΔT = temperature drop from internals to shell.

Thus, q_d is a function of the unknown internals temperature which is a function of q_r. Choosing $q_r = 0.0$ (i.e., all the waste heat is removed from the internals by conduction) and $q_r = q - q_v$ (i.e., all the waste heat is removed by radiation) provides an interval containing a root that satisfies equation (15'). Starting with this interval, the Modified Regula Falsi method quickly finds the root and thus the internals temperature. This is equivalent to solving the radiation and conduction equations simultaneously. However, use of the Modified Regula Falsi method allows one to keep the expressions for conduction and radiation separate. A graphical depiction of this process is shown in Figure 2.4.1. The program was written such that either the kA/x value or the ΔT value can be input. If ΔT is input, the required kA/x value to achieve this ΔT is calculated.

Returning to the convection term, recall that q_v was treated as a known quantity. To obtain an order of magnitude estimate of the hA value required to remove the specified amount of waste heat, Newton's law of cooling can be used. The waste heat removed by convection is thus expressed as:

$$q_v = hA(T - T_c) \qquad (16)$$

where: h = effective heat transfer coefficient,
A = total heat transfer area available,
T = temperature of the internals, and
T_c = average coolant temperature.

An estimate of the value of T_c is made using the algebraic average of the heat exchanger inlet and outlet temperatures. Note that for heat transfer from the internals to the fluid, the fluid temperature must be less than the internals temperature. Also, recall that the outlet temperature of the heat exchanger

is equal to the inlet temperature of the secondary radiator. The inlet temperature of the secondary radiator must be known before the radiator can be sized. Therefore, a guess is made for this temperature and the radiator-sizing calculations and conduction-convection coupling calculations are performed. An updated value is then calculated based on the calculated temperature of the internals. Thus,

$$T_I = T - \Delta t_{min}$$
$$T_O = T_I + \Delta T$$

where: T_I = the secondary radiator inlet temperature (equivalent to the heat exchanger outlet temperature),
T_O = the secondary radiator outlet temperature (equivalent to the heat exchanger inlet temperature),
ΔT = the desired radiator temperature difference,
T = the internals temperature, and
Δt_{min} = the minimum allowed temperature difference between the internals and cooling fluid.

Figure 2.4.2 graphically demonstrates the relationship between the various temperatures. The updated values of T_I and T_O are then used to repeat the radiator sizing and internal temperature calculations.

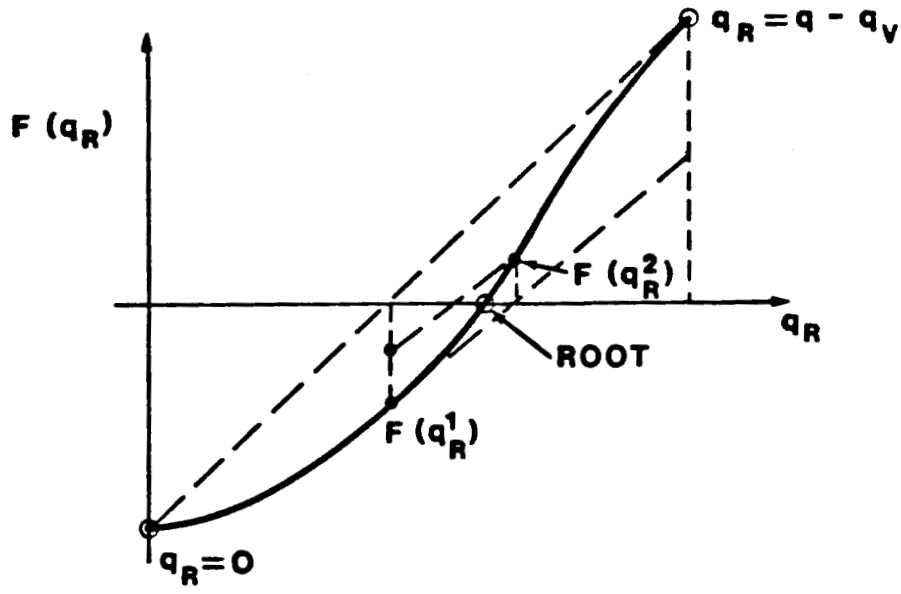


Figure 2.4.1 The Root of the Conduction-Radiation Equation

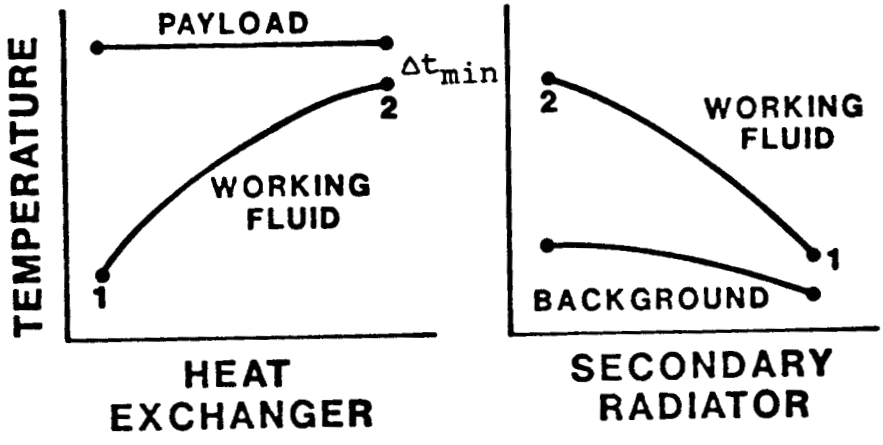


Figure 2.4.2 Radiator and Internal Temperature Relationship

2.5 Refrigerator Model

The computer program has been written so that the use of a refrigerator to cool the payload internals can be investigated. The possible benefit of a refrigerator is that it allows the rejection of payload waste heat at a temperature higher than the payload, thereby decreasing the size of the required secondary radiator. However, because additional power is required to run the refrigerator, more waste heat associated with the main power supply will be generated necessitating a larger main radiator.

The refrigerator coefficient of performance (COP) is calculated as some specified fraction of the Carnot COP. The Carnot COP (COP_C) is calculated as:

$$COP_C = T_l / (T_h - T_l) \qquad (17)$$

where: T_l = the lowest temperature of the working fluid, and
T_h = the highest temperature of the working fluid.

The secondary radiator is assumed to operate at T_h. The working fluid is assumed to operate at the payload temperature minus some specified payload-to-working fluid temperature difference. Because the payload temperature is unknown, an iterative procedure is employed to determine the value of T_l such that T_l equals the calculated payload temperature minus the specified payload-to-working fluid temperature difference.

The amount of electric power needed to power the refrigerator, W, is determined as Q divided by COP where Q is the amount of waste heat to be removed by the refrigerator. (The waste heat associated with the refrigerator is not included in the payload waste heat.) The amount of additional thermal power required is found as W divided by the thermal-to-electric power conversion efficiency. An increase in the power supply increases the amount of waste heat to be rejected by the main radiator. Thus, the required size of the main radiator must be updated each iteration.

3.0 COMPUTER PROGRAM APPLICATION

3.1 Example Input and Output

To demonstrate the use and capabilities of the computer program, several parametric calculations were performed. This section includes a description of these calculations. An annotated example input file is given in Table 3.1.1. The annotations provide a concise description of the required input variables. This example input provides a "base case" on which all subsequent parametric calculations are based. The resulting program output for this example problem is provided in Appendix C. Only three nodes for the main radiator and four nodes for the secondary radiator were used to keep the output relatively short.

Table 3.1.1 Sample Program Input

```
15              MAXIMUM ITERATIONS FOR RADIATOR SIZING (- FOR DEBUG)
0.01            RADIATOR-SIZING RELATIVE CONVERGENCE CRITERIA
20              MAXIMUM ITERATIONS FOR GAUSS-SIEDEL SOLUTION
0.005           GAUSS-SIEDEL RELATIVE CONVERGENCE CRITERIA
3               NUMBER OF MAIN RADIATOR NODES
4               NUMBER OF SECONDARY RADIATOR NODES
0.90            EMISSIVITY OF LEFT SIDE OF MAIN RADIATOR
0.90            EMISSIVITY OF RIGHT SIDE OF MAIN RADIATOR
0.90            EMISSIVITY OF LEFT SIDE OF SECONDARY RADIATOR
0.90            EMISSIVITY OF RIGHT SIDE OF SECONDARY RADIATOR
0.9,0.9,0.9     EMISSIVITY OF INSIDE OF PCU SHELL (LEFT,CENTER,RIGHT)
0.9,0.9,0.9     EMISSIVITY OF OUTSIDE OF PCU SHELL (LEFT,CENTER,RIGHT)
0.9,0.9,0.9     EMISSIVITY OF INSIDE OF PAYLOAD SHELL (LEFT,CENTER,RIGHT)
0.9,0.9,0.9     EMISSIVITY OF OUTSIDE OF PAYLOAD SHELL (LEFT,CENTER,RIGHT)
0.80            EMISSIVITY OF PCU
0.80            EMISSIVITY OF PAYLOAD
300.0           EFFECTIVE TEMPERATURE OF SPACE (K)
480.0           TEMPERATURE AT INNER RADIUS OF MAIN RADIATOR (K)
985.0           TEMPERATURE AT OUTER RADIUS OF MAIN RADIATOR (K)
470.0           TEMPERATURE AT INNER RADIUS OF SECONDARY RADIATOR (K)
400.0           TEMPERATURE AT OUTER RADIUS OF SECONDARY RADIATOR (K)
6.0             INNER RADIUS OF MAIN RADIATOR (M)
7.0             INNER RADIUS OF SECONDARY RADIATOR (M)
1.0             SEPARATION DISTANCE BETWEEN PCU AND MAIN RADIATOR (M)
30.0            SEPARATION DISTANCE BETWEEN MAIN AND SEC RADIATOR (M)
1.0             SEPARATION DISTANCE BETWEEN SEC RADIATOR AND PAYLOAD (M)
8.0             DIAMETER OF PCU SHELL (M)
12.0            LENGTH OF PCU SHELL (M)
10.0            DIAMETER OF PAYLOAD SHELL (M)
15.0            LENGTH OF PAYLOAD SHELL (M)
6.0             DIAMETER OF PCU (M)
10.0            LENGTH OF PCU (M)
8.0             DIAMETER OF PAYLOAD (M)
12.0            LENGTH OF PAYLAOD (M)
40.0E6          TOTAL PLATFORM THERMAL POWER (W)
0.25            THERMAL-TO-ELECTRIC CONVERSION EFFICIENCY
0.0             FRACTION OF CARNOT REFRIGERATOR COP (IF 0.0, NO REFRIGERATOR
0.05            FRACTION OF ELECTRIC POWER CONVERTED TO PCU WASTE HEAT
0.0             FRACTION OF PCU WASTE HEAT REMOVED ACTIVELY (TO SEC RAD)
0.9             FRACTION OF ELECTRIC POWER CONVERTED TO PAYLOAD WASTE HEAT
0.9             FRACTION OF PAYLOAD WASTE HEAT REMOVED ACTIVELY (SEC RAD)
-5.0            MIN DELTA-T BETWEEN PAYLOAD AND SEC RAD WORKING FLUID *
-2.0            KA X (-) OR DESIRED DELTA-T (-) FOR PCU SHELL CONDUCTION
-2.0            KA X (-) OR DESIRED DELTA-T (-) FOR PAYLOAD SHELL CONDUCTION
```

* IF < 0, VARIABLE NOT USED AND THE INPUT VALUES FOR SECONDARY RADIATOR INLET AND OUTLET TEMPERATURE ARE USED AS INPUT (NO ITERATION).
IF A REFRIGERATOR IS USED, THIS IS THE TEMPERATURE DIFFERENCE BETWEEN THE PAYLOAD AND THE REFRIGERATOR WORKING FLUID.

The first page of the output provides information concerning the nodes of the two radiators, such as the node radius, area, temperature, and the effective background temperature for each node. This information is calculated by subroutine RADSIZE. The next page provides the final output, such as radiator areas, and PCU and payload temperatures. The third page provides surface identification numbers for all the surfaces used in the radiant heat transfer solution as computed in subroutine RADHT. Next is a list of the view factors between all the surfaces. Even with only a few nodes for each radiator, there are 841 view factors for this example problem. Many of these view factors are zero, however, and are not printed. The last page of output displays the results of the final call to subroutine RADHT; this includes the radiosities for each of the 29 surfaces.

3.2 Radiator Nodes

The number of nodes used for each radiator affects the final calculated radiator area with the greater number of nodes providing the more accurate results. Table 3.2.1 shows the effect of varying the number of nodes in the secondary radiator (the number of nodes in the main radiator is held constant) for two different values of waste heat delivered to the secondary radiator. This demonstrates that the choice of the number of nodes depends on the particular problem being solved; thus, care should be taken in selecting an appropriate number of radiator nodes. (The separation distance between the two radiators was also found to have a big influence on the number of nodes required.)

Table 3.2.1 Effect of the Number of Radiator Nodes

Waste Heat = 8.1 MW

# Nodes	Secondary Radiator Area (m^2)
3	6198
6	6093
12	6078
20	6075

Waste Heat = 4.5 MW

# Nodes	Secondary Radiator Area (m^2)
6	3905
12	3042
20	2976
30	2966

Figure 3.2.1 demonstrates the convergence of the effective background temperature used in determining radiator size. Twelve nodes were used in the secondary radiator for this example. The initial guess for the effective background temperature for each node was 300 K. The values of the twelve node temperatures for the next three iterations (the curves labeled 2, 3, and 4) show

that convergence occurs after some oscillations. Originally, the oscillations were even more severe. To dampen the oscillations, the updated T_s values were modified according to:

$$T_s = w\ T_s(\text{current}) + (1-w)\ T_s(\text{previous})$$

where w was chosen to be 0.8. This relaxation value, determined by trial and error, was found to work reasonably well for most problems.

Table 3.2.2 shows information related to the iterations required to determine the radiator sizes. In this table, L is the radiator-sizing iteration number and M is the number of iterations required for the radiosity equations (subroutine RADHT) to converge. The total power is the sum of all the node powers. For this example, the desired main radiator total power was 30.0 MW and the desired secondary radiator total power was 8.1 MW. Thus, the radiator sizing iterative scheme converges rapidly for this problem.

Table 3.2.2 Iteration Summary

L	M	Maximum Node Power Relative Error	Total Power (main radiator)	Total Power (sec radiator)
1	9	0.7261	28.71 MW	2.489 MW
2	4	0.3110	29.16 MW	10.450 MW
3	2	0.1309	30.00 MW	7.864 MW
4	1	0.0074	30.00 MW	8.090 MW

All of the calculations discussed in this section are based on the use of an effective temperature of space equal to 300 K. (The effective temperature of space should not be confused with the effective background temperature which accounts for the presence of all platform structures and space.) The effective space temperature accounts for the radiation arriving from the sun (directly or reflected off the earth) along with the radiation emitted by the earth. This value is a function of platform orientation, altitude, orbit inclination, geometry, and surface-coating properties and can be expected to range anywhere from 200 K to 360 K for anticipated platform applications. The value of 300 K was chosen as a representative intermediate value.

Figures 3.2.2 and 3.2.3 show the main and secondary radiator temperatures, respectively. The main radiator has 10 nodes and the secondary radiator has 12 nodes. Also, the radiators are 30 m apart. The fluid inlet to the main radiator was chosen to be at the outer radius of the disk while the inlet for the secondary radiator is at the inner radius. This arrangement resulted in the smallest total radiator area. If the inlet to

the secondary radiator is reversed, the cooler nodes close to the inner radius do not reject heat very well because the presence of the hot main radiator and payload shell result in a very high effective background temperature for those nodes. An alternative to reversing the flow direction would be to increase the inner radius of the secondary radiator, thereby effectively moving the radiator away from the other platform structures.

The effective background temperature for the main radiator nodes is relatively flat indicating that the other surfaces of the platform do not have a significant impact on the main radiators ability to reject heat. This is because the main radiator operates at a high temperature compared to other surfaces. The effective background temperature for the secondary radiator nodes, however, is large relative to the radiator temperature because the temperatures of the other surfaces of the platform are relatively high. These two figures also show that the temperature distributions of the two radiators are completely different. This is due to the different relative influence of each platform surface on each radiator because of their different spacial orientations. Changing the flow direction, the PCU and payload sizes, and the platform structure separation distances all have significant impact on the radiator temperature distribution.

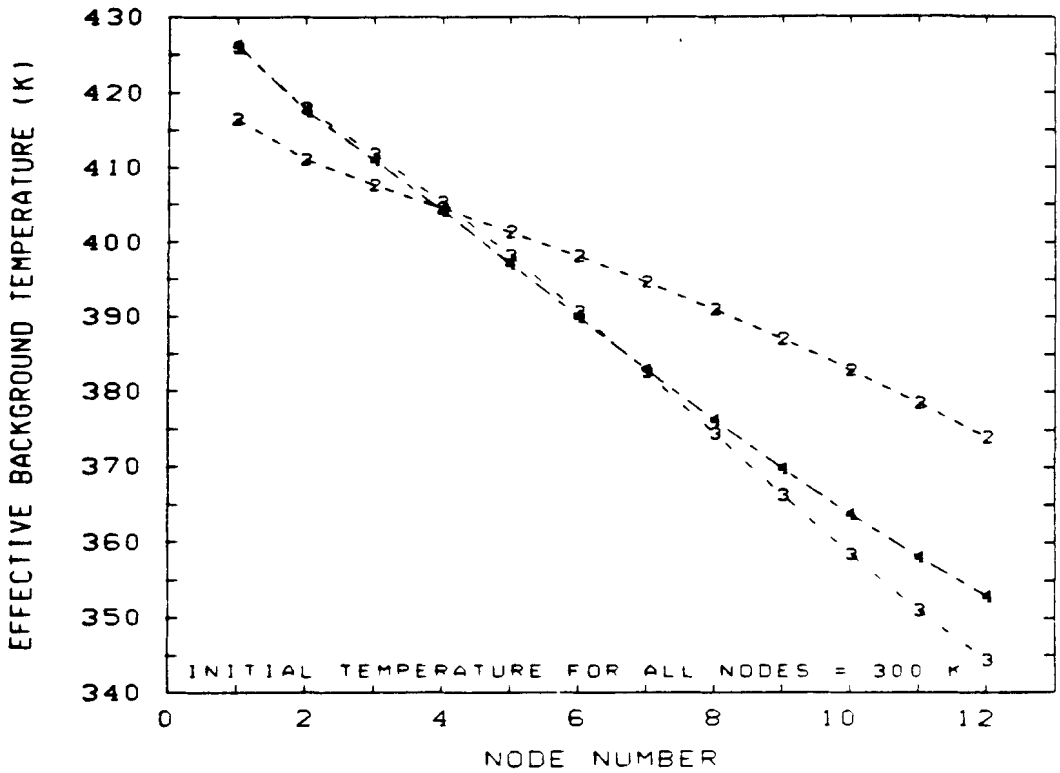


Figure 3.2.1 Radiator Sizing Iterations

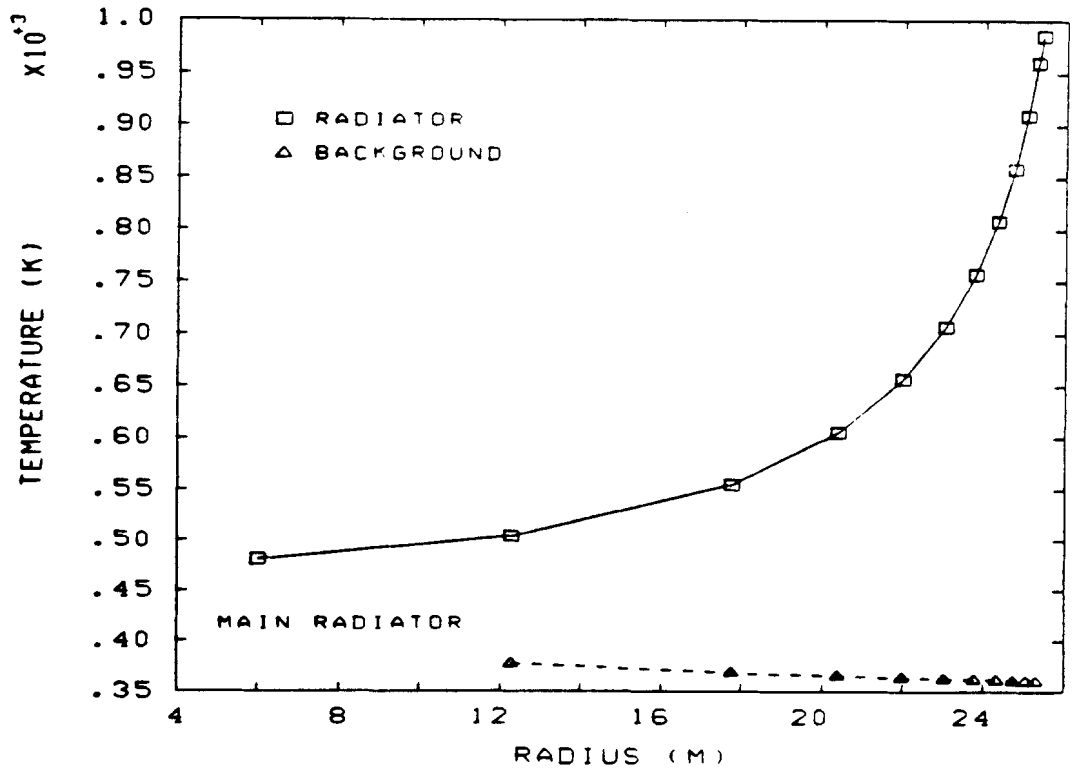


Figure 3.2.2 Main Radiator Temperature Distribution

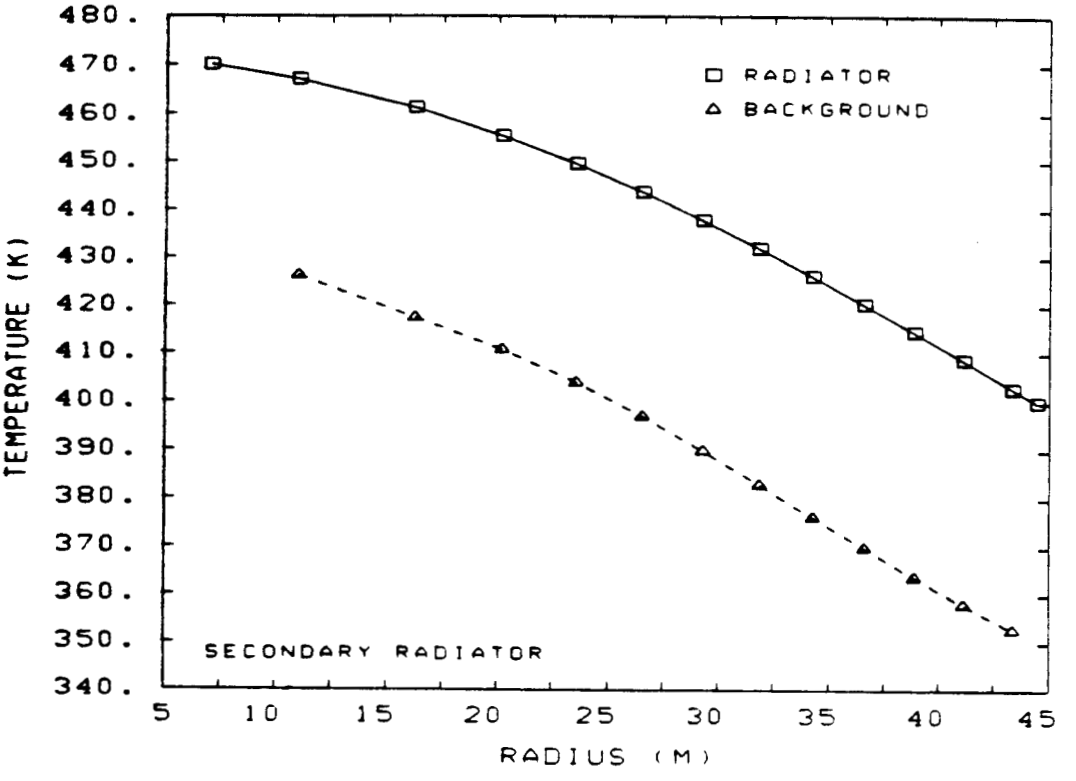


Figure 3.2.3 Secondary Radiator Temperature Distribution

3.3 Conduction

Figure 3.3.1 shows the effect of payload-to-shell conduction on the payload temperature. It is not clear if sufficient room would exist for enough heat pipes to achieve the kA/x values shown on this curve. However, a set of parametric calculations was performed to show the possible benefit of using heat pipes to remove payload waste heat. The payload temperature drops very rapidly as the kA/x value is increased. It is clear that without any heat pipes the payload temperature would be much higher.

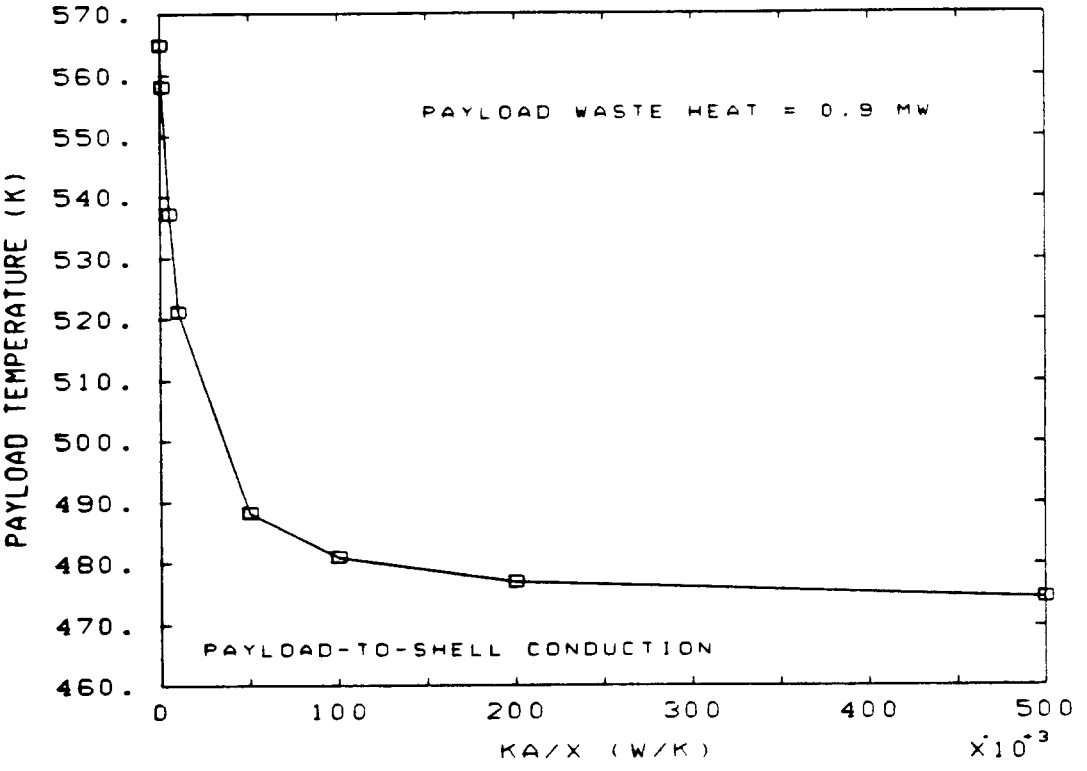


Figure 3.3.1 Payload-to-Shell Conduction

3.4 Separation Distance

The geometric parameter that has the most effect on the size of the radiators is the separation distance between the main and secondary radiators. This effect is demonstrated in Figure 3.4.1 which shows the secondary radiator area as a function of separation distance for two different amounts of waste heat delivered to the secondary radiator. It is apparent that increasing the separation distance greatly reduces the required size of the radiator. The size of the main radiator (not shown on the Figure) varies between 2300 m^2 and 1550 m^2 for separation distances from 10 m to 300 m. The effect of separation distance on the main radiator is not as significant because it operates at a much higher temperature than the secondary radiator. However, if the operating temperature of the secondary radiator is increased or the temperature of the main radiator decreased, the effect on the main radiator size would become more significant.

The radiator separation distance also influences the PCU and payload temperatures as shown in Figure 3.4.2. The payload temperature is affected more because the hot main radiator has the largest influence on the payloads ability to radiate waste heat to space.

Another parameter that affects the size of the radiators and the payload and PCU temperatures is the separation distance between the shells (PCU and payload) and the radiators. (To show this effect, a radiator-to-radiator separation distance of 500 m was used; thus, the radiators are far enough apart to preclude any influence on each other.) Figure 3.4.3 shows the effect of varying these separation distances on the radiator areas. The reason the radiator areas increase for separation distances from about 2 m to 10 m is that more of the shell views the adjacent radiator in this range of separation distances. At zero separation distance, only the curved surface of the shell views the adjacent radiator. As the separation distance is increased, one end of the shell also begins to view the radiator, resulting in an overall increase in the shell-to-radiator view. Further increases in the separation distance result in an overall decrease of this view such that the required radiator area decreases. A similar effect on payload and PCU temperatures is shown in Figure 3.4.4.

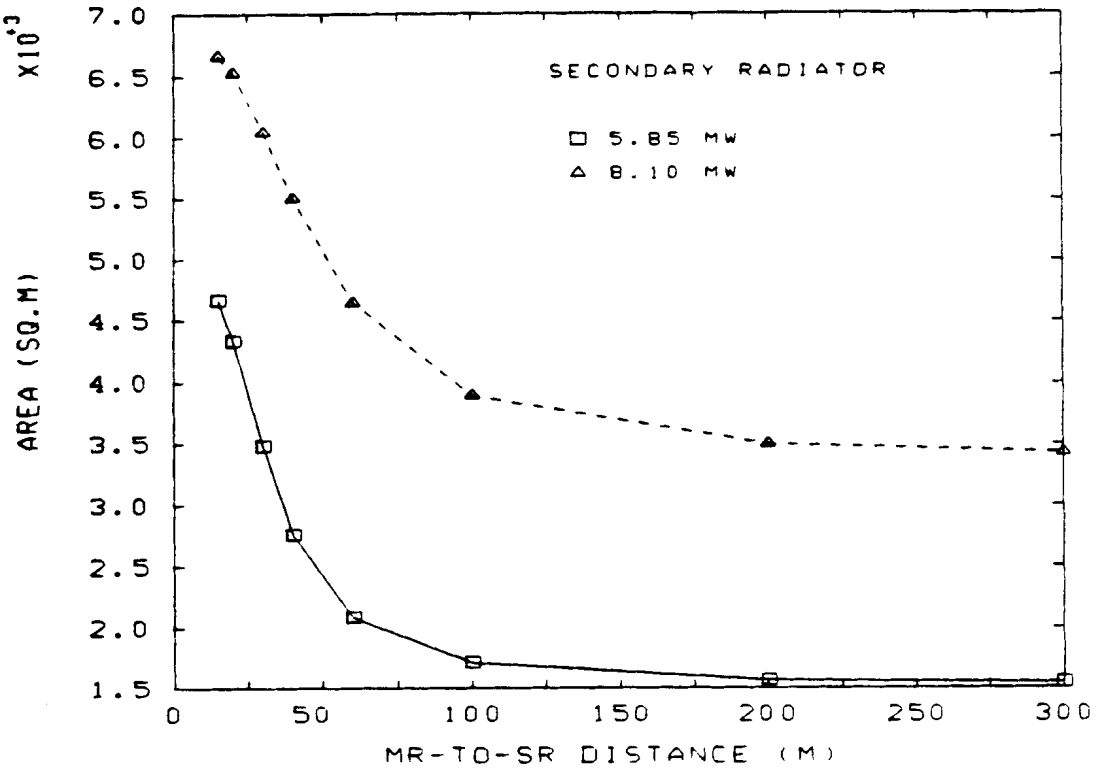


Figure 3.4.1 Radiator Area Versus Separation Distance

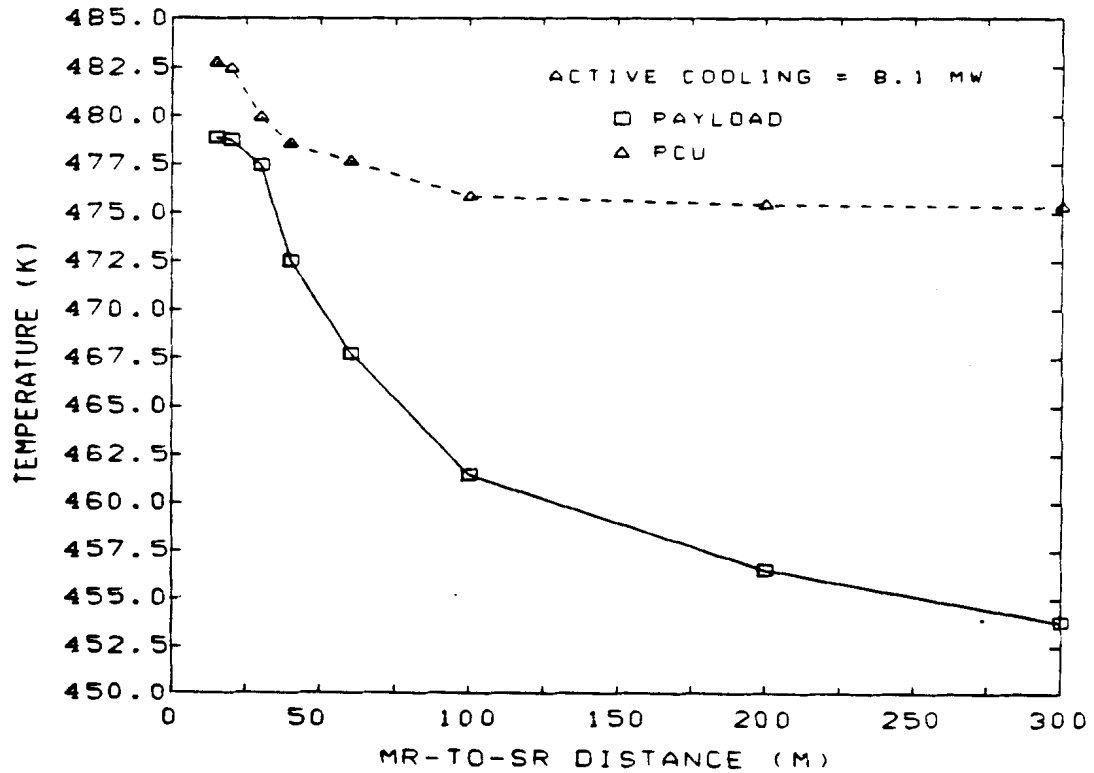


Figure 3.4.2 Temperature Versus Radiator Separation Distance

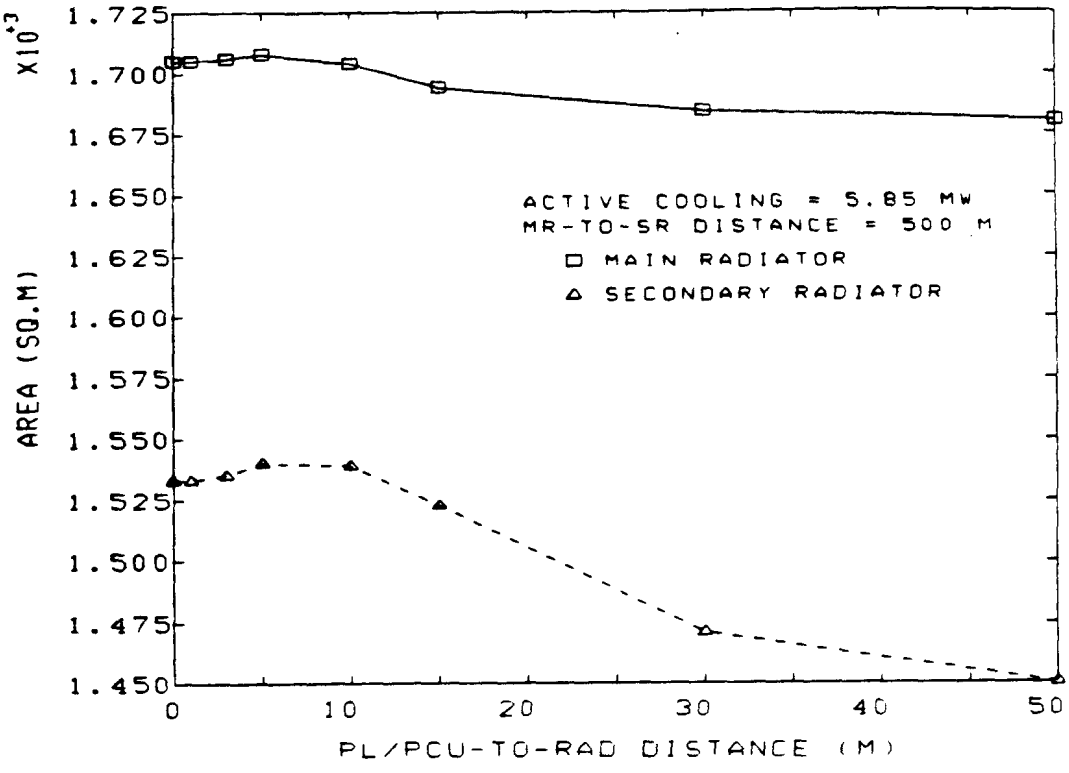


Figure 3.4.3 Radiator Area Versus Shell-to-Radiator Distance

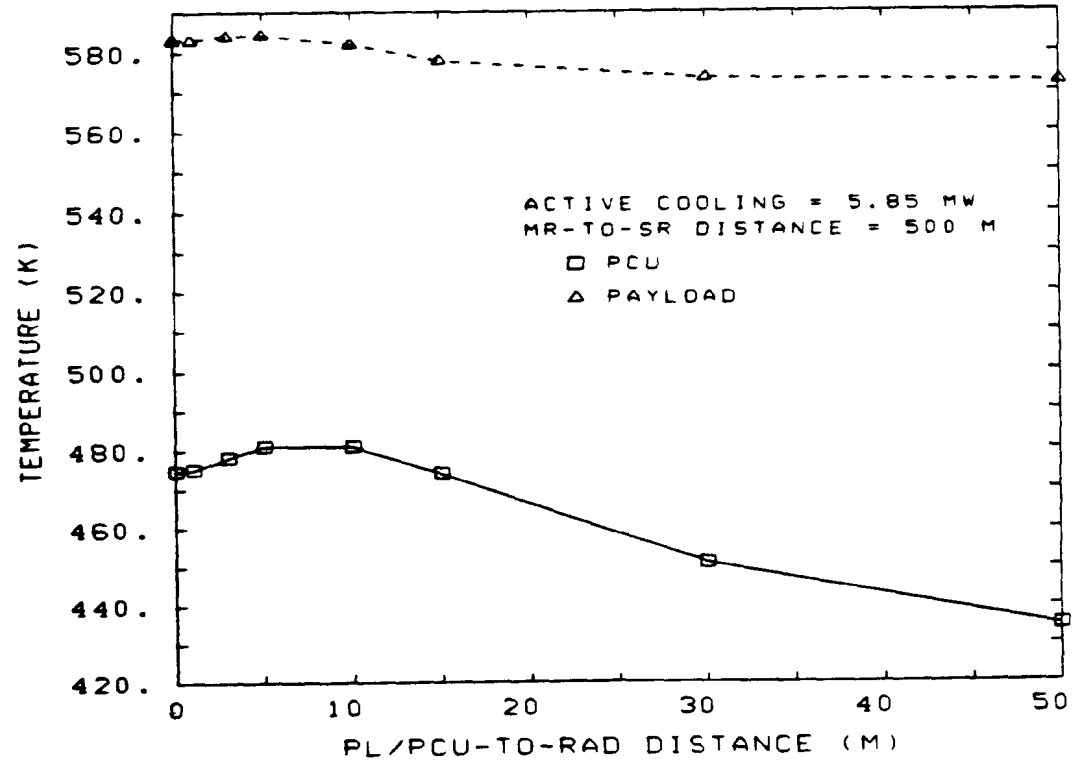


Figure 3.4.4 Temperature Versus Shell-to-Radiator Distance

3.5 Convection

One of the output variables of the computer program is an estimate of the value of hA required for convective cooling of the payload. For a given working fluid and flow rate, an estimate of h can be made; using the estimated hA and h values, the heat transfer area can be determined. This crude estimate can at least be used to provide some idea of the area required by the heat exchanger to actively cool the payload. Figure 3.5.1 shows the effect of different hA values on the payload temperature. Increasing the value of hA has a diminishing influence on the temperature because the temperature difference between the working fluid and the payload decreases as more and more heat is removed from the payload.

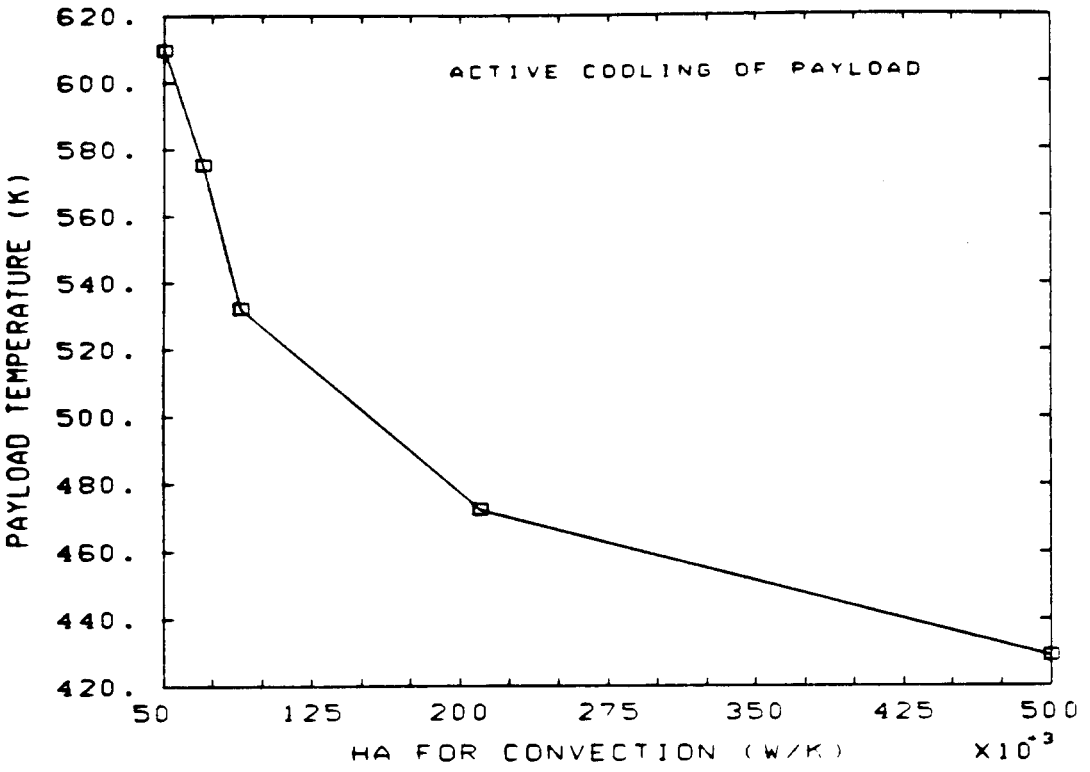


Figure 3.5.1 Effect of Convection on Payload Temperature

3.6 Refrigerators

The effect of a refrigerator was determined by repeating the base case, specifying a refrigerator COP of 70% of the Carnot COP. Also, the secondary radiator was assumed to operate at 700 K and the temperature difference between the payload and the refrigerator working fluid was taken as 40 K. (In the base case without a refrigerator, the log mean temperature difference between the payload and the payload heat exchanger working fluid was also approximately 40 K.) The results indicate that a 6 MWe refrigerator is needed to cool the payload, requiring an additional 24 MW of thermal power. Compared to the base case, the size of the secondary radiator decreased from 6087 m^2 to 395 m^2 while the main radiator increased in size from 1906 m^2 to 2967 m^2.

3.7 Payload Temperature

The principal motivation for creating this radiant heat transfer computer program was to estimate the reduction in secondary radiator area that could be achieved by allowing higher payload and PCU operating temperatures. Electronic components capable of high temperature operation require less active cooling. Also, higher component temperatures allow rejection of waste heat at higher temperature by the secondary radiator. The relationship between the secondary radiator area and payload temperature is provided in Figure 3.7.1 for the base case input parameters. This curve shows that increasing the permissible payload temperature from 450 K to 600 K results in over a factor of two reduction in the radiator area.

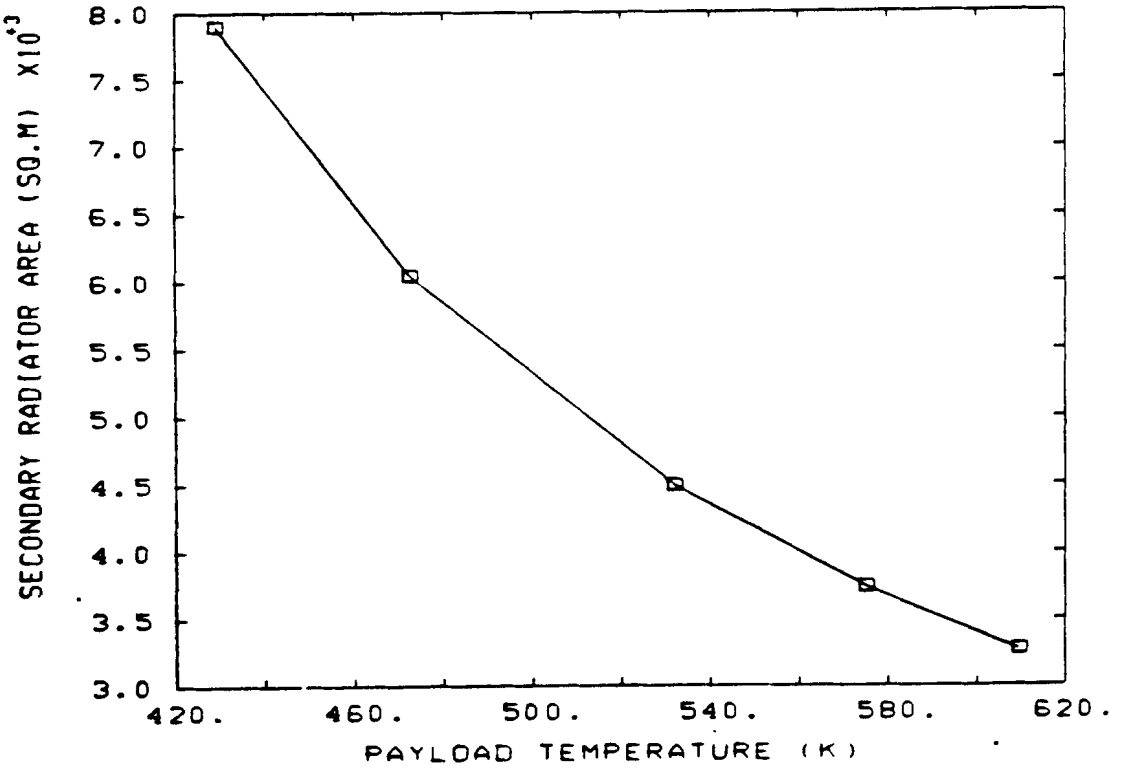


Figure 3.7.1 Effect of Payload Temperature on Radiator Area

4.0 SUMMARY AND CONCLUSIONS

A conceptual space platform consists of a payload, a PCU, and two radiators: the main radiator and a secondary radiator. A computer program was written to determine the required size of the two radiators and the temperatures of the PCU and payload for a given platform power level. The program includes a model for the radiant heat transfer between the various platform surfaces. An iterative algorithm is employed in conjunction with this model to determine the size of the radiators. The program user can subdivide the two radiators into any number of nodes to increase the accuracy of the radiant heat transfer solution. The use of more nodes also allows better prediction of the nonlinear temperature drop that occurs across the radiators as the working fluid deposits the platform's waste heat in the radiator. View factor expressions are automatically calculated for different choices of the number of nodes. The user can also select different separation distances between the various platform structures. A model is included to couple the radiant and conduction heat transfer that occurs between the payload and its shell and between the PCU and its shell. Also, the program allows the use of a refrigerator to cool the payload. If a refrigerator is used, the program determines the amount of additional thermal power needed to run the refrigerator.

This computer program was used to perform a variety of parametric calculations. The results indicate that the secondary radiator size is strongly dependent on its proximity to the main radiator and that the radiant interchange that occurs between the various platform structures has a large effect on the structure temperatures. The size of the secondary radiator also depends on the amount of waste heat that it must radiate to space and the temperature at which it operates. Use of a refrigerator to cool the payload significantly reduces the size of the secondary radiator but at the expense of increased main radiator and power supply size. Results of this computer program indicate that with or without a refrigerator, the use of high temperature electrical components in the PCU and payload can significantly reduce the required size of the secondary radiator by allowing a reduction in the amount of waste heat to be removed and by allowing an increase in the inlet and outlet temperatures of the radiator.

The calculations in this report were included to demonstrate the intended use of the program. In order to perform these calculations for a conceptual space platform it was necessary to assume values for many of the program input variables. It should be noted that there are a lot of variables to consider and that the results can only indicate trends in the various functional relationships. Assuming representative variable values and performing parametric calculations is the best one can do until a detailed platform design has been completed.

5.0 REFERENCES

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3. Seigel, R. and J. R. Howell, Thermal Radiation Heat Transfer, Second Edition, (McGraw-Hill Book Company, 1981).

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APPENDIX A - ASSESSMENT PROBLEMS

SAMPLE PROBLEM (1) - CYLINDRICAL CAVITY AT CONSTANT TEMPERATURE REJECTING HEAT TO BLACKBODY SINK AT 293.3 K

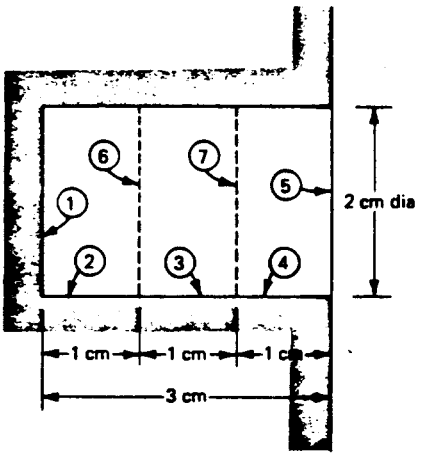
RADIATION ANALYSIS

SURFACE	EMISSIVITY	TEMPERATURE (KELVIN)	QNETPP (W/SQ.M)	RADIOSITY (W/SQ.M)	TEXTBOOK [1] RADIOSITY (W/SQ.M)
1	0.60000	1273.30	0.13282E+05	0.14016E+06	0.14003E+06
2	0.60000	1273.30	0.84339E+04	0.14339E+06	0.14326E+06
3	0.60000	1273.30	0.15274E+05	0.13883E+06	0.13872E+06
4	0.60000	1273.30	0.34994E+05	0.12569E+06	0.12557E+05
5	1.00000	293.30	-.11659E+06	0.41952E+03	0.41952E+06

SAMPLE PROBLEM (2) - CYLINDRICAL CAVITY WITH SURFACE 1 AT 1273.3 K, WITH SURFACES 2,3, AND 4 INSULATED (Q''=0.0), REJECTING HEAT TO BLACKBODY SINK OF 293.3 K

RADIATION ANALYSIS

SURFACE	EMISSIVITY	TEMPERATURE (KELVIN)	QNETPP (W/SQ.M)	RADIOSITY (W/SQ.M)	TEXTBOOK [1] RADIOSITY (W/SQ.M)
1	0.60000	1273.30	0.50442E+05	0.11539E+06	0.11532E+05
2	0.60000	1093.27	0.00000E+00	0.80988E+05	0.81019E+05
3	0.60000	1004.92	0.00000E+00	0.57815E+05	0.57885E+05
4	0.60000	884.84	0.00000E+00	0.34751E+05	0.34767E+05
5	1.00000	293.30	-.38822E+05	0.41952E+03	0.41952E+05



SAMPLE PROBLEM (3)

(PROBLEM 16, PAGE 278 OF REFERENCE [3])

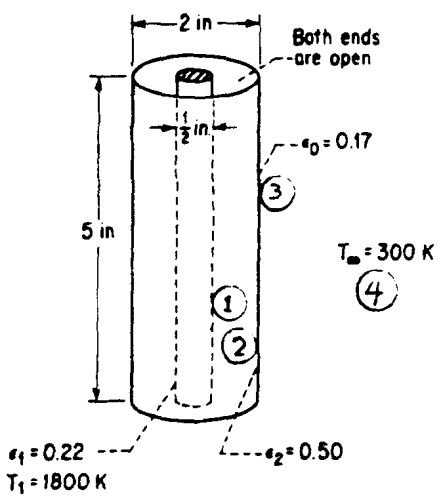
TWO CONCENTRIC CYLINDERS, INNER CYLINDER AT 1800 K,
ENVIRONMENT AT 300 K

THIS PROBLEM TESTS THE TWO-SIDED SURFACE OPTION IN SUBROUTINE RADHT
TEXT BOOK [3] TEMPERATURE OF SURFACES 2,3 (OUTER CYLINDER) = 1048 K

NUMBER OF ITERATIONS = 15
(RELATIVE ERROR = 1.0000E-03)

RADIATION ANALYSIS FOR ALL SURFACES

SURFACE	EMISSIVITY	TEMPERATURE (KELVIN)	QNETPP (W/SQ.M)	RADIOSITY (W/SQ.M)	IRRADIATION (W/SQ.M)
1	0.22000	1800.00	1.1506E+05	1.8694E+05	7.1880E+04
2	0.50000	1047.49	-1.1565E+04	7.9816E+04	9.1382E+04
3	0.17000	1047.92	1.1544E+04	1.2003E+04	4.5919E+02
4	1.00000	300.00	0.0000E+00	4.5919E+02	4.5919E+02



APPENDIX B - COMPUTER PROGRAM LISTING

```
C
C   PROGRAM TO DETERMINE THE SIZE OF A MAIN RADIATOR AND
C   A SECONDARY RADIATOR ALONG WITH THE MAXIMUM OPERATING
C   TEMPERATURES OF THE PCU AND PAYLOAD
C
C   WRITTEN BY DEAN DOBRANICH, NOV. 1986
C
C   INPUT: UNIT 5
C   OUTPUT: UNIT 6 (MAIN), UNIT 7 (VIEW FACTORS), UNIT 8 (ITERATIONS)
C
      COMMON/X/XCPCU,XCPL
      COMMON/EMIS/EMIS(100)
      COMMON/HT/QNETPP(100),T(100),R(100),G(100)
      COMMON/OUT/PMR,PSR,PPCUS,PPCU,PPLS,PPL,PCUWH,PLWH,REFPOWE,
     1           PSR1,PSR2,AREAMR,AREASR,TAVGPCUS,TAVGPLS,COP,
     2           TISMR,TOSMR,TISSR,TOSSR,HAPCU,HAPL,CPCU,CPL,
     3           THPOWER,THPNEW
      COMMON/DIMS/DPCUS,HPCUS,DPCU,HPCU,DPLS,HPLS,DPL,HPL,
     1            SD1,SD2,SD3
      COMMON/AREA/APCUSL,APCUSC,APCUSR,APCUL,APCUC,APCUR,
     1            APLSL,APLSC,APLSR,APLL,APLC,APLR,
     2            APL,APCU,APLS,APCUS
C
      DIMENSION IDSURF(100),IDCON(100),IST(20)
      DIMENSION TSMR(50),TSSR(50),TNODEMR(50),TNODESR(50)
      DIMENSION RADMR(50),RADSR(50),POAMR(50),POASR(50),AMR(50),ASR(50)
      DIMENSION RNODEMR(50),RNODESR(50)
C
      DIMENSION TPCU(4),TPL(4),RPCU(4),RPL(4),FPCU(4,4),FPL(4,4)
      DIMENSION ECPCU(4),ECPL(4)
C
      PI=3.141592654
C
      READ(5,*)NOUTERMAX
      READ(5,*)CONVOUT
      READ(5,*)NRHMAX
      READ(5,*)CONVRH
C
      READ(5,*)NMR
      READ(5,*)NSR
C
      READ(5,*)EMR1
      READ(5,*)EMR2
      READ(5,*)ESR1
      READ(5,*)ESR2
      READ(5,*)EPCUS1L,EPCUS1C,EPCUS1R
      READ(5,*)EPCUS2L,EPCUS2C,EPCUS2R
      READ(5,*)EPLS1L,EPLS1C,EPLS1R
      READ(5,*)EPLS2L,EPLS2C,EPLS2R
      READ(5,*)EPCU
      READ(5,*)EPL
C
      READ(5,*)TSPACE
C
      READ(5,*)TISMR
      READ(5,*)TOSMR
      READ(5,*)TISSR
      READ(5,*)TOSSR
C
      READ(5,*)RADMR1
      READ(5,*)RADSR1
      READ(5,*)SD1
      READ(5,*)SD2
      READ(5,*)SD3
C
      READ(5,*)DPCUS
      READ(5,*)HPCUS
      READ(5,*)DPLS
      READ(5,*)HPLS
      READ(5,*)DPCU
      READ(5,*)HPCU
      READ(5,*)DPL
      READ(5,*)HPL
C
      READ(5,*)THPOWER
      READ(5,*)EFFIC
      READ(5,*)FCCOP
C
      READ(5,*)FEPPCU
      READ(5,*)FPCUWHAC
      READ(5,*)FEPPL
      READ(5,*)FPLWHAC
C
      READ(5,*)DELTSR
      READ(5,*)CPCU
      READ(5,*)CPL
C
      IDEBUG=0
      IF(NOUTERMAX.LT.0)IDEBUG=1
      NOUTERMAX=ABS(NOUTERMAX)
      NCV=2
      TDROPSR=ABS(TISSR-TOSSR)
      IF(DELTSR.LT.0.0)NCV=0
      IF(RADMR1.LE.DPCUS*0.5)RADMR1=1.01*DPCUS*0.5
      IF(RADSR1.LE.DPLS*0.5)RADSR1=1.01*DPLS*0.5
C  IF REFRIGERATOR USED TO COOL PAYLOAD, NO ACTIVE COOLING OF PCU ALLOWED
      IF(FCCOP.NE.0.0)FPCUWHAC=0.0
      COP=0.0
      THPNEW=0.0
      REFPOWE=0.0
C
C  COMPONENT POWERS (BEFORE ADJUSTMENT FOR CONDUCTION AND CONVECTION)
      ELECPOW=THPOWER*EFFIC
      PMR=THPOWER-ELECPOW
```

```
      PCUWH=FEPPCU*ELECPOW
      PSR1=FPCUWHAC*PCUWH
      PPCUS=0.0
      PPCU=PCUWH-PSR1-PPCUS
      PLWH=FEPPL*(ELECPOW-PCUWH)
      PSR2=FPLWHAC*PLWH
      PPLS=0.0
      PPL=PLWH-PSR2-PPLS
      PSR=PSR1+PSR2
C
C  COMPONENT AREAS
      APCUSC=PI*DPCUS*HPCUS
      APLSC=PI*DPLS*HPLS
      APCUSL=PI*DPCUS*DPCUS*0.25
      APLSL=PI*DPLS*DPLS*0.25
      APCUSR=APCUSL
      APLSR=APLSL
      APCUC=PI*DPCU*HPCU
      APLC=PI*DPL*HPL
      APCUL=PI*DPCU*DPCU*0.25
      APLL=PI*DPL*DPL*0.25
      APCUR=APCUL
      APLR=APLL
C
      APCUS=APCUSC+APCUSL+APCUSR
      APLS=APLSC+APLSL+APLSR
      APCU=APCUC+APCUL+APCUR
      APL=APLC+APLL+APLR
C
C  SET UP POINTERS
      IST(1)=1
      IST(2)=IST(1)+NMR
      IST(3)=IST(2)+NMR
      IST(4)=IST(3)+NSR
      IST(5)=IST(4)+NSR
      IST(6)=IST(5)+1
      IST(7)=IST(6)+1
      IST(8)=IST(7)+1
      IST(9)=IST(8)+1
      IST(10)=IST(9)+1
      IST(11)=IST(10)+1
      IST(12)=IST(11)+1
      IST(13)=IST(12)+1
      IST(14)=IST(13)+1
      IST(15)=IST(14)+1
      IST(16)=IST(15)+1
      IST(17)=IST(16)+1
      IST(18)=IST(17)+1
      IST(19)=IST(18)+1
C  TOTAL NUMBER OF SURFACES
      NS=IST(19)
C



C  SET EMIS, IDSURF, AND IDCON ARRAYS
C
      DO 5 K=1,NS
      R(K)=1.0
    5 IDCON(K)=0
C
C    MAIN RADIATOR
      KK=IST(2)
      DO 10 K=IST(1),IST(2)-1
      EMIS(K)=EMR1
      EMIS(KK)=EMR2
      IDSURF(K)=0
      IDSURF(KK)=0
      IDCON(K)=KK
      IDCON(KK)=-K
      KK=KK+1
   10 CONTINUE
C
C    SECONDARY RADIATOR
      KK=IST(4)
      DO 15 K=IST(3),IST(4)-1
      EMIS(K)=ESR1
      EMIS(KK)=ESR2
      IDSURF(K)=0
      IDSURF(KK)=0
      IDCON(K)=KK
      IDCON(KK)=-K
      KK=KK+1
   15 CONTINUE
C
C    PCU SHELL LEFT END
      KK=IST(6)
      DO 20 K=IST(5),IST(6)-1
      EMIS(K)=EPCUS1L
      EMIS(KK)=EPCUS2L
      IDSURF(K)=2
      IDSURF(KK)=2
      IDCON(K)=KK
      IDCON(KK)=-K
      QNETPP(K)=PPCUS/APCUSL/2.0
      QNETPP(KK)=QNETPP(K)
      KK=KK+1
   20 CONTINUE
C
C    PCU SHELL CURVED SURFACE
      KK=IST(8)
      DO 25 K=IST(7),IST(8)-1
      EMIS(K)=EPCUS1C
      EMIS(KK)=EPCUS2C
      IDSURF(K)=2
      IDSURF(KK)=2
      IDCON(K)=KK
```

```
      IDCON(KK)=-K
      QNETPP(K)=PPCUS/APCUSC/2.0
      QNETPP(KK)=QNETPP(K)
      KK=KK+1
   25 CONTINUE
C
C     PCU SHELL RIGHT END
      KK=IST(10)
      DO 30 K=IST(9),IST(10)-1
      EMIS(K)=EPCUS1R
      EMIS(KK)=EPCUS2R
      IDSURF(K)=2
      IDSURF(KK)=2
      IDCON(K)=KK
      IDCON(KK)=-K
      QNETPP(K)=PPCUS/APCUSR/2.0
      QNETPP(KK)=QNETPP(K)
      KK=KK+1
   30 CONTINUE
C
C     PAYLOAD SHELL LEFT END
      KK=IST(12)
      DO 35 K=IST(11),IST(12)-1
      EMIS(K)=EPLS1L
      EMIS(KK)=EPCUS2L
      IDSURF(K)=2
      IDSURF(KK)=2
      IDCON(K)=KK
      IDCON(KK)=-K
      QNETPP(K)=PPLS/APLSL/2.0
      QNETPP(KK)=QNETPP(K)
      KK=KK+1
   35 CONTINUE
C
C     PAYLOAD SHELL CURVED SURFACE
      KK=IST(14)
      DO 40 K=IST(13),IST(14)-1
      EMIS(K)=EPLS1C
      EMIS(KK)=EPCUS2C
      IDSURF(K)=2
      IDSURF(KK)=2
      IDCON(K)=KK
      IDCON(KK)=-K
      QNETPP(K)=PPLS/APLSC/2.0
      QNETPP(KK)=QNETPP(K)
      KK=KK+1
   40 CONTINUE
C
C     PAYLOAD SHELL RIGHT END
      KK=IST(16)
      DO 45 K=IST(15),IST(16)-1
      EMIS(K)=EPLS1R



      EMIS(KK)=EPCUS2R
      IDSURF(K)=2
      IDSURF(KK)=2
      IDCON(K)=KK
      IDCON(KK)=-K
      QNETPP(K)=PPLS/APLSR/2.0
      QNETPP(KK)=QNETPP(K)
      KK=KK+1
   45 CONTINUE
C
C     PCU
      EMIS(IST(17))=EPCU
      IDSURF(IST(17))=1
      QNETPP(IST(17))=PPCU/APCU
C
C     PAYLOAD
      EMIS(IST(18))=EPL
      IDSURF(IST(18))=1
      QNETPP(IST(18))=PPL/APL
C
C     SPACE
      EMIS(IST(19))=1.0
      IDSURF(IST(19))=0
      T(IST(19))=TSPACE
C
C  INITIAL GUESS FOR EFFECTIVE TEMPERATURES
      DO 60 J=1,NMR
   60 TSMR(J)=TSPACE
      DO 65 J=1,NSR
   65 TSSR(J)=TSPACE
C
      RADMR(1)=RADMRI
      RADSR(1)=RADSRI
      PNMR=PMR/NMR
      PNSR=PSR/NSR
      EAVGMR=(EMR1+EMR2)/2.0
      EAVGSR=(ESR1+ESR2)/2.0
C  WRITE SURFACE ID ARRAYS
      CALL IDOUT(NS,NMR,NSR,IDSURF,IDCON)
C  DETERMINE VIEW FACTORS FOR SURFACES NOT DEPENDENT ON
C     THE SIZE OF THE MAIN AND SECONDARY RADIATORS
      CALL VIEW1(NS,IST)
C  SET UP ARRAYS FOR SOLVING COMBINED RADIATION/CONDUCTION
      DO 120 I=1,4
      RPCU(I)=1.0
  120 RPL(I)=1.0
      ECPCU(1)=EPCUS1L
      ECPCU(2)=EPCUS1C
      ECPCU(3)=EPCUS1R
      ECPCU(4)=EPCU
      ECPL(1)=EPLS1L
      ECPL(2)=EPLS1C
```

```
      ECPL(3)=EPLS1R
      ECPL(4)=EPL
      CALL FASSIGN(0,IST,FPCU)
      CALL FASSIGN(1,IST,FPL)
C
C ******
C
      DO 600 ICV=1,NCV+1
      DO 500 IOUTER=1,NOUTERMAX
C
C  FIRST ESTIMATE THE SIZE OF THE MAIN RADIATOR
      CALL RADSIZE(NMR,PMR,TISMR,TOSMR,EAVGMR,TSMR,RADMR,AMR,
     1             TNODEMR,RNODEMR)
C  ASSIGN TNODEMR ARRAY TO T ARRAY
      KK=IST(2)
      K=1
      DO 75 J=IST(1),IST(2)-1
      T(J)=TNODEMR(K)
      T(KK)=TNODEMR(K)
      K=K+1
      KK=KK+1
   75 CONTINUE
C
C  NOW ESTIMATE SIZE OF THE SECONDARY RADIATOR
      CALL RADSIZE(NSR,PSR,TISSR,TOSSR,EAVGSR,TSSR,RADSR,ASR,
     1             TNODESR,RNODESR)
C  ASSIGN TNODESR ARRAY TO T ARRAY
      KK=IST(4)
      K=1
      DO 80 J=IST(3),IST(4)-1
      T(J)=TNODESR(K)
      T(KK)=TNODESR(K)
      K=K+1
      KK=KK+1
   80 CONTINUE
C
C  NOW DETERMINE VIEW FACTORS FOR ALL SURFACES BASED ON ESTIMATED
C    AREAS.  THEN, SOLVE FOR RADIOSITIES, ONETPP'S, AND T'S.
C
      CALL VIEW2(NS,NMR,NSR,IST,RADMR,AMR,RADSR,ASR)
      NITER=NRHMAX
      CALL RADHT(NS,IDSURF,IDCON,CONVRH,NITER)
C
C  DETERMINE POA BASED ON CALCULATED ONETPP'S OF MAIN AND SECONDARY RADIATORS
C    WHERE:  POA = ONETPP(SIDE 1) + ONETPP(SIDE 2)
C    ALSO, CHECK FOR CONVERGENCE OF ONETPP'S
C
C    MAIN RADIATOR FIRST
      RELERRM=0.0
      POWTOTMR=0.0
      KK=IST(2)
      K=1



      DO 100 J=IST(1),IST(2)-1
      POAMR(K)=ONETPP(J)+ONETPP(KK)
      PNMRNEW=POAMR(K)*AMR(K)
      POWTOTMR=POWTOTMR+PNMRNEW
      RELERR=ABS(PNMR-PNMRNEW)/PNMR
      RELERRM=AMAX1(RELERR,RELERRM)
      K=K+1
      KK=KK+1
  100 CONTINUE
C
C    SECONDARY RADIATOR LAST
      POWTOTSR=0.0
      KK=IST(4)
      K=1
      DO 105 J=IST(3),IST(4)-1
      POASR(K)=ONETPP(J)+ONETPP(KK)
      PNSRNEW=POASR(K)*ASR(K)
      POWTOTSR=POWTOTSR+PNSRNEW
      RELERR=ABS(PNSR-PNSRNEW)/PNSR
      RELERRM=AMAX1(RELERR,RELERRM)
      K=K+1
      KK=KK+1
  105 CONTINUE
C
      WRITE(8,88)IOUTER,NITER,RELERRM,POWTOTMR,POWTOTSR
   88 FORMAT(' ',/,4X,I2,3X,I2,3X,1PE12.4,3X,E12.4,3X,E12.4)
      IF(RELERRM.LT.CONVOUT)GO TO 505
C
      IF(IDEBUG.EQ.1.AND.ICV.GT.NCV)THEN
      CALL FOUT(NS)
      CALL ROUT(NMR,NSR,TNODEMR,TNODESR,TSMR,TSSR,
     1          POAMR,POASR,RADMR,RADSR,AMR,ASR,RNODEMR,RNODESR)
      CALL OUT1(NS)
      ELSE
      ENDIF
C
C  CALCULATE NEW EFFECTIVE TEMPERATURES (TSNEW'S) IF CONVERGENCE NOT MET
      CALL TSNEW(NMR,EAVGMR,TNODEMR,POAMR,TSMR)
      CALL TSNEW(NSR,EAVGSR,TNODESR,POASR,TSSR)
C  AND REPEAT THE ENTIRE PROCESS...
C
  500 CONTINUE
      WRITE(6,499)
  499 FORMAT(' ',/,4X,'-*** WARNING - OUTER ITERATION DID
     1 NOT CONVERGE ***-',/)
C
C *****
C
  505 CONTINUE
C
      AREAMR=PI*(RADMR(NMR+1)**2-RADMR1**2)
      AREASR=PI*(RADSR(NSR+1)**2-RADSR1**2)
```

```
C
C  NOW ACCOUNT FOR CONDUCTION BETWEEN PCU AND PCU SHELL
C
C  USE AVERAGE TEMPERATURE OF SHELL TO ALLOW FOR MAXIMUM POSSIBLE
C    TEMPERATURE REDUCTION DUE TO CONDUCTION
      TAVGPCUS=(T(IST(5))*APCUSL+T(IST(7))*APCUSC+
     1          T(IST(9))*APCUSR)/APCUS
      TAVGPLS=(T(IST(11))*APLSL+T(IST(13))*APLSC+
     1         T(IST(15))*APLSR)/APLS
      TPCU(1)=TAVGPCUS
      TPCU(2)=TAVGPCUS
      TPCU(3)=TAVGPCUS
      TPL(1)=TAVGPLS
      TPL(2)=TAVGPLS
      TPL(3)=TAVGPLS
C
C  WRITE FINAL OUTPUT FOR NO-SHELL CONDUCTION CASE
C       CALL OUT2(IST)
C
C  USING MODIFIED REGULA FALSI METHOD TO FIND ROOT OF FUNCTION FUN
C    SUCH THAT FUN(ROOT)=WASTE HEAT-RADIATED HEAT-CONDUCTED HEAT=0
C  FIRST, PCU (H1 AND H2 PROVIDE AN INTERVAL CONTAINING A ROOT)
      IF(CPCU.LE.0.0)GO TO 150
      H1=0.0
      H2=PPCU
      ROOTN=PPCU
      XC=0.0
      CALL FUN(PPCU,APCU,ECPCU,RPCU,FPCU,TPCU,CPCU,XC,H1,FH)
      CALL FUN(PPCU,APCU,ECPCU,RPCU,FPCU,TPCU,CPCU,XC,H2,GH)
      ROOTO=H2
      DO 125 IM=1,20
      GMF=GH-FH
      IF(ABS(GMF).LT.1.0E-15)GO TO 150
      ROOTN=(GH*H1-FH*H2)/GMF
C  CHECK FOR ERROR
      IF(ABS((ROOTN-ROOTO)/ROOTN).GT.0.002)GO TO 140
      CALL FUN(PPCU,APCU,ECPCU,RPCU,FPCU,TPCU,CPCU,XC,ROOTN,FROOT)
      GO TO 150
  140 CALL FUN(PPCU,APCU,ECPCU,RPCU,FPCU,TPCU,CPCU,XC,ROOTN,FROOT)
      IF(FH*FROOT.GT.0.0)GO TO 130
      H2=ROOTN
      GH=FROOT
      FH=0.5*FH
      GO TO 135
  130 H1=ROOTN
      FH=FROOT
      GH=0.5*GH
  135 CONTINUE
      ROOTO=ROOTN
  125 CONTINUE
      GO TO 170
C
  150 CONTINUE
      IF(CPCU.EQ.0.0)GO TO 175
      TPCU(4)=AMAX1(TPCU(1),TPCU(2),TPCU(3))-CPCU
      CALL FUN(PPCU,APCU,ECPCU,RPCU,FPCU,TPCU,CPCU,XCPCU,ROOTN,FROOT)
  170 PPCU=ROOTN
      PPCUS=PCUWH-PSR1-PPCU
      QNETPP(IST(17))=PPCU/APCU
      QNETPP(IST(5))=PPCUS/APCUS
      QNETPP(IST(7))=PPCUS/APCUS
      QNETPP(IST(9))=PPCUS/APCUS
      QNETPP(IST(6))=0.0
      QNETPP(IST(8))=0.0
      QNETPP(IST(10))=0.0
  175 CONTINUE
C
C  REPEAT FOR PAYLOAD
      IF(CPL.LE.0.0)GO TO 250
      H1=0.0
      H2=PPL
      ROOTN=PPL
      XC=0.0
      CALL FUN(PPL,APL,ECPL,RPL,FPL,TPL,CPL,XC,H1,FH)
      CALL FUN(PPL,APL,ECPL,RPL,FPL,TPL,CPL,XC,H2,GH)
      ROOTO=H2
      DO 225 IM=1,20
      GMF=GH-FH
      IF(ABS(GMF).LT.1.0E-15)GO TO 250
      ROOTN=(GH*H1-FH*H2)/GMF
C  CHECK FOR ERROR
      IF(ABS((ROOTN-ROOTO)/ROOTN).GT.0.002)GO TO 240
      CALL FUN(PPL,APL,ECPL,RPL,FPL,TPL,CPL,XC,ROOTN,FROOT)
      GO TO 250
  240 CALL FUN(PPL,APL,ECPL,RPL,FPL,TPL,CPL,XC,ROOTN,FROOT)
      IF(FH*FROOT.GT.0.0)GO TO 230
      H2=ROOTN
      GH=FROOT
      FH=0.5*FH
      GO TO 235
  230 H1=ROOTN
      FH=FROOT
      GH=0.5*GH
  235 CONTINUE
      ROOTO=ROOTN
  225 CONTINUE
      GO TO 270
C
  250 CONTINUE
      IF(CPL.EQ.0.0)GO TO 275
      TPL(4)=AMAX1(TPL(1),TPL(2),TPL(3))-CPL
      CALL FUN(PPL,APL,ECPL,RPL,FPL,TPL,CPL,XCPL,ROOTN,FROOT)
  270 PPCU=ROOTN
      PPL=ROOTN
```

```
      PPLS=PLWH-PSR2-PPL
      QNETPP(IST(18))=PPL/APL
      QNETPP(IST(11))=PPLS/APLS
      QNETPP(IST(13))=PPLS/APLS
      QNETPP(IST(15))=PPLS/APLS
      QNETPP(IST(12))=0.0
      QNETPP(IST(14))=0.0
      QNETPP(IST(16))=0.0
  275 CONTINUE
C
C   RE-SOLVE RADIATION HEAT TRANSFER FOR ENTIRE PLATFORM USING
C     PCU AND PL WASTE HEAT VALUES CORRECTED FOR CONDUCTION TO SHELL
C
      NITER=NRHMAX
      CALL RADHT(NS,IDSURF,IDCON,CONVRH,NITER)
C
      TAVGPCUS=(T(IST(5))*APCUSL+T(IST(7))*APCUSC+
     1          T(IST(9))*APCUSR)/APCUS
      TAVGPLS=(T(IST(11))*APLSL+T(IST(13))*APLSC+
     1         T(IST(15))*APLSR)/APLS
C
C   ADJUST MAX SEC RADIATOR TEMP SO THAT IT DOES NOT EXCEED MAX OF
C     PL OR PCU TEMPS (OTHERWISE, A REFRIGERATION UNIT WOULD BE NEEDED)
      IF(NCV.EQ.0.OR.FCCOP.NE.0.0)GO TO 599
      TM1=T(IST(17))
      IF(PSR1.LT.1.0)TM1=0.0
      TM2=T(IST(18))
      IF(PSR2.LT.1.0)TM2=0.0
      IF(TISSR.GT.TOSSR)THEN
      TISSR=AMAX1(TM1,TM2)-DELTSR*0.97
      TOSSR=TISSR-TDROPSR
      ELSE
      TOSSR=AMAX1(TM1,TM2)-DELTSR*0.97
      TISSR=TOSSR-TDROPSR
      ENDIF
C   CALCULATE REQUIRED HA FOR CONVECTION COOLING OF PCU AND PL
C     (IF HA IS NEGATIVE, A REFRIGERATION UNIT IS REQUIRED)
  599 TCAVG=(TISSR+TOSSR)/2.0
      HAPCU=PSR1/(T(IST(17))-TCAVG)
      HAPL=PSR2/(T(IST(18))-TCAVG)
C   IF A REFRIGERATOR IS USED TO COOL PAYLOAD:
      IF(FCCOP.EQ.0.0.OR.ICV.GT.NCV)GO TO 600
      COP=FCCOP*(1.0/((TISSR/(T(IST(18))-0.96*DELTSR))-1.0))
      REFPOWE=PSR2/COP
      REFPOWT=REFPOWE/EFFIC
      THPNEW=THPOWER+REFPOWT
      ELECPOW=THPNEW*EFFIC
      PMR=THPNEW-ELECPOW
      PNMR=PMR/NMR
      PSR1=0.0
      PPCUS=0.0
      PCUWH=FEPPCU*ELECPOW




      PPCU=PCUWH
      QNETPP(IST(17))=PPCU/APCU
      QNETPP(IST(5))=PPCUS/APCUS
      QNETPP(IST(7))=PPCUS/APCUS
      QNETPP(IST(9))=PPCUS/APCUS
      QNETPP(IST(6))=0.0
      QNETPP(IST(8))=0.0
      QNETPP(IST(10))=0.0
  600 CONTINUE
C
C   NOW WRITE ALL FINAL OUTPUT
      CALL FOUT(NS)
      CALL ROUT(NMR,NSR,TNODEMR,TNODESR,TSMR,TSSR,
     1          POAMR,POASR,RADMR,RADSR,AMR,ASR,RNODEMR,RNODESR)
      CALL OUT1(NS)
      CALL OUT2(IST)
C
      STOP
      END
C
C *---------------SUBROUTINES-----------------*
C
      SUBROUTINE RADSIZE(NN,P,TIS,TOS,EAVG,TS,RAD,A,TNODE,RNODE)
C   THIS SUBROUTINE DETERMINES THE REQUIRED SIZE OF THE RADIATOR NODES
C     BASED ON AN ESTIMATED EFFECTIVE BACKGROUND TEMPERATURE (TS).
C
      DIMENSION RAD(NN+1),TS(NN),TNODE(NN),RNODE(NN),A(NN)
C
      PI=3.141592654
C
      IF(ABS(TIS-TOS).GT.2.0)THEN
C   FOR A BRAYTON CYCLE:
C
C   C2=-1.0/4.0/PI/SIGMA/EAVG
      C2=-1.40373E06/EAVG
      C1=C2*P/ABS(TIS-TOS)
C   LET EACH NODE HAVE THE SAME TEMPERATURE DROP; DETERMINE
C     NODE RADII SUCH THAT POWER DEPOSITED IN NODE EQUALS POWER
C     REMOVED FROM BOTH SIDES OF NODE VIA RADIATION
      DT=(TOS-TIS)/NN
C   FOR OUTSIDE-IN FLOW
      SIGN=1.0
C   FOR INSIDE-OUT FLOW
      IF(DT.LT.0.0)SIGN=-1.0
      DO 5 I=1,NN
      T0=TIS+DT*(I-1)
      T1=TIS+DT*I
      ARG=AMIN1(T0,T1)
C   TS CAN NOT BE GREATER THAN ARG
      IF(TS(I).GE.ARG)TS(I)=ARG*0.998
      TRATIO=(TS(I)+T1)/(TS(I)-T1)*(TS(I)-T0)/(TS(I)+T0)
      RAD(I+1)=(RAD(I)**2+SIGN*C1*0.5/TS(I)**3*
```

```
     1          (ALOG(TRATIO)+2.0*ATAN(T1/TS(I))-
     2          2.0*ATAN(T0/TS(I))))**0.5
C
    5 CONTINUE
C
C  DETERMINE AVERAGE NODE TEMPERATURE BASED ON TEMPERATURES AT END
C    OF EACH NODE AND THE NODE EFFECTIVE BACKGROUND TEMPERATURE;
C    ALSO, CALCULATE R AT WHICH AVERAGE TEMPERATURE OCCURS
C
      C3=C1*PI
      ADT=ABS(DT)
      DO 10 I=1,NN
      A(I)=PI*(RAD(I+1)**2-RAD(I)**2)
      TNODE(I)=(TS(I)**4-2.0*C3*ADT/A(I))**0.25
      T0=TIS+DT*(I-1)
      T1=TNODE(I)
      TRATIO=(TS(I)+T1)/(TS(I)-T1)*(TS(I)-T0)/(TS(I)+T0)
      RNODE(I)=(RAD(I)**2+SIGN*C1*0.5/TS(I)**3*
     1          (ALOG(TRATIO)+2.0*ATAN(T1/TS(I))-
     2          2.0*ATAN(T0/TS(I))))**0.5
   10 CONTINUE
C
      RETURN
C
      ELSE
C  FOR A RANKINE CYCLE:
C
      PONN=P/NN
      TIS4=TIS**4
      C4=2.0*5.669E-8*EAVG
      DO 15 I=1,NN
      A(I)=PONN/C4/(TIS4-TS(I)**4)
      RAD(I+1)=(A(I)/PI+RAD(I)**2)**0.5
      RNODE(I)=0.5*(RAD(I)+RAD(I+1))
      TNODE(I)=TIS
   15 CONTINUE
C
      ENDIF
      RETURN
C
      END
C
C ---*****---
C
      SUBROUTINE TSNEW(NN,EAVG,TNODE,POA,TS)
C  THIS SUBROUTINE FINDS NEW EFFECTIVE BACKGROUND TEMPERATURES
      DIMENSION TNODE(NN),POA(NN),TS(NN)
C
C  C1=1/2/SIGMA/EAVG
      C1=8.820E06/EAVG
C  WEIGHTING FACTOR USED TO DAMPEN OSSCILATIONS AND SPEED CONVERGENCE
      WF=0.8




      DO 5 I=1,NN
      TS(I)=WF*(TNODE(I)**4-POA(I)*C1)**0.25+(1.0-WF)*TS(I)
    5 CONTINUE
C
      RETURN
      END
C
C ---*****---
C
      SUBROUTINE RADHT(N,IDSURF,IDCON,CONV,NITER)
      COMMON/CVIEW/F(100,100)
      COMMON/EMIS/EMIS(100)
      COMMON/HT/ONETPP(100),T(100),R(100),G(100)
      DIMENSION V(100),IDSURF(N),IDCON(N)
C
C  CALCULATE RADIOSITIES,IRRADIATIONS,AND HEAT FLUXES
C  USING NETWORK METHOD FOR RADIATION HEAT TRANSFER
C  (REF. HOLMAN, HEAT TRANSFER)
C
C --------
C  IDSURF = 0 FOR SURFACES WITH KNOWN TEMPERATURE
C  IDSURF = 1 FOR SURFACES WITH KNOWN HEAT FLUX
C  IDSURF = 2 FOR TWO-SIDED SURFACES WITH T1=T2, QT=Q1+Q2
C --------
C  IDCON ARRAY DEFINES WHICH TWO-SIDED SURFACES ARE CONNCECTED;
C  SIDE 2 OF A CONNECTION MUST BE INDICATED AS A NEGATIVE.
C  EXAMPLE:  IF SURFACE 5 AND 22 ARE CONNCECTED -
C   IDCON(5)=22    SIDE 1
C   IDCON(22)=-5   SIDE 2
C
      SIGMA=5.669E-8
C
C  USING GAUSS-SEIDEL TO SOLVE NXN EQUATIONS
C     INITIAL GUESS FOR RADIOSITIES
      DO 51 I=1,N
   51 V(I)=R(I)
C
      DO 99 IT=1,NITER
C  CALCULATE R FOR SURFACES WITH KNOWN TEMPERATURE
      DO 61 I=1,N
      IF(IDSURF(I).NE.0)GO TO 61
      X=1.0-EMIS(I)
      XX=1.0-F(I,I)*X
      SUM=0.0
      DO 71 J=1,N
      IF(J.EQ.I)GO TO 71
      SUM=SUM+F(I,J)*R(J)
   71 CONTINUE
      R(I)=(X*SUM+EMIS(I)*SIGMA*T(I)**4.0)/XX
   61 CONTINUE
C
C  CALCULATE R FOR SURFACES WITH KNOWN HEAT FLUX
```

```
      DO 62 I=1,N
      IF(IDSURF(I).NE.1)GO TO 62
      Y=1.0/(1.0-F(I,I))
      SUM=0.0
      DO 65 J=1,N
      IF(J.EQ.I)GO TO 65
      SUM=SUM+F(I,J)*R(J)
   65 CONTINUE
      R(I)=Y*(SUM+ONETPP(I))
   62 CONTINUE
C
C  CALCULATE R FOR SURFACES THAT ARE OPPOSITE SIDES OF THE SAME
C  STRUCTURE SUCH THAT Q(TOTAL) = Q(I) + Q(K) AND T(I) = T(K).
C  K = IDCON(I) DEFINES SURFACE CONNECTIONS
C
      DO 63 I=1,N
      IF(IDSURF(I).NE.2)GO TO 63
C
      K=IDCON(I)
      IF(K.LE.0)GO TO 63
      X1=1.0/EMIS(I)
      A1=1.0/(X1-F(I,I)*(X1-1.0))
      B1=1.0/(1.0-F(K,K))
      X2=1.0/EMIS(K)
      A2=1.0/(X2-F(K,K)*(X2-1.0))
      B2=1.0/(1.0-F(I,I))
      SUM1=0.0
      SUM2=0.0
      DO 10 J=1,N
      IF(J.EQ.I)GO TO 10
      SUM1=SUM1+F(I,J)*R(J)
      SUM2=SUM2+F(K,J)*R(J)
   10 CONTINUE
      SUM3=0.0
      DO 12 J=1,N
      IF(J.EQ.K)GO TO 12
      SUM3=SUM3+(F(I,J)+F(K,J))*R(J)
   12 CONTINUE
      R(I)=A1*((X1-1.0)*SUM1-(X2-1.0)*SUM2+B1*X2*(ONETPP(I)+
     1     ONETPP(K)+SUM3))/(1.0+A1*B1*X2)
C
      SUM1=0.0
      SUM2=0.0
      DO 15 J=1,N
      IF(J.EQ.K)GO TO 15
      SUM1=SUM1+F(K,J)*R(J)
      SUM2=SUM2+F(I,J)*R(J)
   15 CONTINUE
      SUM3=0.0
      DO 17 J=1,N
      IF(J.EQ.I)GO TO 17
      SUM3=SUM3+(F(I,J)+F(K,J))*R(J)



   17 CONTINUE
      R(K)=A2*((X2-1.0)*SUM1-(X1-1.0)*SUM2+B2*X1*(ONETPP(I)+
     1     ONETPP(K)+SUM3))/(1.0+A2*B2*X1)
C
   63 CONTINUE
C
C
C  CHECK FOR CONVERGENCE
C
      DIFF=0.0
      DO 81 I=1,N
      DN=0.0
      IF(ABS(V(I)).GT.0.0)DN=ABS((R(I)-V(I))/V(I))
   81 DIFF=AMAX1(DIFF,DN)
      IF(DIFF.LT.CONV.AND.DIFF.NE.0.0)GO TO 101
      DO 82 I=1,N
   82 V(I)=R(I)
   99 CONTINUE
  101 CONTINUE
C
C----------
C  DETERMINE IRRADIATIONS G, FOR EACH SURFACE
      DO 120 I=1,N
      SUM=0.0
      DO 110 K=1,N
  110 SUM=SUM+F(I,K)*R(K)
  120 G(I)=SUM
C
C  DETERMINE ONETPP AND T FOR EACH SURFACE (WATTS/M**2, AND K)
C
      DO 125 I=1,N
      IF(IDSURF(I).NE.1)ONETPP(I)=R(I)-G(I)
      IF(IDSURF(I).NE.0)THEN
      XX=0.0
      IF(EMIS(I).NE.0.0)XX=(1.0-EMIS(I))/EMIS(I)*ONETPP(I)/SIGMA
      T(I)=(XX+R(I)/SIGMA)**0.25
      ELSE
      ENDIF
  125 CONTINUE
C
      NITER=IT
      RETURN
      END
C
C ------**--
C
      SUBROUTINE FUN(WH,A,EMIS,R,F,T,C,XC,O,FV)
C  FUN = WASTE HEAT - HEAT RADIATED - HEAT CONDUCTED
C    USED TO COUPLE RADIATION AND CONDUCTION HEAT TRANSFER
C
      DIMENSION EMIS(4),R(4),ONETPP(4),F(4,4),T(4)
      DIMENSION G(4),V(4)
```

```
C
C   CALCULATE RADIOSITIES,IRRADIATIONS,AND HEAT FLUXES
C   USING NETWORK METHOD FOR RADIATION HEAT TRANSFER
C
C   CONDUCTION ENERGY
C       QC(TT)=C/3.0*((TT-T(1))+(TT-T(2))+(TT-T(3)))
C
        SIGMA=5.669E-8
        N=4
        CONV=1.0E-3
        IF(C.LT.0.0)THEN
        IFLAG=1
        NC=N
        ELSE
        IFLAG=0
        NC=N-1
        ENDIF
C
C   USING GAUSS-SEIDEL TO SOLVE 4X4 EQUATIONS
C       INITIAL GUESS FOR RADIOSITIES
        DO 51 I=1,N
        ONETPP(I)=0.0
   51   V(I)=R(I)
        IF(IFLAG.EQ.0)ONETPP(N)=Q/A
C
        DO 99 IT=1,15
C   CALCULATE R FOR SURFACES WITH KNOWN TEMPERATURE
        DO 61 I=1,NC
        X=1.0-EMIS(I)
        XX=1.0-F(I,I)*X
        SUM=0.0
        DO 71 J=1,N
        IF(J.EQ.I)GO TO 71
        SUM=SUM+F(I,J)*R(J)
   71   CONTINUE
        R(I)=(X*SUM+EMIS(I)*SIGMA*T(I)**4.0)/XX
   61   CONTINUE
C
C   CALCULATE R FOR SURFACES WITH KNOWN HEAT FLUX
        DO 62 I=N,N-IFLAG
        Y=1.0/(1.0-F(I,I))
        SUM=0.0
        DO 65 J=1,N
        IF(J.EQ.I)GO TO 65
        SUM=SUM+F(I,J)*R(J)
   65   CONTINUE
        R(I)=Y*(SUM+ONETPP(I))
   62   CONTINUE
C
C   CHECK FOR CONVERGENCE
C
        DIFF=0.0




        DO 81 I=1,N
        DN=0.0
        IF(ABS(V(I)).GT.0.0)DN=ABS((R(I)-V(I))/V(I))
   81   DIFF=AMAX1(DIFF,DN)
        IF(DIFF.LT.CONV.AND.DIFF.NE.0.0)GO TO 101
        DO 82 I=1,N
   82   V(I)=R(I)
   99   CONTINUE
  101   CONTINUE
C
C----------
C   DETERMINE IRRADIATIONS G, FOR EACH SURFACE
        DO 120 I=1,N
        SUM=0.0
        DO 110 K=1,N
  110   SUM=SUM+F(I,K)*R(K)
  120   G(I)=SUM
C
C   DETERMINE QNETPP AND T FOR EACH SURFACE (WATTS/M**2, AND K)
C
        DO 125 I=1,NC
  125   ONETPP(I)=R(I)-G(I)
        IF(IFLAG.EQ.0)THEN
        I=N
        XX=0.0
        IF(EMIS(I).NE.0.0)XX=(1.0-EMIS(I))/EMIS(I)*ONETPP(I)/SIGMA
        T(I)=(XX+R(I)/SIGMA)**0.25
C   DETERMINE VALUE OF FUNCTION
        FV=WH-ONETPP(N)*A-QC(T(N))
        ELSE
        Q=ONETPP(N)*A
        TMAX=AMAX1(T(1),T(2),T(3))
        XC=(WH-Q)/(T(4)-TMAX)
        FV=0.0
        ENDIF
C
        RETURN
        END
C
C --****--
C
        SUBROUTINE VIEW1(N,IST)
C   CALCULATE VIEW FACTORS FOR ALL SURFACES NOT DEPENDENT ON
C     SIZE OF MAIN AND SECONDARY RADIATORS
        DIMENSION IST(20)
        COMMON/CVIEW/F(100,100)
        COMMON/AREA/APCUSL,APCUSC,APCUSR,APCUL,APCUC,APCUR,
       1            APLSL,APLSC,APLSR,APLL,APLC,APLR,
       2            APL,APCU,APLS,APCUS
        COMMON/DIMS/DPCUS,HPCUS,DPCU,HPCU,DPLS,HPLS,DPL,HPL,
       1            SD1,SD2,SD3
C
```

```
C  INITIALIZE ALL F'S TO 0.0
      DO 5 L=1,N
      DO 10 M=1,N
   10 F(L,M)=0.0
    5 CONTINUE
C
C  DETERMINE VIEW FACTOR BETWEEN PCUSR AND PLSL
      F(IST(10),IST(12))=DTOD(0.5*DPCUS,0.5*DPLS,SD1+SD2+SD3)
      F(IST(12),IST(10))=F(IST(10),IST(12))*APCUSR/APLSL
C
C  DETERMINE VIEW FACTORS BETWEEN PCU AND PCU SHELL SURFACES
      I5=IST(5)
      I7=IST(7)
      I9=IST(9)
      I17=IST(17)
      SD=(HPCUS-HPCU)*0.5
      FA=DTOD(0.5*DPCU,0.5*DPCUS,SD)
      CALL CTORING(0.5*DPCU,HPCU,0.5*DPCU,0.5*DPCUS,SD,FB)
      FB=AMAX1(0.0,FB)
      F(I17,I5)=APCUL/APCU*FA+APCUC/APCU*FB
      F(I17,I9)=F(I17,I5)
      F(I17,I7)=2.0*APCUL/APCU*(1.0-FA)+APCUC/APCU*(1.0-2.0*FB)
      F(I5,I17)=APCU/APCUSL*F(I17,I5)
      F(I9,I17)=F(I5,I17)
      F(I7,I17)=APCU/APCUSC*F(I17,I7)
C  ACCOUNT FOR PCU BLOCKAGE
      B=(DPCUS-DPCU)*0.5
      D=B*(HPCUS/(HPCU+SD)-1.0)
      D=AMIN1(D,0.5*DPCU)
      DP=D+B
      CALL FRINGS(0.5*DPCUS-DP,0.5*DPCUS,0.5*DPCU,0.5*DPCUS,
     1            HPCUS,F(I5,I9))
      F(I9,I5)=F(I5,I9)
      F(I5,I7)=1.0-F(I5,I17)-F(I5,I9)
      F(I9,I7)=F(I5,I7)
      F(I7,I5)=APCUSL/APCUSC*F(I5,I7)
      F(I7,I9)=F(I7,I5)
      F(I7,I7)=1.0-2.0*F(I7,I5)-F(I7,I17)
C
C  DETERMINE VIEW FACTORS BETWEEN PL AND PL SHELL SURFACES
      I5=IST(5+6)
      I7=IST(7+6)
      I9=IST(9+6)
      I17=IST(17+1)
      SD=(HPLS-HPL)*0.5
      FA=DTOD(0.5*DPL,0.5*DPLS,SD)
      CALL CTORING(0.5*DPL,HPL,0.5*DPL,0.5*DPLS,SD,FB)
      FB=AMAX1(0.0,FB)
      F(I17,I5)=APLL/APL*FA+APLC/APL*FB
      F(I17,I9)=F(I17,I5)
      F(I17,I7)=2.0*APLL/APL*(1.0-FA)+APLC/APL*(1.0-2.0*FB)
      F(I5,I17)=APL/APLSL*F(I17,I5)




      F(I9,I17)=F(I5,I17)
      F(I7,I17)=APL/APLSC*F(I17,I7)
C  ACCOUNT FOR PL BLOCKAGE
      B=(DPLS-DPL)*0.5
      D=B*(HPLS/(HPL+SD)-1.0)
      D=AMIN1(D,0.5*DPL)
      DP=D+B
      CALL FRINGS(0.5*DPLS-DP,0.5*DPLS,0.5*DPL,0.5*DPLS,
     1            HPLS,F(I5,I9))
      F(I9,I5)=F(I5,I9)
      F(I5,I7)=1.0-F(I5,I17)-F(I5,I9)
      F(I9,I7)=F(I5,I7)
      F(I7,I5)=APLSL/APLSC*F(I5,I7)
      F(I7,I9)=F(I7,I5)
      F(I7,I7)=1.0-2.0*F(I7,I5)-F(I7,I17)
C
      RETURN
      END
C
C --****--
C
      SUBROUTINE VIEW2(N,NMR,NSR,IST,RM,AM,RS,AS)
C  CALCULATE VIEW FACTORS FOR ALL REMAINING SURFACES
      DIMENSION IST(20),RM(NMR+1),AM(NMR),RS(NSR+1),AS(NSR)
      COMMON/CVIEW/F(100,100)
      COMMON/AREA/APCUSL,APCUSC,APCUSR,APCUL,APCUC,APCUR,
     1            APLSL,APLSC,APLSR,APLL,APLC,APLR,
     2            APL,APCU,APLS,APCUS
      COMMON/DIMS/DPCUS,HPCUS,DPCU,HPCU,DPLS,HPLS,DPL,HPL,
     1            SD1,SD2,SD3
C
      PI=3.141592654
C
C  DETERMINE VIEW FACTORS BETWEEN MAIN AND SECONDARY RADIATORS
      K=IST(2)
      DO 15 L=1,NMR
      KK=IST(3)
      DO 20 M=1,NSR
      CALL FRINGS(RM(L),RM(L+1),RS(M),RS(M+1),SD2,FL)
      FL=AMAX1(0.0,FL)
      F(K,KK)=FL
C  RECIPROSITY
      F(KK,K)=FL*AM(L)/AS(M)
   20 KK=KK+1
   15 K=K+1
C
C  DETERMINE VIEW FACTORS BETWEEN RIGHT END OF PCU SHELL AND
C    SECONDARY RADIATOR
      KK=IST(3)
      DO 25 M=1,NSR
      CALL FRINGS(0.0,0.5*DPCUS,RS(M),RS(M+1),SD1+SD2,FM)
      FM=AMAX1(0.0,FM)
```

```
C   IF SD1 IS GREATER THAN ZERO, MUST ACCOUNT FOR BLOCKAGE FROM
C     MAIN RADIATOR
        FB=0.0
        IF(SD1.GT.0.0)THEN
        B=SD1/(SD1+SD2)*(RS(M+1)-0.5*DPCUS)+0.5*DPCUS
        IF(B.GT.RM(1))THEN
        CALL FRINGS(0.0,0.5*DPCUS,RM(1),B,SD1,FB)
        FB=AMAX1(0.0,FB)
        ELSE
        ENDIF
        ELSE
        ENDIF
        F(IST(10),KK)=AMAX1(0.0,FM-FB)
        F(KK,IST(10))=FM*APCUSR/AS(M)
     25 KK=KK+1
C
C   DETERMINE VIEW FACTORS BETWEEN LEFT END OF PL SHELL AND
C     MAIN RADIATOR
        KK=IST(2)
        DO 35 M=1,NMR
        CALL FRINGS(0.0,0.5*DPLS,RM(M),RM(M+1),SD2+SD3,FM)
        FM=AMAX1(0.0,FM)
C   IF SD3 IS GREATER THAN ZERO, MUST ACCOUNT FOR BLOCKAGE FROM
C     SECONDARY RADIATOR
        FB=0.0
        IF(SD3.GT.0.0)THEN
        B=SD3/(SD2+SD3)*(RM(M+1)-0.5*DPLS)+0.5*DPLS
        IF(B.GT.RS(1))THEN
        CALL FRINGS(0.0,0.5*DPLS,RS(1),B,SD3,FB)
        FB=AMAX1(0.0,FB)
        ELSE
        ENDIF
        ELSE
        ENDIF
        F(IST(12),KK)=AMAX1(0.0,FM-FB)
        F(KK,IST(12))=FM*APLSL/AM(M)
     35 KK=KK+1
C
C   DETERMINE VIEW FACTORS BETWEEN PCU SHELL CURVED SURFACE
C     AND MAIN RADIATOR
        K=IST(1)
        DO 45 L=1,NMR
        CALL CTORING(0.5*DPCUS,HPCUS,RM(L),RM(L+1),SD1,FL)
        FL=AMAX1(0.0,FL)
        F(IST(8),K)=FL
        F(K,IST(8))=FL*APCUSC/AM(L)
     45 K=K+1
C
C   DETERMINE VIEW FACTORS BETWEEN PCU SHELL AND SECONDARY RADIATOR
C     IF VIEW IS NOT BLOCKED BY MAIN RADIATOR
        RB=(HPCUS+SD1)/(HPCUS+SD1+SD2)
        K=IST(3)



        DO 50 L=1,NSR
        B=RB*RS(L+1)
        IF(B.LT.RM(1))THEN
        CALL CTORING(0.5*DPCUS,HPCUS,RS(L),RS(L+1),SD1+SD2,FL)
        FL=AMAX1(0.0,FL)
        F(IST(8),K)=FL
        F(K,IST(8))=FL*APCUSC/AS(L)
        ELSE
        ENDIF
     50 K=K+1
C
C   DETERMINE VIEW FACTORS BETWEEN PL SHELL CURVED SURFACE
C     AND SECONDARY RADIATOR
        K=IST(4)
        DO 55 L=1,NSR
        CALL CTORING(0.5*DPLS,HPLS,RS(L),RS(L+1),SD3,FL)
        FL=AMAX1(0.0,FL)
        F(IST(14),K)=FL
        F(K,IST(14))=FL*APLSC/AS(L)
     55 K=K+1
C
C   DETERMINE VIEW FACTORS BETWEEN PAYLOAD SHELL AND MAIN RADIATOR
C     IF VIEW IS NOT BLOCKED BY SECONDARY RADIATOR
        RB=(HPLS+SD3)/(HPLS+SD2+SD3)
        K=IST(2)
        DO 60 L=1,NMR
        B=RB*RM(L+1)
        IF(B.LT.RS(1))THEN
        CALL CTORING(0.5*DPLS,HPLS,RM(L),RM(L+1),SD2+SD3,FL)
        FL=AMAX1(0.0,FL)
        F(IST(14),K)=FL
        F(K,IST(14))=FL*APLSC/AM(L)
        ELSE
        ENDIF
     60 K=K+1
C
C   IF SD1 GREATER THAN ZERO, DETERMINE VIEW FACTOR BETWEEN
C     PCU SHELL (RIGHT END) AND MAIN RADIATOR
        IF(SD1.GT.0.0)THEN
        K=IST(1)
        DO 65 L=1,NMR
        CALL FRINGS(0.0,0.5*DPCUS,RM(L),RM(L+1),SD1,FL)
        FL=AMAX1(0.0,FL)
        F(IST(10),K)=FL
        F(K,IST(10))=FL*APCUSR/AM(L)
     65 K=K+1
        ELSE
        ENDIF
C
C   IF SD3 GREATER THAN ZERO, DETERMINE VIEW FACTOR BETWEEN
C     PAYLOAD SHELL (LETF END) AND SECONDARY RADIATOR
        IF(SD3.GT.0.0)THEN
```

```
      K=IST(4)
      DO 75 L=1,NSR
      CALL FRINGS(0.0,0.5*DPLS,RS(L),RS(L+1),SD3,FL)
      FL=AMAX1(0.0,FL)
      F(IST(12),K)=FL
      F(K,IST(12))=FL*APLSR/AS(L)
   75 K=K+1
      ELSE
      ENDIF
C
C  VIEW FACTORS BETWEEN ALL SURFACES AND SPACE
C    MAIN RADIATOR
      K=IST(2)
      J=IST(1)
      DO 85 L=1,NMR
      SUM=0.0
      KK=IST(3)
      DO 90 M=1,NSR
      SUM=SUM+F(K,KK)
   90 KK=KK+1
      SUM=SUM+F(K,IST(12))+F(K,IST(14))
      F(K,IST(19))=1.0-SUM
      F(J,IST(19))=1.0-F(J,IST(10))-F(J,IST(8))
      K=K+1
   85 J=J+1
C    SECONDARY RADIATOR
      K=IST(3)
      J=IST(4)
      DO 95 L=1,NSR
      SUM=0.0
      KK=IST(2)
      DO 100 M=1,NMR
      SUM=SUM+F(K,KK)
  100 KK=KK+1
      SUM=SUM+F(K,IST(10))+F(K,IST(8))
      F(K,IST(19))=1.0-SUM
      F(J,IST(19))=1.0-F(J,IST(12))-F(J,IST(14))
      K=K+1
   95 J=J+1
C    PCU SHELL
      F(IST(6),IST(19))=1.0
      J=IST(3)
      SUM1=0.0
      SUM2=0.0
      DO 105 L=1,NSR
      SUM1=SUM1+F(IST(10),J)
      SUM2=SUM2+F(IST(8),J)
  105 J=J+1
      K=IST(1)
      DO 110 M=1,NMR
      SUM1=SUM1+F(IST(10),K)
      SUM2=SUM2+F(IST(8),K)



  110 K=K+1
      F(IST(10),IST(19))=1.0-SUM1-F(IST(10),IST(12))
      F(IST(8),IST(19))=1.0-SUM2
C    PL SHELL
      F(IST(16),IST(19))=1.0
      J=IST(2)
      SUM1=0.0
      SUM2=0.0
      DO 115 L=1,NMR
      SUM1=SUM1+F(IST(12),J)
      SUM2=SUM2+F(IST(14),J)
  115 J=J+1
      K=IST(4)
      DO 120 M=1,NSR
      SUM1=SUM1+F(IST(12),K)
      SUM2=SUM2+F(IST(14),K)
  120 K=K+1
      F(IST(12),IST(19))=1.0-SUM1-F(IST(12),IST(10))
      F(IST(14),IST(19))=1.0-SUM2
C    SPACE
      F(IST(19),IST(19))=1.0
C
      RETURN
      END
C
C --****--
C
      SUBROUTINE FASSIGN(IFLAG,IST,FP)
C  ASSIGN VIEW FACTORS FOR PCU AND PL TO USE IN
C    SOLVING COMBINED RADIATION/CONDUCTION
      COMMON/CVIEW/F(100,100)
      DIMENSION FP(4,4),IST(20)
C
      IF(IFLAG.EQ.1)THEN
C  FOR PAYLOAD
      L=11
      M=18
      ELSE
C  FOR PCU
      L=5
      M=17
      ENDIF
C
      K=IST(L)
      DO 5 I=1,4
      IF(I.EQ.4)K=IST(M)
      KK=IST(L)
      DO 10 J=1,4
      IF(J.EQ.4)KK=IST(M)
      FP(I,J)=F(K,KK)
      KK=KK+2
   10 CONTINUE
```

```
      K=K+2
    5 CONTINUE
      RETURN
      END
C
C --*****--
C
      FUNCTION DTOD(R1,R2,H)
C  DETERMINE DISK OF RADIUS R1 TO DISK OF RADIUS R2 VIEW FACTOR
C    WITH H SEPARATION DISTANCE (REF. P.826 #21 OF SIEGEL AND HOWELL)
      H=AMAX1(H,0.0001)
      CR1=R1/H
      CR2=R2/H
      DTOD=0.0
      IF(CR1.LT.1.0E-6)RETURN
      X=1.0+(1.0+CR2*CR2)/CR1/CR1
      Y=CR2/CR1
      DTOD=0.5*(X-(X*X-4.0*Y*Y)**0.5)
      RETURN
      END
C
C --*****--
C
      FUNCTION CTOD(R1,R2,Z)
C  DETERMINE CYLINDER TO DISK VIEW FACTOR (USES VIEW FACTOR ALGEBRA
C    ALONG WITH #28, P.828 OF SIEGEL AND HOWELL)
C    R1 IS CYLINDER RADIUS, R2 IS DISK RADIUS
C    CYLINDER IS ADJACENT AND PERPENDICULAR TO DISK
C    Z IS LENGTH OF CYLINDER
      R=R2/R1
      IF(R.LT.1.0001)THEN
      CTOD=0.0
      RETURN
      ELSE
      ENDIF
      XL=Z/R1
      A=XL*XL+R*R-1.0
      B=XL*XL-R*R+1.0
      C1=((A+2.0)**2-4.0*R*R)**0.5*ACOS(B/R/A)+B*ASIN(1.0/R)
     1-1.570796327*A
      C2=ACOS(B/A)-C1*0.5/XL
      C3=1.0/R-C2/R/3.141592654
      F12=C3*R
      CTOD=0.5*(1.0-F12)
      RETURN
      END
C
C --*****--
C
      SUBROUTINE FRINGS(R1I,R1O,R2I,R2O,H,F)
C  DETERMINE VIEW FACTORS BETWEEN RINGS BASED ON DISK TO DISK
C    VIEW FACTORS AND VIEW FACTOR ALGEBRA



      F=(R1O*R1O*(DTOD(R1O,R2O,H)-DTOD(R1O,R2I,H))-
     1   R1I*R1I*(DTOD(R1I,R2O,H)-DTOD(R1I,R2I,H)))/
     2   (R1O*R1O-R1I*R1I)
      RETURN
      END
C
C --*****--
C
      SUBROUTINE CTORING(R1,Z1,R2I,R2O,H,F)
C  DETERMINE VIEW FACTORS BETWEEN CYLINDER AND RING
C    R1 IS CYLINDER RADIUS, Z1 IS CYLINDER LENGTH
C    R2I IS RING INNER RADIUS, R2O IS RING OUTER RADIUS
C    H IS SEPARATION DISTANCE
      Z1=AMAX1(Z1,0.0001)
C  EXTENDED CYLINDER TO SMALL RADIUS DISK
      FF1=CTOD(R1,R2I,Z1+H)
C  CYLINDER TO SMALL RADIUS DISK
      FFF1=H/Z1*(FF1-CTOD(R1,R2I,Z1))+FF1
C  EXTENDED CYLINDER TO LARGE RADIUS DISK
      FF2=CTOD(R1,R2O,Z1+H)
C  CYLINDER TO LARGE RADIUS DISK
      FFF2=H/Z1*(FF2-CTOD(R1,R2O,Z1))+FF2
C  CYLINDER TO RING
      F=FFF2-FFF1
      RETURN
      END
C
C --*****--
C
      SUBROUTINE OUT1(N)
      COMMON/EMIS/EMIS(100)
      COMMON/HT/ONETPP(100),T(100),R(100),G(100)
C
      WRITE(7,150)
  150 FORMAT('1',/,12X,'NETWORK SOLUTION USING GAUSS-SIEDEL',
     1/,/,1X,'SURFACE EMISSIVITY  TEMPERATURE   ONETPP',
     2 6X,'RADIOSITY   IRRADIATION'/,22X,'(KELVIN)',4X,'(W/SQ.M)',
     3 6X,'(W/SQ.M)',4X,'(W/SQ.M)',/)
C
      WRITE(7,160)(I,EMIS(I),T(I),ONETPP(I),R(I),G(I),I=1,N)
  160 FORMAT(4X,I2,2X,0PF9.5,5X,F7.2,4X,1PE11.4,2X,E11.4,2X,E11.4)
C
      RETURN
      END
C
C --*****--
C
      SUBROUTINE OUT2(IST)
      COMMON/X/XCPCU,XCPL
      COMMON/AREA/APCUSL,APCUSC,APCUSR,APCUL,APCUC,APCUR,
     1            APLSL,APLSC,APLSR,APLL,APLC,APLR,
     2            APL,APCU,APLS,APCUS
```

```
      COMMON/OUT/PMR,PSR,PPCUS,PPCU,PPLS,PPL,PCUWH,PLWH,REFPOWE,
     1           PSR1,PSR2,AREAMR,AREASR,TAVGPCUS,TAVGPLS,COP,
     2           TISMR,TOSMR,TISSR,TOSSR,HAPCU,HAPL,CPCU,CPL,
     3           THPOWER,THPNEW
      COMMON/HT/QNETPP(100),T(100),R(100),G(100)
      DIMENSION IST(20)
      WRITE(6,100)T(IST(17)),T(IST(6)),T(IST(8)),T(IST(10)),TAVGPCUS
  100 FORMAT('1',//,4X,'PCU TEMPERATURES (K):',/,
     16X,'PCU - ',3X,F8.2,/,6X,'LEFT PCU SHELL - ',F8.2,/,
     26X,'CENTER PCU SHELL - ',F8.2,/,
     36X,'RIGHT PCU SHELL - ',F8.2,/,
     46X,'SHELL AVERAGE - ',F8.2)
      WRITE(6,105)T(IST(18)),T(IST(12)),T(IST(14)),T(IST(16)),TAVGPLS
  105 FORMAT(' ',//,4X,'PAYLOAD TEMPERATURES (K):',/,
     16X,'PAYLOAD - ',3X,F8.2,/,6X,'LEFT PAYLOAD SHELL - ',F8.2,/,
     26X,'CENTER PAYLOAD SHELL - ',F8.2,/,
     36X,'RIGHT PAYLOAD SHELL - ',F8.2,/,
     46X,'SHELL AVERAGE - ',F8.2)
      WRITE(6,107)HAPCU,HAPL
  107 FORMAT(' ',//,4X,'TOTAL HA FOR CONVECTION (W/K):',/,
     16X,'PCU ACTIVE COOLING - ',1PE12.4,/,
     26X,'PAYLOAD ACTIVE COOLING - ',E12.4)
      WCPCU=AMAX1(CPCU,XCPCU)
      WCPL=AMAX1(CPL,XCPL)
      WRITE(6,108)WCPCU,WCPL
  108 FORMAT(' ',//,4X,'TOTAL KA/X FOR CONDUCTION (W/K):',/,
     16X,'PCU TO SHELL - ',1PE12.4,/,
     26X,'PAYLOAD TO SHELL - ',E12.4)
      WRITE(6,110)AREAMR,AREASR,APCUS,APCU,APLS,APL
  110 FORMAT(' ',//,4X,'STRUCTURE AREAS (SQ.M):',/,
     16X,'MAIN RADIATOR - ',1PE12.4,/,
     26X,'SECONDARY RADIATOR - ',E12.4,/,
     36X,'PCU SHELL - ',E12.4,/,
     46X,'PCU - ',E12.4,/,
     56X,'PAYLOAD SHELL - ',E12.4,/,
     66X,'PAYLOAD - ',E12.4)
      WRITE(6,115)PCUWH,PSR1,PPCUS
  115 FORMAT(' ',//,4X,'WASTE HEAT GENERATED IN PCU (W) = ',1PE12.4,
     1/,6X,'PCU WASTE HEAT REMOVED ACTIVELY (W) = ',E12.4,/,
     26X,'PCU WASTE HEAT REMOVED BY CONDUCTION TO SHELL (W) = ',
     3E12.4)
      WRITE(6,120)PLWH,PSR2,PPLS
  120 FORMAT(' ',//,4X,'WASTE HEAT GENERATED IN PAYLOAD (W) = ',1PE12.4,
     1/,6X,'PAYLOAD WASTE HEAT REMOVED ACTIVELY (W) = ',E12.4,/,
     26X,'PAYLOAD WASTE HEAT REMOVED BY CONDUCTION TO SHELL (W) = ',
     3E12.4)
      WRITE(6,125)PMR,PSR,PPCUS,PPCU,PPLS,PPL
  125 FORMAT(' ',//,4X,'WASTE HEAT REMOVED BY RADIATION (W):' ,/,
     16X,'MAIN RADIATOR - ',1PE12.4,/,
     26X,'SECONDARY RADIATOR - ',E12.4,/,
     36X,'PCU SHELL - ',E12.4,/,6X,'PCU - ',E12.4,/,
     46X,'PAYLOAD SHELL - ',E12.4,/,6X,'PAYLOAD - ',E12.4)



      POWMAX=AMAX1(THPOWER,THPNEW)
      WRITE(6,130)REFPOWE,COP,POWMAX
  130 FORMAT(' ',//,4X,'REFRIGERATOR ELECTRIC POWER TO COOL PAYLOAD
     1 (W) = ',1PE12.4,/,4X,'REFRIGERATOR COP = ',E12.4,/,
     24X,'TOTAL THERMAL POWER (W) = ',E12.4,/,
     36X,/,6X,25('.'),//)
C
      RETURN
      END
C
C --*****--
C
      SUBROUTINE IDOUT(N,NMR,NSR,IDSURF,IDCON)
      DIMENSION IDSURF(N),IDCON(N)
      WRITE(7,100)
  100 FORMAT(' ',4X,'SURFACE IDENTIFICATION',//,
     16X,'IDSURF = 0  -  SURFACE WITH KNOWN TEMPERATURE',/,
     26X,'IDSURF = 1  -  SURFACE WITH KNOWN HEAT FLUX',/,
     36X,'IDSURF = 2  -  TWO-SIDED SURFACE WITH T(SIDE 1) =
     4 T(SIDE 2) AND',/,21X,'Q(TOTAL) = Q(SIDE 1) + Q(SIDE 2)',/,
     56X,'(IDCON IDENTIFIES CONNECTED SURFACES, 0 FOR NO CONNECTION)',
     6///,7X,'SURFACE',8X,'IDSURF',9X,'IDCON',/)
C
      DO 10 I=1,N
      IF(I.LE.2*NMR)WRITE(7,105)I,IDSURF(I),IDCON(I)
      IF(I.GT.2*NMR.AND.I.LE.2*NMR+2*NSR)
     1WRITE(7,110)I,IDSURF(I),IDCON(I)
      IF(I.GT.2*NMR+2*NSR)WRITE(7,115)I,IDSURF(I),IDCON(I)
   10 CONTINUE
  105 FORMAT(' ',7X,I3,12X,I3,12X,I3,7X,'MAIN RADIATOR NODE')
  110 FORMAT(' ',7X,I3,12X,I3,12X,I3,7X,'SECONDARY RADIATOR NODE')
  115 FORMAT(' ',7X,I3,12X,I3,12X,I3)
      RETURN
      END
C
C --****--
C
      SUBROUTINE FOUT(N)
      COMMON/CVIEW/F(100,100)
      WRITE(7,100)
  100 FORMAT('1',//,6X,'NON-ZERO VIEW FACTORS',//,
     19X,'I',6X,'J',7X,'F(I,J)',6X,'F(J,I)',/)
      DO 10 I=1,N
      DO 20 J=I,N
      IF(ABS(F(I,J)).GT.0.00005.OR.ABS(F(J,I)).GT.0.00005)
     1WRITE(7,105)I,J,F(I,J),F(J,I)
   20 CONTINUE
   10 CONTINUE
  105 FORMAT(' ',6X,I3,4X,I3,6X,F7.4,5X,F7.4)
      RETURN
      END
C
```

```
C --*****--
C
      SUBROUTINE ROUT(NMR,NSR,TNMR,TNSR,TSMR,TSSR,POAMR,POASR,
     1                RMR,RSR,AMR,ASR,RNMR,RNSR)
      COMMON/OUT/PMR,PSR,PPCUS,PPCU,PPLS,PPL,PCUWH,PLWH,REFPOWE,
     1           PSR1,PSR2,AREAMR,AREASR,TAVGPCUS,TAVGPLS,COP,
     2           TISMR,TOSMR,TISSR,TOSSR,HAPCU,HAPL,CPCU,CPL,
     3           THPOWER,THPNEW
      DIMENSION TNMR(NMR),TNSR(NSR),TSMR(NMR),TSSR(NSR)
      DIMENSION POAMR(NMR),POASR(NSR),RMR(NMR+1),RSR(NSR+1)
      DIMENSION AMR(NMR),ASR(NSR),RNMR(NMR),RNSR(NSR)
      WRITE(6,100)RMR(1),RMR(NMR+1),TISMR,TOSMR
  100 FORMAT(' ',3X,'MAIN-RADIATOR NODE OUTPUT',/,
     111X,'INSIDE/OUTSIDE RADII (M) = ',F8.3,'/',F8.3,/,
     211X,'INSIDE/OUTSIDE TEMPERATURES (K) = ',F8.3,'/',F8.3,//,
     35X,'NODE',3X,'RADIUS (M)',3X,'AREA (SQ.M)',4X,'TEMP (K)',
     44X,'TEFF (K)',6X,'POWER (W)',/)
C
      DO 10 I=1,NMR
      P=POAMR(I)*AMR(I)
   10 WRITE(6,115)I,RNMR(I),AMR(I),TNMR(I),TSMR(I),P
C
      WRITE(6,105)RSR(1),RSR(NSR+1),TISSR,TOSSR
  105 FORMAT(' ',/,/,/,3X,'SECONDARY-RADIATOR NODE OUTPUT',/,
     111X,'INSIDE/OUTSIDE RADII (M) = ',F8.3,'/',F8.3,/,
     211X,'INSIDE/OUTSIDE TEMPERATURES (K) = ',F8.3,'/',F8.3,//,
     35X,'NODE',3X,'RADIUS (M)',3X,'AREA (SQ.M)',4X,'TEMP (K)',
     44X,'TEFF (K)',6X,'POWER (W)',/)
C
      DO 20 I=1,NSR
      P=POASR(I)*ASR(I)
   20 WRITE(6,115)I,RNSR(I),ASR(I),TNSR(I),TSSR(I),P
C
  115 FORMAT(' ',4X,I3,4X,2(F8.3,5X),1X,2(F8.2,4X),1PE12.4)
      WRITE(6,120)
  120 FORMAT(' ',//,10X,20('*-*'),//)
      RETURN
      END
C
C --*****--
C
```

APPENDIX C - SAMPLE PROGRAM OUTPUT

MAIN-RADIATOR NODE OUTPUT
INSIDE/OUTSIDE RADII (M) = 6.000/ 25.353
INSIDE/OUTSIDE TEMPERATURES (K) = 480.000/ 985.000

NODE	RADIUS (M)	AREA (SQ.M)	TEMP (K)	TEFF (K)	POWER (W)
1	17.233	1366.934	549.20	372.66	9.9943E+06
2	23.244	381.674	723.57	362.89	9.9986E+06
3	24.909	157.607	893.99	360.90	9.9994E+06

SECONDARY-RADIATOR NODE OUTPUT
INSIDE/OUTSIDE RADII (M) = 7.000/ 44.572
INSIDE/OUTSIDE TEMPERATURES (K) = 470.000/ 400.000

NODE	RADIUS (M)	AREA (SQ.M)	TEMP (K)	TEFF (K)	POWER (W)
1	16.180	1407.115	460.63	419.32	2.0240E+06
2	26.728	1433.203	443.20	396.58	2.0268E+06
3	34.431	1528.808	425.73	375.45	2.0201E+06
4	41.242	1718.179	408.24	356.91	2.0196E+06

-

```
PCU TEMPERATURES (K):
  PCU -       488.12
  LEFT PCU SHELL -    459.17
  CENTER PCU SHELL -    489.85
  RIGHT PCU SHELL -    487.53
  SHELL AVERAGE -    485.75


PAYLOAD TEMPERATURES (K):
  PAYLOAD -       474.75
  LEFT PAYLOAD SHELL -    508.12
  CENTER PAYLOAD SHELL -    468.43
  RIGHT PAYLOAD SHELL -    455.46
  SHELL AVERAGE -    471.80


TOTAL HA FOR CONVECTION (W/K):
  PCU ACTIVE COOLING -    0.0000E+00
  PAYLOAD ACTIVE COOLING -    2.0378E+05


TOTAL KA/X FOR CONDUCTION (W/K):
  PCU TO SHELL -    2.4514E+05
  PAYLOAD TO SHELL -    4.4273E+05


STRUCTURE AREAS (SQ.M):
  MAIN RADIATOR -    1.9062E+03
  SECONDARY RADIATOR -    6.0873E+03
  PCU SHELL -    4.0212E+02
  PCU -    2.4504E+02
  PAYLOAD SHELL -    6.2832E+02
  PAYLOAD -    4.0212E+02


WASTE HEAT GENERATED IN PCU (W) =    5.0000E+05
  PCU WASTE HEAT REMOVED ACTIVELY (W) =    0.0000E+00
  PCU WASTE HEAT REMOVED BY CONDUCTION TO SHELL (W) =    4.9029E+05


WASTE HEAT GENERATED IN PAYLOAD (W) =    9.0000E+06
  PAYLOAD WASTE HEAT REMOVED ACTIVELY (W) =    8.1000E+06
  PAYLOAD WASTE HEAT REMOVED BY CONDUCTION TO SHELL (W) =    8.8545E+05


WASTE HEAT REMOVED BY RADIATION (W):
  MAIN RADIATOR -    3.0000E+07
  SECONDARY RADIATOR -    8.1000E+06
  PCU SHELL -    4.9029E+05
  PCU -    1.4547E+04
  PAYLOAD SHELL -    8.8545E+05
  PAYLOAD -    1.4547E+04


  ........................
```

SURFACE IDENTIFICATION

IDSURF = 0 - SURFACE WITH KNOWN TEMPERATURE
IDSURF = 1 - SURFACE WITH KNOWN HEAT FLUX
IDSURF = 2 - TWO-SIDED SURFACE WITH T(SIDE 1) = T(SIDE 2) AND Q(TOTAL) = Q(SIDE 1) + Q(SIDE 2)
(IDCON IDENTIFIES CONNECTED SURFACES; 0 FOR NO CONNECTION, NEGATIVE FOR SECOND SIDE OF TWO-SIDED SURFACE)

SURFACE	IDSURF	IDCON	
1	0	4	MAIN RADIATOR NODE
2	0	5	MAIN RADIATOR NODE
3	0	6	MAIN RADIATOR NODE
4	0	-1	MAIN RADIATOR NODE
5	0	-2	MAIN RADIATOR NODE
6	0	-3	MAIN RADIATOR NODE
7	0	11	SECONDARY RADIATOR NODE
8	0	12	SECONDARY RADIATOR NODE
9	0	13	SECONDARY RADIATOR NODE
10	0	14	SECONDARY RADIATOR NODE
11	0	-7	SECONDARY RADIATOR NODE
12	0	-8	SECONDARY RADIATOR NODE
13	0	-9	SECONDARY RADIATOR NODE
14	0	-10	SECONDARY RADIATOR NODE
15	2	16	PCU SHELL LEFT END (INSIDE)
16	2	-15	PCU SHELL LEFT END (OUTSIDE)
17	2	18	PCU SHELL CENTER (INSIDE)
18	2	-17	PCU SHELL CENTER (OUTSIDE)
19	2	20	PCU SHELL RIGHT END (INSIDE)
20	2	-19	PCU SHELL RIGHT END (OUTSIDE)
21	2	22	PL SHELL LEFT END (INSIDE)
22	2	-21	PL SHELL LEFT END (OUTSIDE)
23	2	24	PL SHELL CENTER (INSIDE)
24	2	-23	PL SHELL CENTER (OUTSIDE)
25	2	26	PL SHELL RIGHT END (INSIDE)
26	2	-25	PL SHELL RIGHT END (OUTSIDE)
27	1	0	PCU
28	1	0	PAYLOAD (PL)
29	0	0	SPACE

NON-ZERO VIEW FACTORS

I	J	F(I,J)	F(J,I)
1	18	0.0543	0.2462
1	20	0.0016	0.0438
1	29	0.9441	0.0000
2	18	0.0156	0.0197
2	20	0.0001	0.0005
2	29	0.9843	0.0000
3	18	0.0127	0.0066
3	20	0.0000	0.0001
3	29	0.9873	0.0000
4	7	0.2478	0.2408
4	8	0.1650	0.1574
4	9	0.1155	0.1033
4	10	0.0862	0.0686
4	22	0.0167	0.2899
4	29	0.3687	0.0000
5	7	0.1921	0.0521
5	8	0.1613	0.0429
5	9	0.1268	0.0317
5	10	0.0998	0.0222
5	22	0.0108	0.0525
5	29	0.4093	0.0000
6	7	0.1774	0.0199
6	8	0.1576	0.0173
6	9	0.1287	0.0133
6	10	0.1035	0.0095
6	22	0.0097	0.0194
6	29	0.4232	0.0000
7	20	0.0104	0.2906
7	29	0.6769	0.0000
8	20	0.0055	0.1575
8	29	0.7768	0.0000
9	20	0.0034	0.1023
9	29	0.8484	0.0000
10	20	0.0022	0.0747
10	29	0.8976	0.0000
11	22	0.0020	0.0364
11	24	0.0743	0.2218
11	29	0.9237	0.0000
12	22	0.0001	0.0010
12	24	0.0193	0.0587
12	29	0.9807	0.0000
13	22	0.0000	0.0004
13	24	0.0096	0.0311
13	29	0.9904	0.0000
14	22	0.0000	0.0002
14	24	0.0057	0.0208
14	29	0.9943	0.0000
15	17	0.3321	0.0553
15	19	0.0366	0.0366
15	27	0.6313	0.1295
16	29	1.0000	0.0000
17	17	0.2872	0.2872
17	19	0.0553	0.3321
17	27	0.6021	0.7410

18	29	0.7274	0.0000
19	27	0.6313	0.1295
20	22	0.0235	0.0150
20	29	0.3071	0.0000
21	23	0.3226	0.0538
21	25	0.0298	0.0298
21	28	0.6476	0.1265
22	29	0.5852	0.0000
23	23	0.2550	0.2550
23	25	0.0538	0.3226
23	28	0.6375	0.7470
24	29	0.6677	0.0000
25	28	0.6476	0.1265
26	29	1.0000	0.0000
29	29	1.0000	1.0000

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SURFACE	EMISSIVITY	TEMPERATURE (KELVIN)	QNETPP (W/SQ.M)	RADIOSITY (W/SQ.M)	IRRADIATION (W/SQ.M)
1	0.90000	549.20	4.0939E+03	4.7027E+03	6.0883E+02
2	0.90000	723.57	1.3534E+04	1.4035E+04	5.0108E+02
3	0.90000	893.99	3.2146E+04	3.2639E+04	4.9330E+02
4	0.90000	549.20	3.2170E+03	4.8001E+03	1.5831E+03
5	0.90000	723.57	1.2662E+04	1.4132E+04	1.4695E+03
6	0.90000	893.99	3.1299E+04	3.2733E+04	1.4347E+03
7	0.90000	460.63	-2.9950E+02	2.5854E+03	2.8849E+03
8	0.90000	443.20	-1.0456E+02	2.1988E+03	2.3034E+03
9	0.90000	425.73	7.6644E+01	1.8538E+03	1.7772E+03
10	0.90000	408.24	1.8230E+02	1.5544E+03	1.3721E+03
11	0.90000	460.63	1.7373E+03	2.3591E+03	6.2184E+02
12	0.90000	443.20	1.5186E+03	2.0185E+03	4.9990E+02
13	0.90000	425.73	1.2447E+03	1.7241E+03	4.7936E+02
14	0.90000	408.24	9.9310E+02	1.4643E+03	4.7121E+02
15	0.90000	459.18	-6.3371E+02	2.5906E+03	3.2243E+03
16	0.90000	459.17	1.8547E+03	2.3139E+03	4.5919E+02
17	0.90000	489.88	6.9416E+01	3.2572E+03	3.1878E+03
18	0.90000	489.85	1.1506E+03	3.1362E+03	1.9855E+03
19	0.90000	487.53	6.6968E-01	3.2026E+03	3.2019E+03
20	0.90000	487.53	1.2187E+03	3.0673E+03	1.8486E+03
21	0.90000	508.13	8.6508E+02	3.6832E+03	2.8181E+03
22	0.90000	508.12	5.4606E+02	3.7184E+03	3.1724E+03
23	0.90000	468.47	-1.1749E+02	2.7435E+03	2.8610E+03
24	0.90000	468.43	1.5276E+03	2.5598E+03	1.0323E+03
25	0.90000	455.46	-3.7299E+02	2.4809E+03	2.8539E+03
26	0.90000	455.46	1.7822E+03	2.2414E+03	4.5919E+02
27	0.80000	488.12	3.9644E+01	3.2082E+03	3.1638E+03
28	0.80000	474.75	3.6175E+01	2.8707E+03	2.8292E+03
29	1.00000	300.00	0.0000E+00	4.5919E+02	4.5919E+02

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