RADIATION HEAT TRANSFER ANALYSIS FOR SPACE VEHICLES

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FOREWORD

This is one of a series of reports which summarizes the first 6-month phase of a planned 3-year study of thermal and atmospheric control systems of manned and unmanned space vehicles. The study was conducted by the Space and Information Systems Division of North American Aviation, Inc., under contract AF 33(616)-7635, and was sponsored by the Flight Accessories Laboratory of Aeronautical Systems Division (formerly Wright Air Development Division). The Los Angeles Division of North American Aviation, Inc., and AiResearch Manufacturing Company were subcontractors in the study effort.

The reports covering the results of the first 6-month period of this study are listed below. Because of the intention to revise, amplify, and extend the material presented, each report has been designated as Part I. Additional parts of these reports will be published as the program progresses. In addition to publishing these subsequent parts, new phases of the study will result in additional reports.

- ASD TR 61-164 (Part I) Environmental Control Systems Selection for Unmanned Space Vehicles (secret)
- ASD TR 61-240 (Part I) Environmental Control Systems Selection for Manned Space Vehicles, Volume I (unclassified) and Volume II (secret)
- ASD TR 61-161 (Part I) Space Vehicle Environmental Control Requirements Based on Equipment and Physiological Criteria
- ASD TR 61-119 (Part I) Radiation Heat Transfer Analysis for Space Vehicles
- ASD TR 61-30 (Part I) Space Radiator Analysis and Design
- ASD TR 61-176 (Part I) Integration and Optimization of Space Vehicle Environmental Control Systems

ASD TR 61-119 Pt I - iii -
The thermal and atmospheric control program was under the direction of A. L. Ingelfinger and Lieutenant N. P. Jeffries of the Environmental Control Section, Flight Accessories Laboratory. E. A. Zara of the Environmental Control Section acted as monitor of this report. A. C. Martin served as project engineer at S&ID. The radiation heat transfer studies were conducted by J. A. Stevenson and J. C. Grafton.

Appreciation is expressed to the Astronautics and Fort Worth Divisions of Convair (General Dynamics Corporation) and, in particular, John C. Ballinger of the Astronautics Division. Much of the data included in this report was obtained from Convair.

The authors also wish to express their appreciation to G. A. McCue of the Aero-Space Laboratories of S&ID who contributed a major part to the orbiting space vehicle studies at S&ID.
ABSTRACT

This document covers problems associated with one part of the thermal and atmospheric control study—the analysis of radiation heat transfer in space. The basic theory of radiation heat transfer and the thermal radiation environment in space are described. Analysis techniques are included for calculating space vehicle surface temperatures and for solving radiation heat transfer problems in general. Tabulated configuration factor data and emittance data are presented.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

WILLIAM C. SAVAGE
Chief, Environmental Branch
Flight Accessories Laboratory
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Section I

INTRODUCTION

STUDY PROGRAM

The Thermal and Atmospheric Control Study conducted for Aeronautical Systems Division (formerly Wright Air Development Division) is an analytical and experimental program concerned with the problems of environmental control of future space vehicles. Three broadly defined tasks were designated for this study. They are:

1. Improved analysis methods for predicting the requirements for and the performance of space environmental control systems

2. Improved methods, techniques, systems, and equipment required for environmental control

3. Development of criteria and techniques for the optimization of environmental control systems and the integration of these systems with other vehicle systems

To accomplish these tasks, industrial organizations and military establishments were surveyed to obtain data concerned with current and future thermal and atmospheric control technology. Other endeavors include evaluating existing and newly created methods of analysis, selection, integration, and optimization of control systems and components. The refurbishment and development of existing and new analog or digital computer programs, applicable to this study, are included. In addition, laboratory verification of analyses and new design concepts form a part of the effort associated with these tasks.

To guide all of the endeavors along lines which will find immediate and practical application, components and systems associated with specific vehicles were studied. The vehicles selected were representative of a number of earth-orbital and cislunar missions. These hypothetical vehicles were carried through preliminary design and used as thermal and atmospheric control models.

ROLE OF RADIANT HEAT TRANSFER ANALYSIS

Although transfer of heat within a space vehicle or satellite can occur by radiation, conduction, or convection, the only means by which the vehicle...
can exchange heat with its environment is by radiation. Temperature control systems, either active or passive, must eliminate heat by radiation to space. An accurate method of radiation heat transfer analysis is therefore of prime importance for the prediction of vehicle and component temperatures and the performance of temperature control systems.

This report documents a study of available methods of radiation heat transfer analysis and reviews the basic principles of thermal radiation. Included in the appendix sections are tables of emissivity and reflectivity for certain surface coatings which can be applied to space vehicles. This area is also of prime importance because even the most refined analysis techniques are only as accurate as the values of emittance and reflectance which are used.
Section II

GLOSSARY OF RADIATION TRANSFER TERMS

The following terms conform in terminology and symbolic representation to those most widely used in radiation heat transfer literature.

Absorptance or absorptivity $a$  
Ratio of absorbed radiant energy to incident radiation. Related to reflectance and transmittance by

$$a + \rho + r = 1$$

Albedo, $\alpha$  
Ratio of radiant energy reflected by planet or satellite to that received by it. A dimensionless decimal equal to or less than 1. Care must be taken to avoid confusion between the albedos of total and visible radiant energy.

Angstrom, Å  
Unit of measurement of wavelength of electromagnetic waves.

$$1 \text{ cm} = 10^8 \text{ Å} = 10^4 \mu$$

Black body  
Hypothetical body having the characteristic of absorbing all radiant energy striking it and reflecting and/or transmitting none.

$$a = 1.0, \rho = r = 0$$

Diffuse reflection  
Reflection that follows Lambert's cosine law (i.e., intensity $I$ is constant regardless of angle). Nonmetallic surfaces are often nearly perfect diffusive reflectors.

Emittance, $\epsilon$  
Ratio of emissive power $E$ of a body to emissive power $E_b$ of a black body at the same temperature. A dimensionless decimal equal to or less than 1. Distinctions are made between different types of emittance.

Total emittance  
Emittance of the whole range of wavelengths.
<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monochromatic emittance</td>
<td>Emittance radiating at a particular wavelength.</td>
</tr>
<tr>
<td>Hemispherical emittance</td>
<td>Emittance radiating in all directions from the surface.</td>
</tr>
<tr>
<td>Normal emittance</td>
<td>Emittance radiating in a direction normal to the surface.</td>
</tr>
<tr>
<td>Directional emittance</td>
<td>Emittance radiating in a direction at an angle $\phi$ to the normal to the surface.</td>
</tr>
<tr>
<td>Emissive power $E$</td>
<td>Radiant energy emitted at a given temperature per unit time and unit area of radiating surface. Also called flux density. Expressed as Btu/(hour) (square foot).</td>
</tr>
<tr>
<td>Monochromatic emissive power, $E_\lambda$</td>
<td>Emissive power emitted at a single wavelength for a given temperature.</td>
</tr>
<tr>
<td>Total emissive power</td>
<td>Emissive power emitted over the whole spectrum of wavelengths.</td>
</tr>
<tr>
<td>Emissivity, $\epsilon$</td>
<td>See emittance. Characterizes a certain material in pure polished and opaque form, while emittance pertains to a particular specimen. In this report, however, no distinction is made between emissivity and emittance.</td>
</tr>
<tr>
<td>Equilibrium</td>
<td>Condition in which the interchange of radiant energy between bodies becomes and remains constant.</td>
</tr>
<tr>
<td>Flux density</td>
<td>See emissive power and incident radiation.</td>
</tr>
<tr>
<td>Gray body</td>
<td>A body or surface for which $a_\lambda = \epsilon_\lambda = a = \epsilon$ at all wavelengths and temperatures. Its emission distribution curve therefore parallels that of a black body or surface but is of lesser magnitude.</td>
</tr>
<tr>
<td>Term</td>
<td>Definition</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>--------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Hemispherical</td>
<td>Refers to the boundary condition of a specular measurement in which the solid angle being considered is equal to $2\pi$ steradians.</td>
</tr>
<tr>
<td>Incident radiation</td>
<td>Radiant energy impinging on a surface per unit time and per unit area. Also called irradiation or flux density.</td>
</tr>
<tr>
<td>Infrared</td>
<td>Region of the electromagnetic spectrum extending approximately from 0.75 to about 300 microns.</td>
</tr>
<tr>
<td>Intensity of radiation, I</td>
<td>Rate of emission in a direction at an angle $\phi$ to the normal to the surface. Expressed as $\frac{\text{energy}}{\text{area}(\text{time})(\text{solid angle})(\cos \phi)}$ or $\frac{\text{energy}}{\text{time}(\text{solid angle})(\text{projected area})}$</td>
</tr>
<tr>
<td>Irradiation</td>
<td>See incident radiation.</td>
</tr>
<tr>
<td>Isotropic radiation</td>
<td>Radiation impinging on a surface having the same characteristics regardless of the location and direction of the surface.</td>
</tr>
<tr>
<td>Monochromatic</td>
<td>Having a single wavelength and single frequency of electromagnetic vibration.</td>
</tr>
<tr>
<td>Radiance</td>
<td>See emissive power.</td>
</tr>
<tr>
<td>Radiancy</td>
<td>See emissive power.</td>
</tr>
<tr>
<td>Radiant energy</td>
<td>Energy emitted from a surface in the form of electromagnetic waves.</td>
</tr>
<tr>
<td>Radiant heat</td>
<td>Radiant energy emitted in consequence of the temperature of a body. Usually considered to be that part of the electromagnetic or radiant energy spectrum between 2,000 and 50,000 angstroms.</td>
</tr>
<tr>
<td>Radiosity, J</td>
<td>Sum of emitted, reflected, and transmitted radiation flux per unit area. Usually expressed in Btu/(hour)(square foot).</td>
</tr>
<tr>
<td>Term</td>
<td>Definition</td>
</tr>
<tr>
<td>-------------------------------------</td>
<td>------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Reflectance, $\rho$</td>
<td>Ratio of reflected to incident radiant energy. Related to absorptance and transmittance by $\rho + a + r = 1$</td>
</tr>
<tr>
<td>Spectral energy distribution</td>
<td>Monochromatic emissive power over the range of the spectrum of an emitting surface.</td>
</tr>
<tr>
<td>Specular reflection</td>
<td>Refers to reflection which occurs in such a way that the angle between the reflected beam of radiation and the normal to the surface equals the angle made by the impinging beam with the same normal.</td>
</tr>
<tr>
<td>Stefan-Boltzmann constant, $\sigma$</td>
<td>Constant which is independent of surface and temperature and relates heat radiated $q_r$ to absolute temperature, area, and emissivity. The relationship is $q_r = \sigma \epsilon AT^4$</td>
</tr>
<tr>
<td>Thermal radiation</td>
<td>See radiant heat.</td>
</tr>
<tr>
<td>Transmittance, $r$</td>
<td>Ratio of radiant energy transmitted through the body to the incident radiation. Related to absorptance, and reflectance by $r + a + \rho = 1$</td>
</tr>
<tr>
<td>Total radiation</td>
<td>Sum of all radiation over the entire spectrum of emitted wavelengths.</td>
</tr>
<tr>
<td>Ultraviolet</td>
<td>Region of the electromagnetic spectrum extending approximately from 0.01 to 0.4 micron.</td>
</tr>
<tr>
<td>Visible</td>
<td>Region of the electromagnetic spectrum extending approximately from 0.4 to 0.75 micron.</td>
</tr>
<tr>
<td>Wavelength, $\lambda$</td>
<td>Distance measured along line of propagation between two points which are in phase on adjacent waves.</td>
</tr>
</tbody>
</table>
BASIC CONCEPTS OF THERMAL RADIATION

The process of emission of radiant energy by a body, which depends on its temperature, is called thermal radiation. Each body, by virtue of its temperature, is constantly emitting electromagnetic radiation from its surface into the surrounding space and is absorbing radiant energy originating elsewhere and incident upon it. Electromagnetic radiation is composed of all wavelengths, including extremely short-wave secondary gamma rays and the longest radio waves. Theoretically, all bodies emit radiation over the entire electromagnetic spectrum (Figure 1).

The amount of energy emitted generally varies with wavelength in a manner similar to that shown in Figure 2. The curves give the spectral distribution of radiation from a black body at temperatures of 2700, 1980, and 1260 K. The maximum energy emitted by a body increases as the temperature increases, and the wavelength at which the maximum energy is radiated becomes shorter as the temperature increases.

The rate of radiation from a black, or ideal, body is proportional to the fourth power of its absolute temperature. For other bodies, the rate of radiation is also proportional to the fourth power of their absolute temperature, but the magnitude varies depending on material, surface condition, and temperature. The rate of emission of energy per unit area for non-black-body materials is never greater than the rate of energy emission per unit area from a black body. For this reason, the black body is used as a standard or reference, and emission from other bodies is compared with it.

RADIATION LAWS

Kirchhoff's Law

Kirchhoff, in 1860, proposed a system consisting of a completely enclosed hollow space into which a thin plate is placed, the enclosure and plate being at the same temperature.

*The material in this section of the report was gathered from References 1 through 5.*
\[ \mu \text{ or micron} = 10^4 \, \text{Å} = 10^{-4} \, \text{cm} \]

Figure 1. Electromagnetic Spectrum
Figure 2. Energy Distribution of Black Body
By using the electromagnetic theory, which holds that radiation falling upon a surface exerts a pressure upon that surface, and the concept of mechanical equilibrium of radiation, it can be shown that the radiant energy incident upon the plate must equal the energy radiated from the plate, or work will be done upon the plate by moving it. The entire system is at the same temperature, however, and the second law of thermodynamics denies the possibility of transforming heat into external work unless a temperature difference exists. Because the second law of thermodynamics has thus far proven inviolate, the assumption of equal amounts of energy incident upon the plate and radiated from the plate must be accepted.

Kirchhoff also suggested that a nearly perfect black surface can be produced by employing a hollow enclosure into which a small aperture is available. Radiation passing into the enclosure through the aperture, which itself acts as a black surface, can be made to suffer such a large number of reflections around the walls of the enclosure that almost none of the entering radiation can escape out of the enclosure through the aperture, and the absorptance of the aperture approaches the limiting value of unity.

From the assumption of equilibrium of radiation, it is apparent that a constant-temperature enclosure which receives radiant energy from a source at the same temperature must emit an equal amount of radiant energy. Such a system is now considered with the stipulation that the source is emitting the maximum amount of energy that can be emitted from any source of like size at this temperature. The enclosure absorbs all of the incoming energy (\( \alpha = 1 \)). The enclosure, also, must emit back to the source, through the aperture, an equal amount of energy. Then, if the Kirchhoff black surface is acceptable, a black surface has the additional characteristic of emittance equal to unity (\( \epsilon = 1 \)). That is, a black surface must emit the maximum amount of energy (per unit area and unit time) that can be radiated from any surface at the same temperature.

It becomes obvious that Kirchhoff's black surface can be used as either a black surface source or a black surface receiver with the stipulation that the temperature of the entire enclosure must be constant and equal to that for which the black surface characteristics are required.

Lambert's Cosine Law

Lambert's cosine law states that the radiant heat flux from a plane source of radiation varies as the cosine of the angle measured from the normal to the surface. This assumes diffuse radiation as opposed to specular radiation, that is, in diffuse radiation, intensity I, expressed in Btu/(hour)(\( \text{solid angle} \))(projected area), is a constant regardless of the angle from the normal to the surface.
Consider Figure 3, letting the elemental area $dA_1$ represent Lambert's diffusely reflecting surface. When a constant density of radiation in space is assumed and only radiation in the visible range is considered, the area $dA_1 \cos \phi$ viewed from $M$ appears equally as bright as the area $dA_1$ viewed from $N$, and the quantity of light falling upon any area $dA_2$ is directly proportional to the area $dA_1 \cos \phi$. These same concepts apply equally as well to radiation of longer wavelength as they do to radiation of the visible range. The amount of radiant energy reaching a surface $dA_2$ from a black surface $dA_1$ is directly proportional to the area $dA_1 \cos \phi$.

Figure 3. Representation of Lambert's Cosine Law

True surfaces vary from this law depending upon the material. When the radiation intensity of a surface follows the cosine law, the directional emittance is independent of the angle of emission and is identical with the hemispherical emittance. Actually, the emittance of all true surfaces is dependent to a certain degree on the angle of emission.
Stefan-Boltzmann's Law

Stefan empirically found the relationship between the intensity of radiation from a black surface source and the absolute temperature of the surface. Later, Boltzmann theoretically reduced this same relationship, stating that the heat radiated by a black body is proportional to the fourth power of its absolute temperature, or

\[ q = \sigma A T^4 \]  

where

\[ q = \text{Total heat emitted, Btu/hr} \]
\[ \sigma = \text{Stefan-Boltzmann constant} = 0.1713 \times 10^{-8} \text{ Btu/(hr)(sq ft)(°R)}^4 \]
\[ A = \text{Emissive area, sq ft} \]
\[ T = \text{Absolute temperature, °R} \]

For non-black bodies, the heat emitted equals the black body heat emitted multiplied by the emittance, or

\[ q = \epsilon (\sigma A T^4) \]  

where

\[ \epsilon = \text{Emittance of non-black body} \]

Wien's Displacement Law

For black body radiation, if the wave of length \( \lambda_2 \) at \( T_2 \) is displaced from that of length \( \lambda_1 \) at \( T_1 \), such that \( \lambda_2 T_2 = \lambda_1 T_1 \), the monochromatic emissive powers at these two wavelengths are directly proportional to the fifth powers of the absolute temperatures, or

\[ \frac{E\lambda_1}{E\lambda_2} = \left( \frac{T_1}{T_2} \right)^5 \]  

Wien also determined that when the temperature of a radiating black body increases, the wavelength corresponding to the maximum energy decreases in such a way that the product of the absolute temperature and wavelength is a constant. (See Figure 2.) This is expressed as

\[ \lambda_{\text{max}} T = 5216.2 \mu(°R) \]  

- 12 -
Planck's Distribution Law

The present understanding of radiation and the spectrum began to develop in 1900 when Max Planck formulated his theory of the "granular" nature of energy and developed a new kind of statistics, the quantum theory, to handle his concept mathematically. Radiant energy leaving a surface is distributed over the entire wavelength range, and the distribution of the energy with wavelength is a function of the temperature and nature of the surface. The emissive power distribution at a given temperature for a black body is given as

$$E_\lambda = \frac{C_1 \lambda^{-5}}{e^{C_2/\lambda T} - 1}$$  \hspace{1cm} (5)

where

$$C_1 = 1.1870 \times 10^8 \text{ Btu}^4/(\text{hr})(\text{sq ft})$$

$$C_2 = 25,896 \mu (^\circ R)$$

$e$ = Base of natural logarithm

Absorption and Emission of Radiant Energy

The efficacy of the surface to emit or absorb radiation is presented in terms of emissivity and absorptivity factors. These factors are defined as the ratio of energy emitted or absorbed at each wavelength to the energy emitted or absorbed by a black body at the same temperature. These factors are usually presented as the total or average values over all wavelengths for a particular surface.

In addition to being functions of wavelength, emissivity and absorptivity are functions of the angle the light ray makes with the surface. Values are reported usually in terms of the normal (perpendicular to the surface) or hemispherical (average overall angles). The variation between normal and hemispherical emissivity is shown in Figure 4, as taken from Reference 3. Emissivities or absorptivities are often presented as total hemispherical or total normal, or they are given as a function of wavelength for normal or hemispherical radiation. Reflectance, or transmittance for transparent materials, is sometimes given rather than absorptivity. This, of course, is simply $1 - \alpha$.

Absorption or emission of energy up to about 2-microns wavelength is due primarily to raising the energy levels of the orbital electrons. These excited electrons then give up their energy usually in the form of molecular vibrational energy or fluorescence. Most electronic transitions involve
Figure 4. Theoretical and Experimental Values for Ratio of Hemispherical to Normal Emissivity
relatively large energy steps, and the temperature of the surface therefore has little effect on absorption in this range. Because almost all the solar energy lies in the wavelength below 2 microns, solar absorptivity \( \alpha_s \) should be nearly constant with surface temperature. Some minor effects are noted with temperature, caused by such factors as crystal structure changes.

Absorption or emission beyond 2 microns is due to raising the vibrational and kinetic energy levels of the molecules themselves. Organic materials are more sensitive to vibrational absorption than electrically conductive materials. Semiconductor materials are generally transparent to a large portion of the infrared region. The absorptivity or emissivity of any material varies with wavelength, and this variation is not the same for different materials.

Absorption can also occur by optical interference, where light is reflected 90 degrees out of phase from successive layers of a multilayer coating. This interference results in absorption of the energy rather than reflection. The coatings are usually alternate thin layers of metal and a dielectric, as shown schematically in Figure 5. For maximum absorption, the coating should be applied in thicknesses of one-quarter wavelength. If the thickness is one-half wavelength, the rays reinforce rather than cancel each other. By proper choice of materials and thicknesses, narrow or broad bands of light can be absorbed.

Another technique for achieving high absorption is to allow multiple reflections to take place before the radiant energy leaves the surface. This can be accomplished by placing cavities on the surfaces, either by sandblasting or by using wire mesh, honeycomb, or similar techniques. This effect is shown schematically in Figure 6. If the holes are small, only short wavelength radiation is absorbed and the surface appears flat to long wavelength radiation. The effect of sandblasting is to increase emissivity by about 10 percent, as shown in Figure 7 for oxidized 310 stainless steel.

![Figure 5. Absorption by Optical Interference](image-url)
Diffuse and Specular Radiation

Reflection from a surface can be either specular, where the angle of reflection is equal to the angle of incidence, or diffuse, where the reflection follows Lambert's cosine law regardless of incident angle; or it can be various combinations of diffuse and specular. Some of the combinations are indicated in Figure 8. A highly polished surface generally yields specular reflection, while roughened surfaces cause diffuse reflection.

Reflection of infrared energy by metals is caused by the interaction with the conduction electrons. If the unbound electrons remain free during the radiation period, the surface is a perfect reflector; if electrons intercept with other electrons, energy is transferred to the atoms. The reflectivity can be expressed mathematically as (Reference 6)

$$
\rho_\lambda = 1 - 0.365 \sqrt{\frac{P}{\lambda}}
$$

where

- $\rho_\lambda$ = Reflectivity at wavelength
- $P$ = Resistivity, ohm-mm
- $\lambda$ = Wavelength, $\mu$
Figure 7. Effect of Sandblasting on Total Emissivity

ALL SAMPLES HEATED TO 2100 F FOR 15 MIN IN AIR BEFORE TESTING
Figure 8. Reflective Surfaces
Equation 6 holds reasonably well for clean metallic surfaces for wavelengths greater than approximately 2 microns.

Fresnel reflections can occur from the surface of a dielectric material. By the use of alternate layers of materials of low and high index of refraction, highly reflective surfaces can be achieved. For minimum absorption, these coatings are applied with a thickness of one-half wavelength. White paints reflect light due to Fresnel reflection, although the reflecting layers are randomly distributed. The nature of Fresnel reflection is indicated in Figure 9.

RADIANT HEAT EXCHANGE BETWEEN SURFACES

The Stefan-Boltzmann equation for the net radiant exchange of energy between two black body radiators, one completely enclosing the other, is

\[ q_{net} = \sigma A_1 T_1^4 - \sigma A_2 T_2^4 \]

(7)

Figure 9. Fresnel Reflection
Most cases of radiant energy transfer, however, do not consist of one body completely enclosing the other. The interchange between the two surfaces depends upon the view the surfaces have of each other. Usually, only a small fraction of the energy leaving one surface is incident upon the other. To account for this, a configuration factor is introduced into the Stefan-Boltzmann equation, as

$$q_{\text{net}} = \sigma A_1 F_{12} (T_1^4 - T_2^4)$$

(8)

The configuration factor $F_{12}$ is defined as that fraction of the total energy originating at $A_1$ which is intercepted by $A_2$. Although the concept of the configuration factor is widely used in both thermal radiation problems and illuminating engineering, no standard designation or symbol for this quantity is currently used in the literature. Names often used include "configuration factor," "shape factor," "shape modulus," "view factor," "sky factor," "form factor," "P factor," and "flux factor."

The mathematical expression for the configuration factor is derived as follows.

Suppose it is desired to determine the radiant heat exchange between the horizontal and vertical black surfaces of Figure 10. The amount of energy which leaves $dA_1$ and impinges on $dA_2$ is

![Figure 10. Heat Exchange Between Two Surfaces](image)

- 20 -
\[ dq_{12} = I_1 dA_1 \cos \theta_1 \left( \frac{dA_2 \cos \theta_2}{S^2} \right) \]  \hspace{1cm} (9) \\

where 

\[ I = \text{Intensity of radiation, Btu/(hr)(projected area)(solid angle)} \]

Because the radiation is assumed to be of diffuse form, \( I \) is constant in all directions. Therefore, the expression \( I_1 dA_1 \cos \phi_1 \) in Equation 9 determines the rate at which radiant energy leaves \( dA_1 \) in the direction of \( dA_2 \). The amount of this energy which is intercepted by \( dA_2 \) depends on the solid angle which \( dA_2 \) subtends with center at \( dA_1 \). This solid angle is given in Equation 9 by the expression in parentheses.

In a like manner, the amount of energy which flows from \( dA_2 \) to \( dA_1 \) is given by

\[ dq_{21} = I_2 dA_2 \cos \theta_2 \left( \frac{dA_1 \cos \theta_1}{S^2} \right) \]  \hspace{1cm} (10) \\

Therefore,

\[ dq_{\text{net}} = (I_1 - I_2) \frac{\cos \theta_1 \cos \theta_2 dA_1 dA_2}{S^2} \]  \hspace{1cm} (11) \\

For diffuse radiation,

\[ I = \frac{E}{\pi} = \frac{\sigma T^4}{\pi} \]

Therefore,

\[ dq_{\text{net}} = \sigma (T_1^4 - T_2^4) \left( \frac{1}{\pi} \right) \frac{\cos \theta_1 \cos \theta_2 dA_1 dA_2}{S^2} \]  \hspace{1cm} (12) \\

and

\[ q_{\text{net}} = \sigma (T_1^4 - T_2^4) \left( \frac{1}{\pi} \right) \int_{A_1} \int_{A_2} \frac{\cos \theta_1 \cos \theta_2 dA_1 dA_2}{S^2} \]  \hspace{1cm} (13)
It follows from Equations 8 and 13 that

\[ A_1F_{12} = \frac{1}{\pi} \int \int \frac{\cos \theta_1 \cos \theta_2 dA_1 dA_2}{S^2} \]  

(14)

and

\[ F_{12} = \frac{1}{A_1 \pi} \int \int \frac{\cos \theta_1 \cos \theta_2 dA_1 dA_2}{S^2} \]  

(15)

Equation 15 is the integral expression for the configuration factor and is dependent on the geometry of the system only. Although this discussion has been limited to black surfaces, it is evident that for a non-black surface the configuration factor \( F_{12} \) also represents the fraction of radiation from \( A_1 \) intercepted by \( A_2 \) (but not necessarily absorbed). It should also be evident that

\[ F_{12} + F_{13} + F_{14} + \ldots = 1 \]  

(16)

where \( F_{13}, F_{14}, \ldots \) are the configuration factors for other surfaces which are seen by \( A_1 \). If \( A_1 \) is not flat, it may see portions of itself and have a finite \( F_{11} \).

It should also be pointed out that

\[ F_{12}A_1 = F_{21}A_2 \]  

(17)

Equation 17 is often called the reciprocity theorem. Thus, for the net exchange between two black surfaces,

\[ q_{\text{net}} = A_1F_{12} \sigma T_1^4 - A_2F_{21} \sigma T_2^4 \]  

(18)

and

\[ q_{\text{net}} = \sigma A_1F_{12}(T_1^4 - T_2^4) \]

\[ = \sigma A_2F_{21}(T_1^4 - T_2^4) \]  

(19)

In most cases, radiant heat exchange between two surfaces is influenced by the absorption, reflection, and emission from connecting surfaces. If the surfaces are non-black (i.e., gray or real), a complete accounting of
all the interreflections is quite difficult to accomplish analytically. Fortunately, methods are available for the more complicated radiation problems. These are discussed in Section VI.
Section IV

THERMAL RADIATION ENVIRONMENT IN SPACE

Incident radiation consists of the direct radiation from the sun, scattered and reflected sun radiation from a nearby planetary body, and radiation directly emitted by the planetary body. The value of irradiance varies over the surface of a vehicle and depends on the relative position of the surface with respect to the sun and other planetary bodies.

DIRECT SOLAR RADIATION

The release of energy from the sun produces radiation in many forms. Most of the radiation is thermal, concentrated in the visible and infrared spectrum. The total energy radiated in X-ray and ultraviolet bands is only a very small portion, measured in thousandths of a percent, of the total energy output of the sun.

Radiation intensity is inversely proportional to the square of the distance from the sun. At 1 astronomical unit (the distance from the sun to the earth), the total value of the solar constant is 443 Btu/(hour)(square foot) (Reference 7). The variation of irradiance for the solar system is shown in Figure 11. The solar constant is influenced by sunspot and other activity, but variations are small (less than 0.4 percent).

Many calculations are based on the assumption that the sun radiates as a 10,340°F black body. The black body radiant temperature, however, varies for each wavelength, and these variations should be analyzed for more exact calculations. Examples of approximate temperatures at which the sun radiates are given in Table 1 for several wavelengths (Reference 8). The deviation in spectral energy distribution from black body radiation is probably caused by variations in absorption by the solar atmospheric gases. The spectral energy curve of the sun is shown in Figure 12 (Reference 7).

The minimum temperature for any wavelength is approximately 6750°F. For the production of very short ultraviolet wavelengths and X-rays, the temperature in the corona is in the range of 1 x 10⁶°F. Sunspot temperatures are approximately 3600°F less than the photosphere; they emit only about 10 percent as much energy as equal areas of the solar surface.

Curves of intensity and wavelength of the solar spectrum show that most of the energy from the sun is carried in wavelengths between 2000 and
Figure 11. Solar Radiation at Various Distances From Sun
Figure 12. Spectral Energy Curve of Sun
Table 1. Solar Radiation Temperatures

<table>
<thead>
<tr>
<th>Wavelength (Å)</th>
<th>Temperature (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3500</td>
<td>9430</td>
</tr>
<tr>
<td>2900</td>
<td>9430</td>
</tr>
<tr>
<td>2600</td>
<td>8530</td>
</tr>
<tr>
<td>2200</td>
<td>8360</td>
</tr>
<tr>
<td>2000</td>
<td>7650</td>
</tr>
<tr>
<td>1500</td>
<td>7650</td>
</tr>
<tr>
<td>1200</td>
<td>10,500</td>
</tr>
</tbody>
</table>

20,000 angstroms, with the maximum energy centered about 4700 angstroms. The approximate energy distribution of solar radiance by percent of the total is given in Table 2 for several wavelength intervals (Reference 8).

Table 2. Energy Distribution of Solar Electromagnetic Radiation

<table>
<thead>
<tr>
<th>Type</th>
<th>Wavelength Interval (Å)</th>
<th>Approximate Radiant Energy (percent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-ray and ultraviolet</td>
<td>1 to 2000</td>
<td>0.2</td>
</tr>
<tr>
<td>Ultraviolet</td>
<td>2000 to 3800</td>
<td>7.8</td>
</tr>
<tr>
<td>Visible</td>
<td>3800 to 7000</td>
<td>41</td>
</tr>
<tr>
<td>Infrared</td>
<td>7000 to 10,000</td>
<td>22</td>
</tr>
<tr>
<td>Infrared</td>
<td>10,000 to 20,000</td>
<td>23</td>
</tr>
<tr>
<td>Infrared</td>
<td>20,000 to 100,000</td>
<td>6</td>
</tr>
</tbody>
</table>

The normal sun produces X-rays with power density on the order of 0.316 Btu/(hour)(square foot). These are probably produced in the corona. During a quiet sun, X-rays reaching the earth are neither very intense nor energetic. Wavelengths as short as 20 angstroms are present and penetrate the atmosphere to within 60 miles of the earth's surface when the sun is overhead. During maximum coronal activity the total output of X-rays may increase by a factor of 2 or 3 and, at the same time, tend to become harder with wavelengths as short as 6 or 7 angstroms. Flares are a still more important factor in producing hard X-rays, but their intensity near the earth is still low.

In the ultraviolet portion of the spectrum below 2000 angstroms, the greatest portion of the energy is found at the wavelength (1216 angstroms) of the resonance emission line of hydrogen atoms. In spectroscopy, this is
known as the Lyman alpha line. Below the wavelength of Lyman alpha are many other emission lines. One which appears to have more energy than the rest combined, but still much less than Lyman alpha, is found at 304 angstroms, which is the wavelength emitted by ionized helium. These emissions are detected only above the earth's atmosphere.

The small amount of ozone present in the atmosphere absorbs all wavelengths of ultraviolet radiation below about 2900 angstroms and attenuates those up to 3500 angstroms. Consequently, ultraviolet is much more penetrating and intense above approximately 19 miles (100,000 feet). Above about 47 miles the ultraviolet light is practically unfiltered.

At the infrared end of the spectrum, a number of bands are absorbed in the atmosphere by water vapor and carbon dioxide, but the cutoff wavelength does not occur until in the far infrared. The effect of the absorption, then, is to diminish the intensity but not to eliminate completely the near infrared even at the surface.

A thorough discussion of visible and infrared thermal radiation can be found in Reference 8.

REFLECTED SOLAR RADIATION

The ratio of solar radiation scattered back into space without absorption to that incident upon the planet is termed "albedo". The albedo of an object is the fraction of the incident energy which is reflected by the object in the entire band from ultraviolet to the far infrared. The spectral reflectance of an object ideally is the fraction of monochromatic incident energy of wavelength \( \lambda \) reflected by the object, but in practice it always refers to a finite narrow band. The visual albedo of an object refers only to the visible part of the spectrum. The luminous reflectance of various objects is shown in Table 3 (Reference 9).

The planetary albedo is caused by scattering at the planet's surface, scattering by clouds and dust in its atmosphere, and molecular scattering by atmospheric gases. The characteristics of the radiation emerging from the top of a planetary atmosphere are complex as they are functions of terrain, cloud covers, optical thickness of the atmospheric gases, the sun's elevation angle, nadir angle, azimuth angle with respect to sun, and radiation wavelength. The albedo of the various planets is shown in Table 4 (References 10 and 11).

The visual albedo of the earth as determined from earth shine varies with the seasons from 0.52 in October to 0.32 in July, with an average value of 0.35. Variations in cloudiness may account for most of the seasonable variations. Reference 11 reports that albedo of clouds alone is about 0.5, which is in keeping with maximum seasonal values stated. Taking the measured visual albedo of the whole earth as 0.39 (Reference 11), the albedo
<table>
<thead>
<tr>
<th>Object</th>
<th>Smithsonian Tables</th>
<th>Sewing Handbook</th>
<th>Krinov</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water surfaces</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bay</td>
<td>3 to 4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bay and river</td>
<td>6 to 10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inland water</td>
<td>5 to 10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ocean</td>
<td>3 to 7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ocean, deep</td>
<td>3 to 5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bare areas and sand</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Snow, fresh</td>
<td>70 to 86</td>
<td>77</td>
<td></td>
</tr>
<tr>
<td>Snow, with ice</td>
<td></td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>Limestone, clay</td>
<td></td>
<td>63</td>
<td></td>
</tr>
<tr>
<td>Calcareous rocks</td>
<td></td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Granite</td>
<td></td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Mountain tops, bare</td>
<td></td>
<td></td>
<td>24</td>
</tr>
<tr>
<td>Sand, dry</td>
<td></td>
<td>31</td>
<td>24</td>
</tr>
<tr>
<td>Sand, wet</td>
<td></td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>Clay soil, any</td>
<td></td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Clay soil, wet</td>
<td></td>
<td>7.5</td>
<td>9</td>
</tr>
<tr>
<td>Ground, bare, dry</td>
<td>10 to 20</td>
<td>7.2</td>
<td>9</td>
</tr>
<tr>
<td>Ground, bare, wet</td>
<td></td>
<td>5.5</td>
<td></td>
</tr>
<tr>
<td>Ground, black earth</td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Field, plowed</td>
<td>20 to 25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vegetative formations</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coniferous forest, winter</td>
<td></td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Coniferous forest, summer</td>
<td>3 to 10</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Deciduous forest, fall</td>
<td></td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Deciduous forest, summer</td>
<td></td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Coniferous forest, summer,</td>
<td></td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>from airplane</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dark hedges</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Meadow, dry, grass</td>
<td>3 to 6</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Grass, lush</td>
<td>15 to 25</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Meadow, low grass</td>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Field crops, ripe</td>
<td></td>
<td>7</td>
<td>15</td>
</tr>
<tr>
<td>Roads and buildings</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Earth roads</td>
<td></td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Black top roads</td>
<td></td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Concrete road, smooth, dry</td>
<td></td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>Concrete road, smooth, wet</td>
<td></td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Concrete road, rough, dry</td>
<td></td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>Concrete road, rough, wet</td>
<td></td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>Buildings</td>
<td></td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>Limestone tiles</td>
<td></td>
<td>25</td>
<td></td>
</tr>
</tbody>
</table>

- 30 -
Table 4. Planetary Albedos

<table>
<thead>
<tr>
<th>Planet</th>
<th>Albedo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>0.07</td>
</tr>
<tr>
<td>Venus</td>
<td>0.76</td>
</tr>
<tr>
<td>Earth</td>
<td>0.35</td>
</tr>
<tr>
<td>Mars</td>
<td>0.15</td>
</tr>
<tr>
<td>Jupiter</td>
<td>0.51</td>
</tr>
<tr>
<td>Saturn</td>
<td>0.50</td>
</tr>
<tr>
<td>Uranus</td>
<td>0.66</td>
</tr>
<tr>
<td>Neptune</td>
<td>0.62</td>
</tr>
<tr>
<td>Pluto</td>
<td>0.16</td>
</tr>
</tbody>
</table>

of the earth in total sunlight is computed to be 0.35. The albedos of the earth’s surface, clouds, and atmosphere are computed separately in ultraviolet, visible, and infrared. After 2 percent is allowed for absorption by ozone, the albedo of the whole earth is 0.5 in ultraviolet, 0.39 in visible, and 0.28 in infrared wavelengths. Of the total incident light on the earth, the percentage reflected is 2.3 percent by the earth’s surface, 23 percent by clouds and 9 percent by the atmosphere, making a total of 35 percent.

Because of the complexity of the problem and because variations in terrain affect the albedo greatly, the planetary albedo is assumed to be constant over the surface of a planet; and the planet is considered to be a diffuse reflector. It should be kept in mind, however, that the average value is open to question and that local variations could be large.

PLANETARY EMITTED RADIATION

A planet radiates thermal energy into space due to its temperature. The nature of this radiation is a function of latitude, surface characteristics of the planet, composition and optical thickness of atmospheric gases, clouds, and the wavelength region of the radiation under consideration. The temperatures of the various planets are shown in Table 5 (Reference 2).

Difficulties are encountered with the earth-atmosphere model used to determine earth emission. If the usual assumption is made that the earth system is in a state of thermal equilibrium, the magnitude of the average earth emission becomes a function of the average albedo. However, the effective temperature at which the earth-atmosphere system radiates and the spectral distribution of the energy are not well defined. Some sources estimate effective temperatures near -6 F. Such temperatures are effective black body temperatures based on an average albedo and an equilibrium earth system. With only 25 percent of the earth emission
Table 5. Planetary Temperatures

<table>
<thead>
<tr>
<th>Planet</th>
<th>Probable Temperature (F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>339</td>
</tr>
<tr>
<td>Venus</td>
<td>-46</td>
</tr>
<tr>
<td>Earth</td>
<td>-6</td>
</tr>
<tr>
<td>Mars</td>
<td>-68</td>
</tr>
<tr>
<td>Jupiter</td>
<td>-276</td>
</tr>
<tr>
<td>Saturn</td>
<td>-323</td>
</tr>
<tr>
<td>Uranus</td>
<td>-372</td>
</tr>
<tr>
<td>Neptune</td>
<td>-400</td>
</tr>
<tr>
<td>Pluto</td>
<td></td>
</tr>
</tbody>
</table>

coming from the earth and 75 percent coming from the atmosphere, it might be expected that the spectral energy distribution would be different from that for a black body.

The effective temperature of the earth-atmosphere system is low enough to cause the bulk of the earth emission to fall in the infrared, where the spectral characteristics of many materials are not very sensitive to wavelength. Also, the local heat balance of the earth system is too complex to yield useful values for local variations.
Section V

SPACE VEHICLE SURFACE TEMPERATURE ANALYSIS

INTRODUCTION

This section of the report presents some available analytical techniques and solutions for space vehicle thermal problems. These satellite studies include the following:

1. A simplified steady-state analysis for near-earth orbits based on a cylindrical satellite configuration with its axis on a line passing through the center of the earth

2. An IBM 7090 program for the transient heat transfer analysis of a multi-sided space vehicle in any elliptical or circular orbit

3. A space thermal environment study, including spherical, cylindrical, hemispherical, and flat-sided satellites

Regardless of the type of temperature control system used aboard a space vehicle, system requirements are a function of the vehicle's outer surface temperature. These surface temperatures, in turn, are dependent on the following parameters:

Orbital characteristics
Optical properties of surfaces and components, such as emittance and absorptance
Vehicle orientation to sun and planet
Heat capacity of vehicle walls and equipment
Conductive, radiative, and possibly convective heat transfer between surfaces and equipment
Internal heat generation
Aerodynamic heating for near-earth orbits below 200 miles
Solar constant
Planetary albedo
Planetary emission
Vehicle configuration
It is also true that, by proper selection of optical properties, the surface temperatures can be controlled to different levels anywhere within a very large range. In optimizing a vehicle design, however, the selection of the proper control system is made complex because of the many variations that can exist in the parameters listed. Variations caused by errors in orbital characteristics, unknowns in the nature of the radiation environment, vehicle stabilization errors which affect orientation, instability of surface coatings, and other uncertainties all influence the heat balance on the vehicle that determines the surface temperature.

Determination of aerodynamic heating in the free-molecular flow regime will not be considered in this report. For low-altitude orbits below 200 miles, however, it may be significant in comparison with the magnitude of the other energy inputs.

The analytical techniques presented in this section illustrate the complexity of the problem. They point out ways of determining the form factor between the space vehicle and the planet and sun, and the manner in which each of the factors enters into the heat balance.
SIMPPLIED SPACE RADIATION ANALYSIS

The discussion here is of a simplified space radiation analysis which takes into account the contributions of solar and terrestrial radiation and assumes steady-state heat transfer. The material was prepared by AiResearch Manufacturing Division for incorporation in this report.

NOMENCLATURE

\( a \) Earth albedo
\( D \) Diameter of radiator cylinder, ft
\( L \) Length of radiator cylinder, ft
\( q_{CY} \) Internal heat input to element, Btu/hr
\( q_{E(SR)} \) Solar radiation reflected from earth and absorbed by element, Btu/hr
\( q_{E(TR)} \) Thermal radiation from earth absorbed by element, Btu/hr
\( q_S \) Total solar energy absorbed by radiator, Btu/hr
\( q_{SR} \) Direct solar radiation absorbed by element, Btu/hr
\( q_{TR} \) Heat radiated from element, Btu/hr
\( S \) Solar constant = 443 Btu/(sq ft)(hr)
\( T \) Radiator surface temperature, °R
\( T_E \) Effective radiating temperature of earth, °R
\( a_s \) Solar absorptivity of radiator surface
\( a_T \) Absorptivity of radiator surface to earth emission
\( \epsilon \) Emissivity of earth for thermal radiation
\( \sigma \) Stefan-Boltzmann radiation constant = \(0.1713 \times 10^{-8}\) Btu/(sq ft)(hr)(°R)\(^4\)
\( \Omega \) Solar elevation angle measured from vertical, deg
HEAT BALANCE

The thermodynamic aspects of the heat transfer problem are illustrated by considering the steady-state heat flow balance equation (heat outflow equals heat inflow) for an element of surface area

\[ dq_{\text{TR}} = dq_{\text{CY}} + dq_{\text{SR}} + dq_{E(\text{TR})} + dq_{E(\text{SR})} \]  

(20)

To determine the radiator surface area required per unit of internal heat flow, it is necessary to determine what physical orientation of the surface maximizes the sum of \( q_{\text{SR}} \), \( q_{E(\text{TR})} \), and \( q_{E(\text{SR})} \), because this situation imposes the most severe requirement on the radiator surface. The radiator is assumed to be a cylindrical surface with its axis on a line passing through the center of the earth, located at a known distance \( h \) above the earth's surface. For this geometry (shown in Figure 13), \( q_{E(\text{TR})} \) is essentially independent of the sun's position, whereas \( dq_{\text{SR}} \) and \( dq_{E(\text{SR})} \) are both functions of the sun's position relative to earth and vehicle, and \( dq_{E(\text{SR})} \) is also a function of the earth's albedo. When an appropriate assumption is made regarding the earth's albedo, the radiator design considers the solar position relative to earth and vehicle for which the sum of \( q_{\text{SR}} \) and \( q_{E(\text{SR})} \) is a maximum.

![Figure 13. Space Vehicle Orientation](image-url)
ANALYSIS DESCRIPTION

In the analysis which follows, the radiator surface required per unit heat flow rate is determined as a function of the radiator surface temperature and a parameter which includes the effects of the values chosen for the various emissivities and absorptivities involved and for the earth's albedo.

The analysis was performed in two parts: (1) consideration of a simplified geometry in which the earth is assumed to be an infinite plane, and (2) refinement of the simplified geometric model to take into account the spherical shape of the earth. This approach has an advantage in that the first part illustrates the essential physical phenomena, unobscured by the procedural complications of the second part.

Simplified Geometry Analysis

To determine the solar elevation angle \( \omega \), at which the sum of \( q_{SR} \) and \( q_{E(SR)} \) is maximized, the definition is made that

\[
q_s = q_{SR} + q_{E(SR)} \quad (21)
\]

The term \( q_s \) is thus the total solar energy absorbed by the radiator.

Defining further,

\[
q_{SR} = a_s DLS \sin \Omega \quad (22)
\]

\[
q_{E(SR)} = \frac{1}{2} a_s DLaS \cos \Omega \quad (23)
\]

The factor 1/2 is used in Equation 23 for \( q_{E(SR)} \) because the infinite plane is 50 percent effective in enclosing the radiator.

To determine the maximum value of \( q_s \) and the value of \( \Omega \) at which this maximum occurs, \( dq_s / d\Omega \) is set equal to zero. It follows that

\[
\frac{dq_s}{d\Omega} = \frac{d}{d\Omega} \left[ a_s DLS \left( \sin \Omega + \frac{\pi a}{2} \cos \Omega \right) \right] \quad (24)
\]

\[
0 = a_s DLS \left( \cos \Omega - \frac{\pi a}{2} \sin \Omega \right) \quad (25)
\]
To define the angle $\Omega_{\text{max}}$ at which the total solar radiation absorbed by the radiator is maximized,

$$\Omega_{\text{max}} = \tan^{-1} \left( \frac{2}{\pi a} \right)$$  \hspace{1cm} (26)

From which

$$\sin \Omega_{\text{max}} = \frac{2}{\pi a \sqrt{1 + \frac{4}{\pi^2 a^2}}}$$  \hspace{1cm} (27)

and

$$\cos \Omega_{\text{max}} = \frac{1}{\sqrt{1 + \frac{4}{\pi^2 a^2}}}$$  \hspace{1cm} (28)

The maximum solar radiation absorbed by the radiator is

$$q_{S}(\text{max}) = a_S \cdot \text{DLS} \left( \frac{\frac{2}{\pi a} + \frac{\pi a}{2}}{\sqrt{1 + \frac{4}{\pi^2 a^2}}} \right)$$  \hspace{1cm} (29)

$$= a_S \cdot \text{DLS} \sqrt{1 + \frac{2}{\pi^2 a^2}}$$

The effect of earth albedo $a$ on $\Omega_{\text{max}}$ and $q_{S}(\text{max})$ is shown in the following table:

<table>
<thead>
<tr>
<th>Earth Albedo $a$</th>
<th>Solar Elevation Angle $\Omega_{\text{max}}$ (deg)</th>
<th>$\frac{q_{S}(\text{max})}{a_S \cdot \text{DLS}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>90</td>
<td>1.00</td>
</tr>
<tr>
<td>0.2</td>
<td>72.5</td>
<td>1.05</td>
</tr>
<tr>
<td>0.4</td>
<td>57.9</td>
<td>1.18</td>
</tr>
<tr>
<td>0.6</td>
<td>46.7</td>
<td>1.37</td>
</tr>
<tr>
<td>0.8</td>
<td>38.5</td>
<td>1.61</td>
</tr>
<tr>
<td>1.0</td>
<td>28.3</td>
<td>1.86</td>
</tr>
</tbody>
</table>
For a small element of radiator surface, dA, the heat balance equation is

\[ dq_{TR} = dq_{CY} + dq_{E(TR)} + dq_{S(max)} \]  

(30)

From which can be obtained

\[ \sigma T^4 A = q_{CY} + \sigma \epsilon E a_T T_E^4 \left( \frac{A}{2} \right) + a_S \left( \frac{SA}{\pi} \right) \sqrt{1 + \frac{n^2 a^2}{4}} \]  

(31)

**Refined Geometry Analysis**

Refinement of the previous analysis, to account for a spherical earth rather than an infinite plane, is desirable because the simplified analysis may be conservative to an unrealistic degree.

The analytical process to be followed is similar in principle to that discussed previously. In the present analysis, expressions for \( q_{E(SR)} \) and \( q_{E(TR)} \) contain shape factors in the form of integrals which must be evaluated numerically. Because the mechanics of the derivations are quite cumbersome, only the results of each analysis are reported in the following discussion.

**Evaluation of \( q_{E(TR)} \)**

Evaluation of \( q_{E(TR)} \), assuming a spherical earth of 3960-mile radius and a radiator altitude of approximately 300 miles above the earth's surface, leads to the result

\[ q_{E(TR)}^2 = 0.2722 \sigma \epsilon E a_T A T_E^4 \]  

(32)

which compares with the previous result given by Equation 31

\[ q_{E(TR)}^1 = \sigma \epsilon E a_T T_E^4 \left( \frac{A}{2} \right) \]  

(33)

Equation 33 was calculated assuming the earth to be an infinite plane. This result indicates that the radiator surface absorbs only 54.4 percent of the thermal radiation from the earth as estimated previously.
Evaluation of $q_E(SR)$

Evaluation of $q_E(SR)$, again assuming a spherical of 3960-mile radius and a radiator altitude of 300 miles, yields

$$q_E(SR) = 0.2696 \alpha S_{DLS} \pi a \cos \Omega$$  \hspace{1cm} (34)

which is, again, about 54 percent of that calculated assuming the earth to be an infinite plane.

Evaluation of $\Omega_{\text{max}}$

Using the relation given in Equation 34 for $q_E(SR)'$

$$q_s = q_E(SR) + q_{SR}$$

is written

$$q_s = \alpha S_{DLS} \sin \Omega + 0.2696 \alpha S_{DLS} \pi a \cos \Omega$$  \hspace{1cm} (35)

By differentiating Equation 35 and equating the result to zero, $\Omega_{\text{max}}$ is found to be

$$\Omega_{\text{max}} = \tan^{-1} \left( \frac{1}{0.2696 \pi a} \right)$$  \hspace{1cm} (36)

Evaluation of $q_s(\text{max})$

Using the result for $\Omega_{\text{max}}$ (Equation 36),

$$q_s(\text{max}) = \alpha S_{DLS} \sqrt{1 + (0.2696)^2 \pi a^2}$$  \hspace{1cm} (37)

This relation is valid only for values of $\Omega_{\text{max}}$ where the entire portion of the earth visible from the radiator is illuminated by the sun. For the assumed radiator elevation of 300 miles, this implies $0 \leq \Omega_{\text{max}} \leq 67.6$ degrees.
IBM 7090 PROGRAM FOR TRANSIENT HEAT TRANSFER ANALYSIS OF ORBITING SPACE VEHICLES

An IBM 7090 program has been developed at S&ID which will simulate the thermal environment of a multisided space vehicle in any earth orbit. This program will determine the transient temperature history of the satellite shell; and, if desired, will also provide the complete history of the radiant energy incident upon the vehicle surfaces due to direct solar radiation, earth emission, and earth reflected solar radiation. These heat loads can be used as input data in a general heat transfer program if it is desired to obtain a detailed thermal analysis of the interior of the vehicle.

The evaluation studies presented in Section VIII were obtained through the use of this program. They demonstrate the flexibility of the program when a parametric study is conducted.

A description of the analysis techniques utilized by the program is presented in this discussion. The areas covered are orbital mechanics, earth shadow intersection points, vehicle configuration and orientation, temperature determination, and vehicle-to-earth geometric configuration factors. A complete presentation of these subjects, as well as programing techniques and program philosophy, can be found in report SID 61-105, "Program for Determining Temperatures of Orbiting Space Vehicles," by G. A. McCue (Reference 33). Data entry, data output, sample problems, the program listing, and program flow diagram are also contained in report SID 61-105.

NOMENCLATURE

A       Surface area of satellite, sq ft
a       Semimajor axis of orbit ellipse
a_s     Semimajor axis of shadow ellipse
A_1     Angle defined in Figures 27 and 28
b       Semiminor axis of orbit ellipse
c       Construction defined in Figure 25
\( c_p \) Specific heat, \( \text{Btu/(lb}_m \) (°R) \\
\( d \) Construction defined in Figure 25 \\
\( E \) Eccentric anomaly \\
\( E_E \) Planetary emission, \( \text{Btu/(hr)} \) (sq ft) \\
\( e \) Eccentricity of orbit ellipse \\
\( F_E \) Geometric form factor for planetary emission \\
\( F_R \) Geometric form factor for reflected solar radiation \\
\( F_s \) Geometric form factor for direct solar radiation \\
\( h \) Height above earth's surface \\
\( i \) Inclination of orbit ellipse \\
\( M \) Mean anomaly \\
\( m \) Subscript indicating mass \\
\( P \) Semilatus rectum of orbit ellipse \\
\( \bar{P} \) Perigee vector \\
\( q \) Internal heat load, \( \text{Btu/hr} \) \\
\( q_0 \) Construction defined in Figure 25 \\
\( r \) Radius of spherical vehicle \\
\( r_E \) Planetary albedo \\
\( r_o \) Radius from geocenter (orbit ellipse) \\
\( r_s \) Radius from geocenter (shadow ellipse) \\
\( R \) Earth's radius \\
\( R_E \) Reflected solar energy from planet, \( \text{Btu/(hr)} \) (ft^2) \\
\( S \) Solar constant, \( \text{Btu/(hr)} \) (ft^2) \\
\( S_{\odot} \) Sun's projection upon the orbit plane \\
\( s \) Construction defined in Figures 27 and 28 \\
\( t \) Time, hr \\
\( T \) Temperature, °R \\
\( T_0 \) Epoch time
$T_m$  Maximum expected temperature, °R
$T_e$  Fraction of orbit time in earth's shadow
$V$  Velocity
$W$  Mass of satellite or surface, lbm
$x, y, z$  Rectangular coordinates of equatorial coordinate system

$a$  Construction defined in Figures 26 through 28
$a_s$  Solar absorptivity of satellite or surface
$a_E$  Infrared absorptivity of satellite or surface
$a_R$  Absorptivity to reflected solar
$\beta$  Angle between $\overrightarrow{S I_o}$ and $\overrightarrow{P}$ vectors
$\gamma$  Construction defined in Figures 26 through 28
$\delta$  Construction defined in Figures 27 and 28
$\epsilon$  Construction defined in Figures 27 and 28
$\epsilon_s$  Emissivity of satellite surface
$\eta$  Construction defined in Figures 27 and 28
$\theta$  True anomaly increment between satellite's position and the line of nodes
$\theta - \omega$  True anomaly
$\theta_s$  Angle between earth-sun line and the vertical between the earth and satellite
$\theta_N$  Angle between the normal to a satellite surface and the line between the sun and satellite
$\theta_1$  Angle between the normal to a satellite surface and the line between the earth and satellite
$\theta_2$  Half of the angle subtended by the earth as viewed from the satellite
$\mu$  Gravitation constant
$\sigma$  Stefan-Boltzmann constant = 0.1713 x 10$^{-8}$ Btu/(hr) (sq ft) (°R$^4$)
$\sigma_0$  Mean anomaly at epoch
The physical model of orbital motion to be utilized in this analysis is an isolated dynamic system consisting of an earth, an earth satellite, and a sun which revolves in the ecliptic in the astronomical place of the apparent sun, but is infinitely distant from earth. It is assumed that the earth has no atmosphere, and is represented gravitationally by the zero-order and second-order spherical harmonics of its potential. It is further assumed that such a trajectory can be described as a function of time by considering a set of six varying orbital elements. The elements which will be used for this analysis are semimajor axis, eccentricity, argument of perigee, right ascension of the ascending node, inclination, and the mean anomaly at epoch \((a, e, \Omega, i, \sigma_0)\). These elements, along with pertinent equations of elliptical motion, are indicated in Figure 14. The position of the satellite in the ellipse is described by the angular advance from perigee, \(\theta - \omega\) (true anomaly). The presence of harmonics in the earth's gravitational potential will cause periodic and secular variations in several of the orbital elements. Only the secular perturbations which result in regression of the nodes and advance of the perigee position are considered in this analysis. Other periodic changes have negligible effect upon the shadow intersection problem. First-order perturbation theory as developed by Cunningham (Reference 4) has been applied to determine these variations.

The angles \(\Omega\) and \(\omega\) are then described as a function of time by the linearized expressions

\[
\Omega = \Omega_0 + \dot{\Omega}(t - T_0) \tag{38}
\]

\[
\omega = \omega_0 + \dot{\omega}(t - T_0) \tag{39}
\]

where \(\dot{\Omega}\) and \(\dot{\omega}\) are obtained from Cunningham's equations, and \(t - T_0\) is the time since epoch.

The geocentric position of the sun is computed by the program from linearized expressions involving the earth's mean motion and the equation of time as a function of date. A simple transformation of coordinates can then
Figure 14. Elements of Elliptic Orbits

\[
e = \sqrt{1 - \frac{b^2}{a^2}}
\]

\[
r_o = \frac{a(1 - e^2)}{1 + e \cos(\theta - \omega)}
\]

\[
V^2 = \mu \left( \frac{2}{r_o} - \frac{1}{a} \right)
\]

\[
r^2\dot{\theta} = \sqrt{\mu a (1 - e^2)}
\]

\[
\mathcal{P} = \frac{2\pi a^{3/2}}{\mu^{1/2}}
\]

\[
M = \frac{\mu^{1/2}}{a^{3/2}} t + \sigma_o
\]

\[
M = E - e \sin E
\]

\[
\tan \frac{E}{2} = \sqrt{\frac{1 - e}{1 + e}} \tan \frac{(\theta - \omega)}{2}
\]
be employed to yield the sun's position relative to an orbit plane coordinate system. (It should be noted that a more detailed description of the orbital mechanics and associated vector algebra can be found in Reference 33.)

SOLUTION FOR SHADOW INTERSECTION POINTS

Perhaps the most important factor that contributes to temperature variations during any orbital revolution is the satellite's being eclipsed by the earth's shadow. For this reason it is important to accurately incorporate this effect into any temperature prediction program.

A method for determining the shadow entrance and exit true anomalies from the coordinates of the sun relative to the orbit plane system was devised and packaged as a Fortran subroutine for the IBM 7090. Further information about this subroutine and its use in computing the percent of eclipse time as a function of various orbit parameters may be found in Reference 13. A brief description of the calculation scheme employed by this subroutine appears below.

The relative orientation of the orbit, earth, and sun having been specified, it is seen that the earth casts a shadow which will at times eclipse the satellite. In reality the sun is not at infinity, and casts a converging conical umbral shadow. However, a rigorous specification of the position at which the satellite enters and exits from earth's true shadow leads to needlessly complicated expressions. For this reason, the following simplifying assumptions concerning shadow geometry were made:

1. The earth was assumed spherical with its radius $R$ equal to 3960 statute miles.

2. The earth's shadow was assumed cylindrical and umbral (sun at infinity).

3. Atmospheric refraction and penumbral effects were neglected.

The soundness of these assumptions was verified through telescopic observation of satellites as they entered the earth's shadow. Actual entrance times observed during several transits of 1959 Alpha II and 1960 Iota I usually differed from predictions by only a few seconds.

The points of intersection of an elliptical orbit and a cylinder axially oriented toward the sun are the required solution to the stated problem. Describing these positions in three-dimensional notation results in rather complicated expressions. Considerable simplification can be achieved by considering the projection of the cylindrical shadow upon the orbit plane. (See Figure 15.)
Figure 15. Shadow Geometry (Projection Upon Orbital Plane)
A geocentric ellipse results from the shadow cylinder's cutting the orbit plane, and is described in polar coordinates by

$$r_s = \frac{a_s}{\sqrt{(1 - a_s^2 \cos^2 \phi + a_s^2 \cos^2 \phi)}}$$

(40)

where \( r_s \) and \( a_s \) are in earth radii.

The elliptical orbit can be represented in polar coordinates by

$$r_o = \frac{a(1 - e^2)}{1 + e \cos (\phi + \beta)}$$

(41)

where \( r_o \) and \( a \) are in earth radii.

It is apparent from the geometry of Figure 15 that the two ellipses need not intersect; they may be tangent or may intersect in as many as four points. Of course, no more than two of these intersections can represent the required sunlight-shadow transitions, and the remaining solutions must be eliminated.

The required solutions must satisfy the condition

$$\Delta r = r_o - r_s = 0$$

(42)

A similar expression,

$$(\Delta r)^2 = r_o^2 - r_s^2 = 0$$

(43)

was incorporated into the subroutine since it yielded less complex equations. A functional iteration scheme was employed to seek the necessary solutions to the problem.

The fraction of orbit time \( T_s \) spent in the earth's shadow can be computed by the equations of Figure 14 through introduction of the eccentric anomaly \( E \) and the use of Kepler's equation. Thus,

$$T_s = \frac{1}{2\pi} \left( (E_4 - e \sin E_4) - (E_3 - e \sin E_3) \right)$$

(44)

As an illustration of the use of this program, the fraction of each day spent in the shadow was calculated as a function of date for several parameters including inclination, semimajor axis, eccentricity, and launch time.

The percent of eclipse time for various orbit classes was computed from Equation 44, and is presented in Figures 16 through 23 as a function of date. Except as otherwise noted, the initial conditions were as follows:
Figure 16. Eclipse Time as Function of Date (Zero Eccentricity, 0-Degree Inclination)
Figure 17. Eclipse Time as Function of Date (Zero Eccentricity, 33-Degree Inclination)
Figure 18. Eclipse Time as Function of Date
(Zero Eccentricity, 48-Degree Inclination)
Figure 19. Eclipse Time as Function of Date
(Zero Eccentricity, 65-Degree Inclination)
SEMIMAJOR AXIS $a$, AS NOTED
ECCENTRICITY $e$, 0.0
INCLINATION $i$, 80 DEG
YEAR, 1961

Figure 20. Eclipse Time as Function of Date
(Zero Eccentricity, 80-Degree Inclination)
Figure 21. Effect of Variation in Eccentricity on Eclipse Time as Function of Date.
Figure 22. Effect of Variation in Launch Time on Eclipse Time as Function of Date
Figure 23. Seasonal Boundaries of Shadow Intersection Characteristics
\[ e = 0.0 \]
\[ \omega = 0.0 \]
\[ \Omega = 0.0 \]
\[ T_0 = 1 \text{ January 1961} \]

The results are generally self-explanatory and, therefore, only a few of the more interesting points are mentioned here.

Figures 16 through 20 illustrate the effects of varying the semimajor axis and/or inclination. With zero inclination (Figure 16), eclipse time is seen to vary seasonally as the sun moves between the northern and southern hemisphere. Increasing the semimajor axis results in increased seasonal variations, although maximum eclipse time is decreased. Changes in precession rates that arise from variations in semimajor axis and inclination are illustrated by Figures 17 through 20. It is to be noted that increasing the inclination and/or the semimajor axis generally yields less eclipse time.

Figure 21 is concerned with variations in eccentricity. The maxima, which occur each time the sun is in the orbit plane, are not always equal as was the case for circular orbits. Also, increasing the eccentricity tends to decrease the probability of obtaining total sunlight because the perigee remains nearer the earth.

Initial right ascension of the ascending node was assigned four different values to produce the curves of Figure 22. This variable, which is a function of launch time and date, is seen to cause a phase shift in the occurrence of maxima and minima. Thus, within limits, the launch time can be chosen to produce the most desirable eclipse conditions.

Figure 23 superimposes the curves of Figure 22 to illustrate seasonal effects upon eclipse characteristics. It will be noted that at the equinoxes, when the sun is near the earth's equatorial plane, there is only a slight day-to-day variation in eclipse time. Conversely, at the solstices, the minima become quite pronounced.

**VEHICLE CONFIGURATION AND ORIENTATION**

No attempt was made to write a completely general program with respect to satellite shape. Thus it was decided that the problem of specifying vehicle configuration and subsequently orienting the vehicle in space would be handled by a separate subroutine within the program. This requires a new subroutine for each vehicle configuration, but the extra cost for their writing can be amortized through less complex programs, increased reliability, and better problem understanding.
At the present time, subroutines are available for handling the satellite shapes shown in Figure 24; these are explained in detail in the sample problem section of Reference 33. It is felt that an experienced Fortran programmer should be able to devise subroutines for different configurations as the need arises.

The information determined by the orientation subroutine is utilized in turn by the geometric form factor subroutine which calculates the geometric form factors necessary in the temperature analysis. The geometric form factor subroutine is described in the next discussion.

GEOMETRIC CONFIGURATION FACTORS

In order to calculate the temperature of an orbiting space vehicle, it is necessary to determine the geometric form factors, which always constitute a basic problem with radiation heat transfer analysis. As explained in the previous discussion, an orientation subroutine supplies information relative to the position of the vehicle with respect to space, the earth, and the sun. This information, in turn, is used by a geometric form factor subroutine which calculates the form factors needed in the analysis.

Since the form factor subroutine is a separate closed subroutine within the main program, it may easily be replaced or changed to incorporate whatever method of form factor computation is desired. Several routines that have been devised to compute the form factors for rotating spheres, plane surfaces, and rotating cylindrical surfaces are described here. Listings of the three subroutines for these cases appear in Reference 33.

Rotating Sphere

The direct solar form factor for a uniformly rotating sphere is derived thusly

\[ F_s = \frac{\text{Projected area}}{\text{Total surface area}} \]

\[ = \frac{\pi r^2}{4 \pi r^2} = 0.25 \]  \hspace{1cm} (45)

The geometric form factor for earth emission \( F_E \) may be derived by considering the satellite to be a point source in space viewing the earth. This assumption is correct if the satellite is rotating or has a uniform surface temperature. Referring to Figure 25, it is seen that \( F_E \) is therefore equal to the shaded percentage of the sphere with radius \( c \).
Figure 24. Satellite Configurations Used in Transient Temperature Analysis
Figure 25. Planetary Emission Form Factor (Rotating Sphere)
Considering the right triangle formed by $R$, $c$, and $(R + h)$, one may write

$$c^2 = (h + R)^2 - R^2$$

$$c = \sqrt{h (h + 2R)} \quad (46)$$

Considering the auxiliary constructions which yield $d$ and $q$, and comparing the similar right triangles, it is seen that

$$\frac{d}{c} = \frac{c}{R + h}$$

and therefore,

$$d = \frac{c^2}{R + h}$$

and

$$q_o = c - d = c \left(1 - \frac{c}{R + h}\right) \quad (47)$$

$F_E$ is computed by comparing the area of spherical segment with height $q_o$ to the sphere's total surface area. Thus,

$$F_E = \frac{2\pi c q_o}{4\pi c^2} = c \left(1 - \frac{c}{R + h}\right)$$

or

$$F_E = \frac{1}{2} \left(1 - \frac{\sqrt{h (h + 2R)}}{R + h}\right) \quad (48)$$

Form factors for reflected solar were approximated by the equation

$$F_R = F_E \cos \theta_s \quad (49)$$

This simplification results in an error due to the reflected solar being set equal to zero at the terminator. Actually, the vehicle can still receive some reflected solar radiation when beyond the terminator. However, the error introduced by this assumption is felt to be negligible.
Form Factors for Plane Surfaces

The direct solar form factor for a plane surface is simply the ratio of the projected area exposed to the sun to the total surface area, or

\[ F_s = \cos \theta_N \] (50)

Computation of the earth emission form factor \( F_E \) is considerably more complicated. It is accomplished by one of three methods, depending upon the geometry. The unit sphere method is employed to derive the form factor equations.

Case I

The first case occurs when the surface can "view" the entire earth. Referring to the geometry of Figure 26, it is seen that \( \theta_1 \) is the angle between the surface normal and the radius vector to earth, and \( \theta_2 \) is half the angle subtended by the earth. \( \theta_2 \) may be found from the expression

\[ \sin \theta_2 = \frac{R}{R + h} \] (51)

Let \( a \) be the radius of the earth's projection upon a unit sphere constructed upon the surface (note auxiliary constructions). Then,

\[ a = \sin \theta_2 = \frac{R}{R + h} \] (52)

The circle of radius \( a \) may then be projected upon the plane representing the vehicle surface to form an ellipse with semimajor axis \( a \) and semiminor axis \( \gamma \) (plan view). \( \gamma \) equals the projected length of \( a \), or

\[ \gamma = a \cos \theta_1 \] (53)

The earth emission form factor for this case is therefore given by

\[ F_E = \frac{\text{Area of ellipse}}{\text{Area of unit circle}} \]

\[ = \frac{\pi a \gamma}{\pi} = a \gamma \]

or

\[ F_E = a^2 \cos \theta_1 \] (54)
Figure 26. Form Factor Determination (Case I)
Case II

When the sum of $\theta_1$ and $\theta_2$ exceeds 90 degrees (Figure 27), part of the earth is not visible to the surface. The projection upon the surface of the earth's projection upon a unit sphere forms an ellipse with dimensions $a$ and $\gamma$. The areas of interest are the shaded half-ellipse and the similarly shaded segments of the ellipse and circle. The dimensions $\delta$ and $\eta$ must be found in order to evaluate the area of the ellipse segment. Referring to the auxiliary constructions of Figure 27, the derivation proceeds as follows:

$$\epsilon = \cos \theta_2$$

and therefore,

$$s = \epsilon \tan (90 - \theta_1) = \cos \theta_2 \tan (90 - \theta_1)$$

Noting that

$$\tan (90 - \theta_1) = \frac{\cos \theta_1}{\sin \theta_1}$$

and

$$\cos \theta_2 = \sqrt{1 - \sin^2 \theta_2} = \sqrt{1 - a^2}$$

it follows that

$$s = \sqrt{1 - a^2} \frac{\cos \theta_1}{\sin \theta_1}$$

Therefore,

$$\eta = s \cos \theta_1 = \sqrt{1 - a^2} \frac{\cos^2 \theta_1}{\sin \theta_1}$$

(55)

The derivation of $\delta$ proceeds as follows:

$$\delta = a \cos \phi_c = a \sqrt{1 - \sin^2 \phi_c}$$

where

$$\sin \phi_c = \frac{s}{a} = \frac{1}{a} \sqrt{1 - a^2} \frac{\cos \theta_1}{\sin \theta_1}$$
Figure 27. Form Factor Determination (Case II)
Substitution and trigonometric manipulation yields

$$\delta = \frac{1}{\sin \theta_1} \sqrt{a^2 - \cos^2 \theta_1}$$

(56)

The required form factor is given by the equation

$$F_E = \frac{1}{2} \left( \text{Area of ellipse} + \text{Segment of ellipse} + \text{Segment of circle} \right) \frac{\text{Area of circle}}{\text{Area of circle}}$$

which becomes

$$F_E = \frac{1}{2} \left[ \frac{\pi}{2} a \gamma + \delta \eta + a \gamma \sin^{-1} \frac{\eta}{\gamma} + \frac{1}{2} (A_1 - \sin A_1) \right]$$

(57)

where $A_1$ is found from

$$\sin \frac{A_1}{2} = \delta$$

(58)

Case III

A third case occurs when $\theta_1$ is greater than 90 degrees as seen in Figure 28. Again, the projection upon the surface of earth's projection upon the unit sphere is an ellipse with dimensions $a$ and $\gamma$. The area required for form factor determination is the shaded portion of the circle excluded from the ellipse. Utilizing auxiliary constructions once more, it is seen that

$$\epsilon = \cos \theta_2$$

and

$$s = \epsilon \tan (\theta_1 - 90) = \cos \theta_2 \tan (\theta_1 - 90)$$

Noting that

$$\cos \theta_2 = \sqrt{1 - \sin^2 \theta_2} = \sqrt{1 - a^2}$$

and

$$s = \sqrt{1 - a^2} \tan (\theta_1 - 90)$$
Figure 28. Form Factor Determination (Case III)
it follows that

\[ \eta = -s \cos \theta_1 = -\sqrt{1 - a^2} \cos \theta_1 \tan (\theta_1 - 90) \quad (59) \]

\[ \delta \] may be derived from the auxiliary construction by first noting that

\[ \delta = a \cos \phi_c = a \sqrt{1 - \sin^2 \phi_c} \]

where

\[ \sin \phi_c = \frac{s}{a} = \frac{1}{a} \sqrt{1 - a^2} \tan (\theta_1 - 90) \]

Substitution and trigonometric manipulation yields

\[ \delta = \frac{1}{\cos (\theta_1 - 90)} \sqrt{a^2 - \sin^2 (\theta_1 - 90)} \quad (60) \]

The earth emission form factor is found from the expression

\[ F_E = \frac{\text{Segment of circle} + \text{Segment of ellipse} - \frac{1}{2} (\text{Area of ellipse})}{\text{Area of circle}} \]

which becomes

\[ F_E = \frac{1}{\pi} \left[ \frac{1}{2} (A_1 - \sin A_1) + \delta \eta + a\gamma \sin \left( \frac{\eta}{\gamma} - \frac{\pi}{2} \right) \right] \quad (61) \]

where \( A_1 \) is found from

\[ \sin \frac{A_1}{2} = \delta \]

By inspection of the geometry of Figure 28, it is apparent that \( F_E \) becomes zero when \( \theta_1 - \theta_2 > 90 \) degrees.

It was assumed that the reflected solar form factor could be approximated by the expression

\[ F_R = F_E \cos \theta_s \quad (62) \]

The formulas just developed were incorporated into the form factor routine for plane surfaces which appears in Reference 33.
Form Factors for Curved Surfaces

A good approximation to a curved surface may be obtained by dividing it into an adequate number of plane surfaces. This procedure was utilized to simulate the rotating cylindrical vehicle of sample problem 4 of Reference 33. In this example, the cylindrical surface was approximated by 24 plane surfaces equally spaced around the principal axis. The contributions of each plane were then averaged to obtain a single form factor for the rotating cylindrical surface. (The assumption of rapid rotation results in a uniform surface temperature.)

TEMPERATURE DETERMINATION

The surface temperature of a space vehicle in orbit about the earth is determined by the heat balance between the vehicle surface and its environment, which includes the sun, the earth and its atmosphere, and space which acts as a heat sink (Figure 29). The vehicle receives solar energy directly from the sun or indirectly (reflected) from the earth and its atmosphere. Energy emitted by the earth and its atmosphere also contributes measurably to this heat balance. (The largely geometrical problem of determining what radiation the vehicle receives from each source at successive positions around the orbit was presented in the previous discussion, which described the procedures used in calculating the geometric form factors.)

Other factors which influence this heat balance are the value of the solar constant, the planetary albedo, and assumptions concerning planetary emission. The planetary emitted energy was assumed to be uniform over the earth's surface and approximately equivalent to that of a black body for the temperatures shown in Table 5. The vehicle's surface absorptivity for this energy was assumed equivalent to the total hemispherical emissivity of the surface at approximately the same temperature.

The rate of change of the temperature of a surface of an orbiting satellite may be obtained from

\[
W_c \frac{dT}{dt} = \alpha_s A F S + \alpha_E E A E + \alpha_R R A R E + q - \epsilon \sigma AT^4
\]

(63)

where

- \( T \) = Temperature of shell, °R
- \( t \) = Time, hr
- \( W \) = Mass of satellite or surface, lbm
Figure 29. Space Vehicle Heat Balance

\[ c_p = \text{Specific heat, Btu/(lbm) } (^\circ \text{R}) \]
\[ A = \text{Surface area of satellite, sq ft} \]
\[ q = \text{Internal heat load, Btu/hr} \]
\[ \sigma = \text{Stefan-Boltzmann constant } = 0.171 \times 10^{-8} \text{ Btu/(hr)(sq ft)(} ^\circ \text{R}^4) \]
\[ \alpha_s = \text{Solar absorptivity of satellite} \]
\[ \alpha_E = \text{Infrared absorptivity of satellite} \]
\[ \alpha_R = \text{Absorptivity to reflected solar} \]
\[ F_s = \text{Geometric form factor for direct solar radiation} \]
\[ F_E = \text{Geometric form factor for planetary emission} \]
\[ F_R = \text{Geometric form factor for reflected solar radiation} \]
\[ S = \text{Solar constant, Btu/(hr)(sq ft)} \]
\[ E_E = \text{Planetary emission, Btu/(hr)(sq ft)} \]
\[ R_E = \text{Reflected solar energy from planet, Btu/(hr)(sq ft)} \]
\[ \varepsilon_s = \text{Emissivity of satellite surface} \]

The temperature prediction program incorporates a finite difference version of the Equation 63. The following assumptions are made:

\[
\begin{align*}
\alpha_s &= \alpha_R \\
\alpha_E &= \varepsilon_s \\
R_E &= S r_E \\
E_E &= \frac{1 - r_E}{4} S \\
F_R &= F_E \cos \theta_s
\end{align*}
\]

where

\[ r_E = \text{Planetary albedo} \]
\[ \theta_s = \text{Angle between earth-sun line and vertical from planet to satellite} \]

The program utilizes several tolerances to ensure that the finite difference method will yield valid results. Steps are taken to ensure that the maximum time interval used during any step in true anomaly will not exceed a time tolerance entered as data or one computed from the equation

\[
TOL = \frac{1}{16} \left( \frac{W \sigma_p}{3 \left( \frac{T_m \varepsilon_s A}{\sigma T} \right)} \right)
\]
Computation is begun by providing approximate values of the various surface temperatures at perigee. The program will then compute temperatures at successive intervals around the orbit until it has returned to perigee. Chances are that the approximate value and the newly computed temperature at perigee will not agree. The program then repeats the computation, utilizing the new temperature as an initial value. This iteration process is repeated until initial and final temperatures converge to within an acceptable tolerance.

Thus, the program obtains a transient temperature history during a particular revolution of the satellite. Figure 30 shows the described convergence effect for a case involving a rotating sphere. Computation was begun with an initial temperature guess of 100 F. The lower curve shows the temperature history computed during the first iteration, while the upper curve represents the results of the third iteration. After three iterations, the initial and final temperatures coincide. This curve therefore represents the transient temperature history during the revolution in question.

That the lower curve would represent the temperature history during the first orbital revolution of a satellite injected into orbit with an initial temperature of 100 F is noteworthy. By the third revolution, the temperature curve would become rather stable. Thereafter, it would experience slight day-to-day changes brought about by orbital precession and other factors.

Although the foregoing discussion was confined to temperature determination, it should be noted that the amount of radiant energy that is absorbed by each satellite surface from the space environment is also available from the program. This information may be utilized as input data in a general heat transfer program if it is desired to obtain a detailed thermal analysis of the interior of the vehicle. This capability of the program may prove to be more important than its capability to compute satellite shell temperature histories.

PROGRAM LISTING AND DECK SETUP

Figures 31 and 32 illustrate the general approach used in the program by showing the main program flow diagram and deck setup. It is beyond the scope of this report to go into detail with respect to these diagrams, since they are primarily of interest to program writers. It is recommended that Reference 33 be consulted for a complete explanation of these areas of interest.
Figure 30. Satellite Temperature Determination

TRUE ANOMALY (DEGREES)

TEMPERATURE (F)

THIRD ITERATION

INITIAL ITERATION

-73-
Figure 31. Deck Setup
Figure 32.
Figure 32. Main Program Flow Diagram
SPACE THERMAL ENVIRONMENT STUDY

The results of parametric analyses conducted by the Astronautics Division of Convair (General Dynamics Corporation) are presented here (Reference 15). Elemental vehicle shapes, including a sphere, cylinder, hemisphere, and plane surfaces, are considered with attitudes and altitudes as parameters. The development of the analysis for the planetary reflected solar takes into account the incident radiation as the vehicle crosses the terminator, thus representing a more detailed solution of the form factor than previously discussed.

NOMENCLATURE

A Area, sq ft

a Albedo

b Distance defined in Figure 39

D Cylinder diameter, ft

d Radius defined in Figure 39

ds Element of planet surface area, sq ft

$E_r$ Solar energy rate reflected per planet unit area, Btu/(hr)(sq ft)

$E_t$ Total energy rate emitted per planet unit area, Btu/(hr)(sq ft)

$E_d$ Energy rate emitted or reflected per planet unit area in the direction $a$, Btu/(hr) (sq ft)

F View factor for flat plate

h Altitude above planet surface, nautical miles

L Length of cylinder, ft

P Area of flat plate, sq ft

p Radius of integrating hemisphere (Figure 39)

q Radiant energy rate received by vehicle, Btu/hr
R Radius of planet, nautical miles
r Radius of sphere or hemisphere, ft
S Solar constant, Btu/(hr)(sq ft)
x Distance defined in Figure 39 or Figure 42
\( \alpha \) Angle between normal to planetary element and vector to vehicle, deg
\( \beta \) Angle between earth-sun vector and extended normal to planetary elemental area, deg
\( \gamma \) Angle between vertical to vehicle and cylinder or hemisphere axis or normal to flat plate, deg
\( \Delta \) Angle between axis of cylinder or hemisphere or normal to flat plate and vector from vehicle to planetary elemental area, deg
\( \delta \) Angle between vehicle-earth vector and vector from vehicle to planetary elemental area, deg
\( \theta \) Spherical ordinate, deg
\( \theta_0 \) Spherical ordinate of horizon as seen from vehicle, deg
\( \lambda \) Angle defined in Figure 39, deg
\( \rho \) Distance between planet surface element and vehicle, naut mi
\( \phi \) Spherical abscissa, deg
\( \phi_c \) Angle of rotation of axis of cylinder or hemisphere or normal to flat plate about vertical to the vehicle, measured from plane of the earth-vehicle and earth-sun vectors, deg
\( \psi \) Angle defined in Figure 39, deg
\( \omega \) Angle defined in Figure 39, deg

Subscripts
0, 1, 2, ... Refer to various intersections on planetary sphere
PLANETARY THERMAL EMISSION

Analysis Method

Thermal energy is radiated by planets in the same manner as by any heated body. The magnitude of this radiation depends on the surface temperature and its emission characteristics. The latter involves the properties of any atmosphere which may exist, as well as the emissivity of the surface itself. Consequently, changes of atmospheric conditions, topography, season, and time of day introduce variations in the planetary thermal radiation. Neglecting details of the planet surface, however, it is possible to compute the average energy radiated by a planet using a thermal balance based on the solar radiation absorbed by the planet. As the temperatures of most planets do not vary appreciably over extended periods, it can be concluded that the thermally radiated energy is equivalent to the absorbed solar energy. Therefore, since the incident solar energy and average albedo are well known for most planets, the average thermal radiation can be readily calculated.

The energy balance is

$$(1 - a) S \pi R^2 = 4 \pi R^2 E_t$$

or

$$E_t = \left( \frac{1 - a}{4} \right) S$$

where

$S = \text{Solar heat flux per unit projected area of planet (as seen from sun)}$

Since the magnitudes of the thermal radiation from the various planets are established, there remains only the calculation of this energy in space as it will be intercepted by a space vehicle. To make this analysis possible parametrically, it is assumed that the planet surface is radiating uniformly so that the average value applies to any region of the surface. Because of the expected spacecraft velocities and trajectories, this appears to be a reasonable assumption. In addition, since thermal radiation is only significant for altitudes less than about three planet diameters, the radiation is far from being parallel and, consequently, the vehicle external configuration must be specified for a heat flux value in space to be meaningful. The shapes considered here include the sphere, hemisphere, cylinder, and flat plate. In general, any space vehicle shape could be analyzed, for practical purposes, as an assembly of flat plates, making it unnecessary to study, in
parametric detail, specific configurations whose analytical treatments are appreciably more complex than that of the flat plate. Configurations other than those mentioned will generally be in this area of higher complexity.

For convenience, thermal radiation heating data calculated for the stated configurations are plotted in reference to the earth. To use the curves for a vehicle in the proximity of another planet, it is only necessary to correct the altitude being considered to an equivalent earth altitude by multiplying it by the ratio of the earth radius to the planet radius, and using the appropriate planetary thermal radiation value ($E_t$) in the ordinate term.

**Emission to Sphere**

The geometrical relationship for a spherical body is shown in Figure 33. The radiant heat flux, incident to a sphere of radius $r$ from the element of planet surface $ds$ is

$$dq = \frac{\pi r^2 E_a}{\rho^2} \, ds$$

(68)

where the energy radiated in the direction determined by $\alpha$ is

$$E_a = \frac{E_t \cos \alpha}{\pi}$$

(69)

Then

$$dq = \frac{r^2 E_t \cos \alpha \, ds}{\rho^2}$$

(70)

Making the substitutions,

$$H = h + R$$

(71)

$$\cos \alpha = \frac{H \cos \theta - R}{\rho}$$

(72)

$$ds = R^2 \sin \theta \, d\theta \, d\phi$$

(73)

$$\rho^2 = R^2 + H^2 - 2RH \cos \theta$$

(74)

The total incident heating rate from the planet to the sphere is

$$q = 2r^2 R^2 \frac{E_t}{\rho^2} \int_0^\theta \int_0^\theta \frac{(H \cos \theta - R) \sin \theta}{(R^2 + H^2 - 2RH \cos \theta)^{3/2}} \, d\theta \, d\phi$$

(75)
Figure 33. Geometry of Planetary Thermal Emission to Sphere

which, after integration and substitution of \( \cos \theta_0 = R/H \), yields

\[
q = 2\pi r^2 E_t \left( 1 - \frac{\sqrt{2Rh + h^2}}{H} \right)
\]

Figure 34 shows the value \( q/\pi r^2 E_t \), the planetary thermal radiation to a sphere per unit of great circle (or projected) area and per unit of surface thermal radiation, as a function of the altitude above the earth surface. The term \( E_t \) is included in the ordinate scale definition rather than in the curve plot itself to preclude obsolescence of the curves in the event a more accurate value for earth albedo is determined in the future.

**Emission to Cylinder**

The configuration for a cylindrical body is shown in Figure 35. A new variable, the attitude of the cylinder with respect to the planet, defined by the angle \( \gamma \), has to be considered.
Figure 34. Geometric Factor for Earth Thermal Emission Incident to Sphere Versus Altitude.
The radiant heat flux incident to the lateral surface of a cylinder of
diameter $D$ and length $L$ from the element of planet surface $ds$ is

$$\frac{DL \sin \Delta E_t \cos \alpha \, ds}{\pi \rho^2}$$  \hspace{1cm} (77)

where $DL \sin \Delta$ is the projection of the cylinder surface as seen from $ds$,
and $E_t \cos \alpha / \pi$ is the energy radiated in the direction $\alpha$. The values of $H$, $\cos \alpha$, $ds$, and $\rho^2$ are given again by Equations 71 through 74.

The value of $\sin \Delta$ is

$$\sin \Delta = \sqrt{1 - (\cos \delta \cos \gamma + \sin \delta \sin \gamma \cos \phi)}^2$$  \hspace{1cm} (78)
where

\[
\cos \delta = \frac{H - R \cos \theta}{\rho} \tag{79}
\]
\[
\sin \delta = \frac{R \sin \theta}{\rho} \tag{80}
\]

After substitutions and some algebraic manipulation, the total incident heat flux from the planet to the cylinder can be written as

\[
q = \frac{2DLE_t R^2}{\pi} \int_0^\pi \int_0^\theta \frac{(H \cos \theta - R) \sin \theta}{(H^2 + R^2 - 2RH \cos \theta)^2} \times \left( \sqrt{A + B \cos \phi - C \cos^2 \phi} \right) \, d\theta d\phi \tag{81}
\]

where

\[
A = R^2 + H^2 - H^2 \cos^2 \gamma - 2RH \cos \theta \sin^2 \gamma - R^2 \cos^2 \theta \cos^2 \gamma \tag{82}
\]
\[
B = 2R^2 \sin \theta \cos \theta \sin \gamma \cos \gamma - 2RH \sin \theta \sin \gamma \cos \gamma \tag{83}
\]
\[
C = R^2 \sin^2 \theta \sin^2 \gamma \tag{84}
\]

Equation 81 cannot be integrated analytically; a numerical integration is required. To perform this, and other numerical integrations mentioned later, the solutions were programed on an automatic digital computer. The results are plotted in Figure 36, where the values of \(q/DLE_t\) are given as a function of the altitude above the earth surface \(h\), with the attitude angle \(\gamma\) as a parameter.

To apply the curves of Figure 36 to a vehicle in the proximity of a planet other than earth, the same procedure and correction term as given for the case of the sphere may be used.

Emission to Hemisphere

The configuration for a hemispherical body is shown in Figure 37. The orientation parameter \(\gamma\) for the hemisphere, although similar to that for a cylinder, must assume values throughout 180 degrees because the hemisphere is only symmetrical about one orthogonal axis.
Figure 36. Geometric Factor for Earth Thermal Emission Incident to Cylinder Versus Altitude as Function of Attitude Angle
The radiant heat flux incident to the hemispherical surface of radius $r$ from the element of planet surface $ds$ is

$$dq = \frac{1}{2} \pi r^2 (\cos \Delta + 1) E_t \cos a ds$$  \hspace{1cm} (85)$$

where $1/2 \pi r^2 (\cos \Delta + 1)$ is the projection of the hemispherical surface as seen from $ds$, and $E_t \cos a / \pi$ is the energy radiated in the direction $a$. The values of $H$, $\cos a$, $ds$, and $\rho^2$ are given again by Equations 71 through 74.

The value of $\cos \Lambda$ is

$$\cos \Lambda = \cos \delta \cos \gamma + \sin \delta \sin \gamma \cos \phi$$  \hspace{1cm} (86)$$

where $\cos \delta$ and $\sin \delta$ are as defined in Equations 79 and 80.
After substitutions and algebraic manipulation, the total incident heat flux from the planet to the hemispherical surface can be written as

\[
q = E_t \pi R^2 \int_0^{\pi} \int_0^{\pi} \frac{(H \cos \theta - R) \sin \theta}{(H^2 + R^2 - 2RH \cos \theta)^{3/2}} \, d\theta d\phi
\]

\[
+ \int_0^{\pi} \int_0^{\pi} \frac{(H \cos \theta - R) \sin \theta (A + B \cos \phi)}{(H^2 + R^2 - 2RH \cos \theta)^2} \, d\theta d\phi
\]

where

\[
A = H \cos \gamma - R \cos \theta \cos \gamma
\]
\[
B = R \sin \theta \sin \gamma
\]

The first term of the integration may be performed analytically to give the heat flux as

\[
q = E_t \pi R^2 \left[ \pi \left( 1 - \frac{\sqrt{2Rh + h^2}}{H} \right) \right]
\]

\[
+ R^2 \int_0^{\pi} \int_0^{\pi} \frac{(H \cos \theta - R) \sin \theta (A + B \cos \phi)}{(H^2 + R^2 - 2RH \cos \theta)^2} \, d\theta d\phi
\]

The second term was integrated numerically. The results are plotted in Figure 38, where the geometric factor \( q/\pi R^2 E_t \) is given as a function of altitude \( h \) above the earth's surface with the attitude angle \( \gamma \) as a parameter. These curves may be used for other planets as explained for the case of the sphere.

**Emission to Flat Plate**

For a flat plate, an integration method similar to that explained for spheres may be used. However, a similar solution can be found by resorting to a geometrical method of obtaining the view factor.

It can be proved that the view factor of a surface from a small flat plate can be geometrically determined. The surface is projected from the viewing point onto a sphere having its center at the viewing point. The image on the
Figure 38. Geometric Factor for Earth Thermal Emission Incident to Hemisphere Versus Altitude as Function of Attitude Angle
sphere is then projected onto the plane of the small flat surface. The view
factor is then determined from

\[ F = \frac{\text{area projected on plane}}{\pi \rho^2} \quad (89) \]

For this case, the surface is the region of the planet which the flat
plate can see, and the radius of the sphere is taken as the distance between
the plate and the tangency point T, as shown in Figure 39. The general
case, in which the plane of the plate intersects the planet, will be analyzed
first.

The area of the circular segment \( A_1 \) is

\[ A_1 = \frac{\pi d^2 \omega_1}{360} - \frac{d^2 \sin \omega_1}{2} \quad (90) \]

To obtain the value of \( \omega_1 \),

\[ \omega_1 = 180 - 2 \psi \quad (91) \]

\[ \psi = \sin^{-1} \frac{b}{d} \quad (92) \]

\[ b = \frac{h + x}{\tan \gamma} \quad (93) \]

\[ h + x = p \sin \theta_0 \quad (94) \]

\[ \sin \theta_0 = \frac{p}{H} \quad (95) \]

\[ h + x = \frac{p}{H} \quad (96) \]

\[ b = \frac{p}{H \tan \gamma} \quad (97) \]

\[ d = p \cos \theta_0 = \frac{pR}{H} \quad (98) \]

\[ \omega_1 = 180 - 2 \sin^{-1} \frac{p}{R \tan \gamma} \quad (99) \]
Figure 39. Geometry of Planetary Thermal Emission to Flat Plate
and since

\[ p = \sqrt{H^2 - R^2} \]
\[ \omega_1 = 180 - 2 \sin^{-1} \frac{\sqrt{H^2 - R^2}}{R \tan \gamma} \]  
(100)

The area \( A_1 \) is subtracted from \( \pi d^2 \) to give \( A_2 \). The area of the circular segment \( A_3 \) is

\[ A_3 = \frac{\pi p^2 \omega_2}{360} - \frac{p^2 \sin \omega_2}{2} \]  
(101)

As for \( \omega_2 \), it can be found that

\[ \omega_2 = 180 - 2 \sin^{-1} \left( \frac{\sqrt{H^2 - R^2}}{H \sin \gamma} \right) \]  
(102)

The view factor is obtained, then, by projecting the areas \( A_2 \) and \( A_3 \) on the plane of the flat plate, and dividing the sum of their projections by \( \pi p^2 \). The resulting expression is

\[ F = \frac{1}{360} \left[ 180 - 2 \sin^{-1} \left( \frac{\sqrt{H^2 - R^2}}{H \sin \gamma} \right) \right] - \frac{1}{2\pi} \sin \left[ 2 \sin^{-1} \left( \frac{\sqrt{H^2 - R^2}}{H \sin \gamma} \right) \right] \]
\[ + \left[ \frac{R^2}{H^2} - \frac{1}{360} \left( \frac{R^2}{H^2} \right) \right] \left[ 180 - 2 \sin^{-1} \left( \frac{\sqrt{H^2 - R^2}}{R \tan \gamma} \right) \right] \]
\[ + \frac{1}{2\pi} \left( \frac{R^2}{H^2} \right) \sin \left[ 2 \sin^{-1} \left( \frac{\sqrt{H^2 - R^2}}{R \tan \gamma} \right) \right] \cos \gamma \]  
(103)

A much simpler expression is obtained when the plane of the plate does not intersect the planet. In that case \( A_1 = A_3 = 0 \) and \( A_2 = \pi d^2 \). Then

\[ F = \frac{A_2 \cos \gamma}{\pi p^2} = \frac{R^2}{H^2} \cos \gamma \]  
(104)

In either case, the total heat flux from the planet to the flat plate is given by

\[ q = E_t F P \]  
(105)
where $P$ is the area of the plate. Figure 40 is a plot of the thermal radiation to a flat plate as a function of altitude with the attitude angle $\gamma$ as a parameter. Again, to apply these curves to planets other than the earth, the procedure given for the sphere may be used.

PLANETARY REFLECTED SOLAR RADIATION

As mentioned earlier, planetary albedo is the ratio of reflected to total incident solar radiation. As such, the units of the term albedo are dimensionless; however, the expression has been used more and more frequently in recent years to mean the reflected energy itself. Whatever the final, precise definition of the term, it clearly differentiates the portion of the incident solar energy which is reflected by the planet from that which is absorbed and reradiated.

The average albedo for planets located up to 10 astronomical units from the sun is known with reasonable accuracy, the value for the earth being the least accurate. At distances greater than about 10 astronomical units from the sun, the accuracy of the planetary albedo falls off significantly because of the very small magnitude of the reflected energy.

To permit a parametric analysis of the solar energy reflected from a planet, the same assumption which was made for thermal radiation (i.e., a uniform planet surface with regard to radiation characteristics) will be made. It is further assumed that the planet surface reflects diffusely (i.e., it obeys Lambert's law). While these assumptions may not be entirely accurate, particularly for the earth where large bodies of water exist, they can be justified by consideration of vehicle trajectories, orbits, and velocities used in the analysis.

Based upon these assumptions, it is clear that the reflected energy has a cosine distribution, not only with respect to the angular radiation from a given area but over the sunlit surface of the planet as well. This considerably complicates the problem over the case of thermal radiation, with the result that a direct analytical solution is not available even for the case of a spherical vehicle; for the cases of vehicles other than a sphere, the number of computations is greatly increased by the increased number of variables. The result is that some 97 pages of curves are necessary to adequately describe reflected heating to the sphere, hemisphere, cylinder, and flat plate which were used in the thermal radiation analyses. As a consequence of the bulk involved, these albedo heating data are included as Appendix B of this report.

As in the case of the thermal radiation analysis, the heating data is plotted in reference to the earth. Also, the data may be used for vehicles in the proximity of other planets by applying the same radius ratio correction terms to obtain an equivalent earth altitude and then using the appropriate
Figure 40. Geometric Factor for Earth Thermal Emission Incident to Flat Plate Versus Altitude as Function of Attitude Angle
ordinate multiplying factor. This factor takes into account the albedo and solar heat input to the planet considered.

**Reflected Solar to Sphere**

Considering the reflected (or albedo) heat flux incident to a sphere in space, the most general configuration is given in Figure 41. As in the case of thermal radiation, this heat flux to a sphere of radius \( r \) from the element of planet surface \( ds \) is

\[
dq = \frac{\pi r^2 E_a \, ds}{\rho^2}
\]

(106)

where

\[
E_a = \frac{E_r \cos \alpha}{\pi}
\]

Figure 41. Geometry of Planetary Reflected Solar Radiation to Sphere
is the fraction of reflected solar radiation in the direction determined by \( a \). 

\( E_r \) is the total reflected energy per unit of planet surface, and is given by

\[
E_r = S_a \cos \beta
\]  

(107)

where \( S \) (the direct solar heat flux normal to the sun direction), \( a \), and \( \beta \) are as shown in Figure 41. Then

\[
dq = \frac{r^2}{\rho^2} S_a \cos a \cos \beta \, ds
\]  

(108)

The values of \( \cos a \), \( ds \) and \( \rho^2 \) are given by Equations 72 through 74. The value of \( \cos \beta \) is

\[
\cos \beta = \cos \theta \cos \theta_S + \sin \theta \sin \theta_S \cos \phi
\]  

(109)

By substituting these expressions in Equation 108 and integrating for \( \theta \) and \( \phi \), \( q \) can be obtained. Careful consideration, however, has to be given to the limits of integration. Two cases should be considered, as illustrated in Figure 42.

The first occurs when the region of the planet seen from the satellite is completely sunlit. This condition can be expressed as

\[
\theta_o \leq \frac{\pi}{2} - \theta_S
\]

wherein the limits of integration for \( \theta \) are 0 and \( \theta_o \) and for \( \phi \) are 0 and \( \pi \) (the integral with respect to \( \phi \) is multiplied by 2).

When the region of the planet seen from the satellite is only partially sunlit,

\[
\theta_o > \frac{\pi}{2} - \theta_S
\]

wherein a variable upper limit for \( \phi \) has to be introduced. It is convenient to perform the integration for two regions, as shown in Figure 42. Region 1 is totally sunlit, and the limits are 0 to \( \pi/2 - \theta_S \) for \( \theta \) and 0 to \( \pi \) for \( \phi \). The limits for region 2 are \( \pi/2 - \theta_S \) to \( \theta_0 \) for \( \theta \) and 0 to \( \pi/2 + \sin^{-1}(\cot \theta_S \cot \theta) \) for \( \phi \). This variable limit can be obtained as follows. From Figure 42 it is evident that

\[
\phi = \frac{\pi}{2} + \lambda
\]  

(110)
Figure 42. Cases for Limits of Integration in Reflected Solar Radiation to Sphere

CASE I

$\theta_{o} \leq \frac{\pi}{2} - \theta_{s}$

CASE II

$\theta_{o} > \frac{\pi}{2} - \theta_{s}$
Also

\[ x = R \cos \theta \cot \theta_S \]  \hspace{1cm} (111)

and

\[ \sin \lambda = \frac{x}{R \sin \theta} = \cot \theta_S \cot \theta \]  \hspace{1cm} (112)

Therefore

\[ \phi = \frac{\pi}{2} + \sin^{-1}(\cot \theta_S \cot \theta) \]  \hspace{1cm} (113)

Finally, by adding the integrals over regions 1 and 2 in Figure 42, the total solar radiation reflected by the planet incident upon the sphere is

\[ q = 2r^2 S a \int_{0}^{\frac{\pi}{2}} \int_{0}^{\theta_S} \frac{(H \cos \theta - R)(\cos \theta \cos \theta_S + \sin \theta \sin \theta_S \cos \phi) \sin \theta d\theta d\phi}{(R^2 + H^2 - 2RH \cos \theta)^{3/2}} \]

\[ + 2r^2 S a R^2 \int_{\frac{\pi}{2} - \theta_S}^{\pi} \int_{0}^{\theta_S} \frac{\sin^{-1}(\cot \theta_S \cot \theta)}{(H \cos \theta - R)(\cos \theta \cos \theta_S + \sin \theta \sin \theta_S \cos \phi) \sin \theta d\theta d\phi}{(R^2 + H^2 - 2RH \cos \theta)^{3/2}} \]  \hspace{1cm} (114)

Equation 114 holds for \( \theta_S < \pi/2 \). For \( \theta_S \geq \pi/2 \), the first term disappears and the lower lower limit on \( \theta \) of the second term becomes \( \theta_S - \pi/2 \).

Integration with respect to \( \phi \) is immediate, but not so with respect to \( \theta \) which requires a numerical method. Figure 43 shows the value of \( q/\pi r^2 S a \), which is the heat flux to a sphere per unit of great circle (projected) area per unit of reflected solar radiation, as a function of altitude above the earth surface, with \( \theta_S \) as a parameter.

**Reflected Solar to Cylinder**

The albedo to a cylinder is computed by a numerical method similar to that used for a sphere; however, the integrand is more complex because two additional parameters defining the attitude of the cylinder must be included. The general configuration is shown in Figure 44.
Figure 43. Geometric Factor for Earth Reflected Solar Radiation Incident to Sphere Versus Altitude as Function of Sun Angle
Figure 44. Geometry of Planetary Reflected Solar Radiation to Cylinder

The radiant heat flux incident to the cylinder lateral surface of diameter D and length L due to reflected solar energy from the element of planet surface ds is

\[ dq = \frac{DLE_a \sin \Delta \ ds}{\rho^2} \]  \hspace{1cm} (115)

where

\[ E_a = \frac{E_r \cos \alpha}{\pi} \]
is the fraction of reflected solar radiation in the direction determined by \( \alpha \). 

\( E_r \) is the total reflected energy per unit of planet surface, and is given by Equation 107.

\[ D_L \sin \Delta \] is the projection of the lateral surface of the cylinder as seen from \( ds \). With the symbols defined, the elemental incident flux to the cylinder may be written as

\[ dq = \frac{D_L \alpha \cos \beta \cos \alpha \sin \Delta \ ds}{\pi \rho^2} \]  

(116)

The terms \( \cos \alpha \), \( ds \), and \( \rho^2 \) are given by Equations 72 through 74, and \( \sin \Delta \) is given by

\[ \sin \Delta = \left[ 1 - \left( \cos \delta \cos \gamma + \sin \delta \sin \gamma \cos (\phi - \phi_c) \right)^2 \right]^{1/2} \]  

(117)

where \( \cos \delta \) and \( \sin \delta \) are as defined in Equations 79 and 80.

The angle \( \phi_c \) is one of the attitude parameters, the angle of rotation of the cylinder axis about a vertical to the cylinder. \( \phi_c = 0 \) when the axis lies in the plane containing the earth-cylinder vector and the earth-sun vector. The angle \( \gamma \) is the other attitude parameter, the angle between the vertical to the cylinder and the axis of the cylinder.

The value of \( \cos \beta \) may be expressed as given in Equation 110, where \( \theta_S \) is as defined for albedo to a sphere and may be referred to as the zenith distance from the vehicle to the sun, and \( \theta \) and \( \phi \) are the variables of integration. After substitution and integration with respect to \( \theta \) and \( \phi \), \( q \) can be obtained.

Again as in the case of a sphere, two cases should be considered: when the entire area of the planet seen from the cylinder is sunlit, and when the area is only partially sunlit, that is, when the satellite can see a portion of the terminator, in which case a variable limit for \( \phi \) is required and is again given by Equation 114. If symmetry about the plane containing the earth-vehicle vector and the earth sun vector is recognized, total reflected solar heat flux from the planet incident on the cylindrical surface can be written for \( \theta_S < \pi/2 \) as

\[ q = \frac{2D_L \alpha \pi r^2}{\pi} \left[ \int_0^{\pi/2 - \theta_S} \int_0^\pi \frac{A \cdot B \cdot C \cdot D}{E^2} \ d\theta d\phi + \int_{\theta_S}^{\theta_S + \sin^{-1}(\tan \theta_S \tan \theta)} \int_0^{\pi/2 - \theta_S} \frac{A \cdot B \cdot C \cdot D}{E^2} \ d\theta d\phi \right] \]  

(118)

-100-
where

\[ A = H \cos \theta - R \]
\[ B = \cos \theta_S \cos \theta + \sin \theta_S \sin \theta \cos \phi \]
\[ C = \sin \theta \]
\[ D = \frac{\sqrt{R^2 + H^2 - 2R \sin^2 \gamma \cos \theta - H^2 \cos^2 \gamma - R^2 \cos^2 \gamma \cos \theta}}{2R \cos \gamma \sin \gamma \sin \theta \cos(\phi - \phi_c)} \]
\[ + \frac{2R \cos \gamma \sin \gamma \sin \theta \cos \theta \cos(\phi - \phi_c) - R^2 \sin^2 \gamma \sin^2 \theta \cos^2(\phi - \phi_c)}{2} \]
\[ E = R^2 + H^2 - 2RH \cos \theta \]

When

\[ \frac{\pi}{2} \leq \theta_S \leq \frac{\pi}{2} + \theta_o \]

the integration limits change and integration occurs over only one zone with limits given as

\[ q = \frac{2DLSaR^2}{\pi} \int_{\theta_o - \frac{\pi}{2}}^{\theta_o} \int_{0}^{\frac{\pi}{2} + \sin^{-1}(\text{ctg} \theta_S \text{ctg} \theta)} \frac{A \cdot B \cdot C \cdot D}{E^2} \, d\theta \, d\phi \] (119)

The heat flux integrals (Equations 118 and 119) have been integrated numerically on an IBM 704 computer. The results are tabulated in Appendix B as the geometric factor (q/DLSa) as a function of altitude with zenith distance \( \theta_S \), angle between the vertical to the cylinder and the cylinder axis \( \gamma \) and angle of rotation \( \phi_c \) of the axis of the cylinder about the vertical to the cylinder referenced to the plane containing the vertical and the earth-sun vector (Figure 44). The values considered for the attitude parameters were \( \gamma = 0, 30, 60, \) and 90 degrees and simultaneously \( \phi_c = 0, 30, 60, 90, 120, 150, \) and 180 degrees. The parameter \( \gamma \) need only be considered to 90 degrees as the cylinder has end-for-end symmetry.
Figure 45. Geometry of Planetary Reflected Solar Radiation to Hemisphere

Reflected Solar to Hemisphere

The solution for albedo to a hemisphere is very similar to that for a cylinder, the two major differences being that the expression for the projected area of the hemisphere with respect to ds is somewhat different and that values of γ from 0 to 180 degrees must be considered because end-for-end symmetry is not present. The general configuration for albedo to a hemisphere is shown in Figure 45.

The radiant heat flux incident to the hemispherical surface of radius r due to reflected solar energy from the planet surface ds is
where $\frac{1}{2} \pi r^2 (1 + \cos \Delta)$ is the projected area of the hemispherical surface as seen from $ds$ and the remaining symbols are as defined for a cylinder. Thus, the elemental incident heat flux to a hemisphere may be written as

$$dq = \frac{\pi^2}{2} \frac{(1 + \cos \Delta)(\cos \beta \cos \alpha) ds}{\rho^2}$$

(120)

The term $\cos \Delta$ is given by

$$\cos \Delta = \cos \gamma \cos \delta + \sin \gamma \sin \delta \cos (\phi - \phi_c)$$

(122)

with the terms defined as for the cylinder solution. Again, $\cos \beta$ is given by Equation 109, and $\cos \alpha$, $ds$, and $\rho^2$ are given by Equations 72 through 74.

The integration techniques and limits are as defined for albedo to a cylinder. The total reflected solar heat flux from the planet incident on the hemispherical surface can be written for $\theta_S < \pi/2$ as

$$q = r^2 \int_0^{\pi/2} \int_0^\pi A \cdot B \cdot C \left( \frac{\sqrt{R^2 + H^2 - 2RH \cos \theta}}{E^2} \right) d\theta d\phi$$

$$+ \int_0^{\theta_0} \frac{\pi}{2} \sin^{-1} \left( \frac{\cos \theta}{\cos \theta_S \cos \theta + \sin \theta_S \sin \theta \cos \phi} \right) d\theta d\phi$$

(123)

where

$$A = H \cos \theta - R$$

$$B = \cos \theta_S \cos \theta + \sin \theta_S \sin \theta \cos \phi$$

$$C = \sin \theta$$

$$E = R^2 + H^2 - 2RH \cos \theta$$

$$F = H \cos \gamma - R \cos \gamma \cos \theta + R \sin \gamma \sin \theta \cos (\phi - \phi_c)$$
When

\[ \frac{\pi}{2} \leq \theta_S \leq \frac{\pi}{2} + \theta_o \]

the heat flux to the hemisphere is

\[ q = r^2 S_a R^2 \int_{\frac{\pi}{2}}^{\theta_o} \frac{\pi}{2} + \sin^{-1}(\cot \theta_S \cot \theta) \int_0^\pi \frac{A \cdot B \cdot C (\sqrt{E + F})}{E^2} \, d \theta \, d \phi \]  \hspace{1cm} (124)

The heat flux integrals (Equations 123 and 124) have been integrated numerically on an IBM 7090 computer. The results are displayed as the geometric factor \( q/v \) \( r^2 S_a \) as a function of altitude with the three angles \( \theta_S, \gamma, \) and \( \phi_c \) as parameters. This tabular presentation is given in Appendix B. The values considered for the attitude parameters were 0, 30, 60, 90, 120, 150, and 180 degrees for \( \gamma \) and simultaneously 0, 30, 60, 90, 120, 150, and 180 degrees for \( \phi_c \).

Reflected Solar to Flat Plate

The most general configuration used in considering the albedo heat flux incident on one side of a flat plate in space is given in Figure 46. Development of the integral takes the same form as that for a cylinder or a hemisphere. The heat flux incident to a flat plate of area \( P \) from the element of planet surface \( ds \) is

\[ dq = \frac{P \cos \Delta E_\delta ds}{\rho^2} \]  \hspace{1cm} (125)

where \( P \cos \Delta \) is the projected area of the plate as seen from \( ds \). Since the remaining symbols to be defined are identical to those for a cylinder, Equation 125 may be written as

\[ dq = \frac{P S_a \cos \beta \cos \alpha \cos \Delta ds}{\pi \rho^2} \]  \hspace{1cm} (126)

wherein \( \cos \gamma, ds, \) and \( \rho^2 \) are given by Equations 72 through 74, and \( \cos \beta \) is given by Equation 109.

The term \( \cos \Delta \) is given by Equation 122, with the terms defined as for the cylinder solution. The total reflected solar heat flux from the planet incident on the flat plate can be written as an indefinite integral.
Figure 46. Geometry of Planetary Reflected Solar Radiation to Flat Plate

\[
q = \frac{PSaR^2}{\pi} \int \int \frac{A \cdot B \cdot C \cdot (G + F)}{E^2} \, d\theta \, d\phi \tag{127}
\]

where A, B, C, and E are as defined for a cylinder, and

\[
F = R \sin \gamma \sin \theta \cos(\phi - \phi_c)
\]

\[
G = \cos \gamma (H - R \cos \theta)
\]

The problem of limits for the integration of Equation 127 is severely complicated in that the plane of the flat plate may cut off portions of the sunlit area of the planet.
The limits considered are discussed with respect to the computer solution of Equation 127. Two major conditions are considered: (1) if the flat plate sees the sunlit surface of the planet with the plane in which it lies not cutting any portion of the sunlit area, and (2) if the plane of the flat plate cuts the sunlit area. If the plane does not cut the sunlit area, two conditions may be involved. Either the plane sees a full sunlit zone (i.e., does not see the terminator), in which case Equation 127 becomes

\[ q = \frac{2PSaR^2}{\pi} \int_{0}^{\theta_{o}} \int_{0}^{\pi} \frac{A \cdot B \cdot C \cdot (G + F)}{E^2} \, d\theta \, d\phi \]  

(128)

or the plane sees part of the terminator, in which case, when \( \theta_{s} < \pi/2 \), Equation 128 becomes

\[ q = \frac{2PSaR^2}{\pi} \left[ \int_{0}^{\pi/2} \theta_{s} \int_{0}^{\pi} \frac{A \cdot B \cdot C \cdot (G + F)}{E^2} \, d\theta \, d\phi \right] + \frac{2PSaR^2}{\pi} \left[ \int_{\pi/2}^{\theta_{o}} \int_{0}^{\pi/2 + \sin^{-1}(\text{ctg} \theta_{s} \text{ctg} \theta)} \frac{A \cdot B \cdot C \cdot (G + F)}{E^2} \, d\theta \, d\phi \right] \]  

(129)

when

\[ \frac{\pi}{2} \leq \theta_{s} \leq \frac{\pi}{2} + \theta_{o} \]

then

\[ q = \frac{2PSaR^2}{\pi} \left[ \int_{\theta_{s}}^{\theta_{o}} \int_{0}^{\pi/2 + \sin^{-1}(\text{ctg} \theta_{s} \text{ctg} \theta)} \frac{A \cdot B \cdot C \cdot (G + F)}{E^2} \, d\theta \, d\phi \right] \]  

(130)

The problem becomes more complex when the plane cuts the sunlit area because the limits of \( \theta \) and \( \phi \) are determined by more complex equations. If the plane cuts the sunlit area but the plane does not see the terminator, Equation 127 becomes for \( \theta_{s} < \pi/2 \) and \( \gamma < \pi/2 \),
\[
q = \frac{PSaR^2}{\pi} \left[ \int_{\theta_1}^{\pi} \int_{-\pi}^{\pi} \frac{A \cdot B \cdot C \cdot (G + F)}{E^2} \, d\theta \, d\phi \right]
\]

where \( \theta_1 \) was determined by the Newton-Raphson iteration procedure for determining roots from

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

For \( \pi/2 < \gamma < \pi/2 + \theta_0 \), \( q \) is given by Equation 131 with the first integral term eliminated. It should be noted that for \( \gamma > \pi/2 + \theta_0 \), \( q \) is equal to 0, (i.e., the plane surface does not see the earth).

A number of forms of Equation 127 are possible if the plane of the flat plate cuts the sunlit area and also sees a portion of the terminator. For the case where the plane of the flat plate for \( \gamma < \pi/2 \) intersects the terminator in two points, \( (\phi_3, \theta_3) \) and \( (\phi_4, \theta_4) \), and \( \theta_3 \) and \( \theta_4 > \theta_0 \), \( \phi_3 > \phi_4 \), and \( \phi_4 < \pi \), Equation 127 becomes
\[ q = \frac{PSaR^2}{\pi} \left\{ \int_{\theta_1}^{\theta_3} \int_{-\pi}^{\pi} \frac{A \cdot B \cdot C (G + F)}{E^2} \, d\theta \, d\phi \right. \]

\[ + \int_{\theta_1}^{\theta_4} \int_{\theta_4}^{\theta_3} \int_{-\pi}^{\pi} \frac{A \cdot B \cdot C (G + F)}{E^2} \, d\theta \, d\phi \]

\[ - \left[ \frac{\pi}{2} - \phi_c + \sin^{-1} \left( \frac{\tan \left( \cos^{-1} \left( \frac{R \sin \theta}{\sqrt{R^2 + H^2 - 2RH \cos \theta}} \right) \right)}{\tan \gamma} \right) \right] \]

\[ + \frac{PSaR^2}{\pi} \left\{ \int_{\theta_4}^{\theta_3} \int_{\frac{\pi}{2}}^{\theta_4} \frac{A \cdot B \cdot C (G + F)}{E^2} \, d\theta \, d\phi \right. \]

\[ - \left[ \frac{\pi}{2} - \phi_c + \sin^{-1} \left( \frac{\tan \left( \cos^{-1} \left( \frac{R \sin \theta}{\sqrt{R^2 + H^2 - 2RH \cos \theta}} \right) \right)}{\tan \gamma} \right) \right] \]

\[ + \int_{\theta_3}^{\theta_4} \int_{\theta_3}^{\frac{\pi}{2}} \frac{A \cdot B \cdot C (G + F)}{E^2} \, d\theta \, d\phi \]

\[ - \left[ \frac{\pi}{2} + \sin^{-1} \left( \frac{\tan \left( \cos^{-1} \left( \frac{R \sin \theta}{\sqrt{R^2 + H^2 - 2RH \cos \theta}} \right) \right)}{\tan \gamma} \right) \right] \]

where \( \theta_4 \) and \( \theta_3 \) were determined by the Newton-Raphson method from Equations 134 and 135, respectively.

\[ \sin^{-1} \left( \cot \theta_S \cot \theta_4 \right) = \phi_c + \sin^{-1} \left( \frac{\tan \left( \cos^{-1} \left( \frac{R \sin \theta_4}{\sqrt{R^2 + H^2 - 2RH \cos \theta_4}} \right) \right)}{\tan \gamma} \right) \]

(134)
\[ -\sin^{-1}(\text{ctg} \theta_3 \text{ctg} \theta_3) = \phi_c - \sin^{-1} \left( \frac{\tan \gamma}{\frac{\cos^{-1} \left( \frac{R \sin \theta_3}{\sqrt{R^2 + H^2 - 2RH \cos \theta_3}} \right)}{\tan \gamma}} \right) \]

(135)

For \( \phi_4 > \pi \), two conditions may be considered. If \( \pi/2 - \theta_S < \theta_1 \), Equation 127 becomes

\[
q = \frac{PSaR^2}{\pi} \left[ \int_{0}^{\pi/2} \int_{0}^{\pi} \int_{-\pi}^{\pi} \frac{A \cdot B \cdot C (G + F)}{E^2} \ d\theta \ d\phi \right. \\
+ \int_{\pi/2}^{\pi} \int_{0}^{\pi/2} \int_{0}^{\pi} \frac{A \cdot B \cdot C (G + F)}{E^2} \ d\theta \ d\phi \\
- \left. \int_{\pi/2}^{\pi} \int_{0}^{\pi/2} \int_{0}^{\pi} \frac{A \cdot B \cdot C (G + F)}{E^2} \ d\theta \ d\phi \right]
\]

(136)
\[
\theta_3 \text{ is determined by Equation 135, and } \theta_4 \text{ is determined by}
\]
\[
\pi + \sin^{-1} \left( \cot \theta_S \cot \theta_4 \right) = \phi_c + \sin^{-1} \left[ \tan \left( \cos^{-1} \left( \frac{R \sin \theta_4}{\sqrt{R^2 + H^2 - 2RH \cos \theta_4}} \right) \right) \right]
\]
\[
\text{(137)}
\]

If \( \frac{\pi}{2} - \theta_S > \theta_1 \), the limits change somewhat.

\[
q = \frac{P \sin R^2}{\pi} \left[ \int \int_{0}^{\pi} \frac{A \cdot B \cdot C (G + F)}{E^2} \, d\theta \, d\phi \right.
\]
\[
+ \left. \int \int_{\frac{\pi}{2} - \theta_S}^{\pi - \theta} \frac{A \cdot B \cdot C (G + F)}{E^2} \, d\theta \, d\phi \right]
\]
\[
\left. + \int \int_{\theta_1}^{\frac{\pi}{2} - \phi} \frac{A \cdot B \cdot C (G + F)}{E^2} \, d\theta \, d\phi \right]
\]
\[
\left. + \frac{P \sin R^2}{\pi} \left[ \int \int_{\frac{\pi}{2} - \theta_4}^{\pi - \phi} \frac{A \cdot B \cdot C (G + F)}{E^2} \, d\theta \, d\phi \right. \right]
\]
\[
\left. \left. + \int \int_{\frac{\pi}{2} - \theta_4}^{\pi - \phi} \frac{A \cdot B \cdot C (G + F)}{E^2} \, d\theta \, d\phi \right) \right]
\]

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\[
\int_{\theta_3} \int_{\pi/2 - \theta_S}^{\theta_3} \frac{\pi/2 + \sin^{-1}(\text{ctg} \theta_S \text{ctg} \theta)}{A \cdot B \cdot C (G + F)} \, d \theta \, d \phi \\
\int_{\pi/2 - \phi_c}^{\pi/2 - \phi_c + \sin^{-1} \left( \frac{R \sin \theta}{\sqrt{R^2 + H^2 - 2RH \cos \theta}} \right)} \tan \left[ \cos^{-1} \left( \frac{R \sin \theta}{\sqrt{R^2 + H^2 - 2RH \cos \theta}} \right) \right] \, \tan \gamma 
\]

\[
+ \frac{PSaR^2}{\pi} \int_{\theta_3}^{\theta_0} \int_{\theta_3}^{\pi/2 + \phi_c + \sin^{-1} \left( \frac{R \sin \theta}{\sqrt{R^2 + H^2 - 2RH \cos \theta}} \right)} \tan \left[ \cos^{-1} \left( \frac{R \sin \theta}{\sqrt{R^2 + H^2 - 2RH \cos \theta}} \right) \right] \, \tan \gamma 
\]

For the case where the plane of the flat plate intersects the terminator in one point, \((\phi_4, \theta_4)\), and the circle defined by \(\theta = \theta_o\) in one point, \((\phi_3, \theta_o)\), and \(\phi_4 < \pi\), Equation 127 becomes

\[
q = \frac{PSaR^2}{\pi} \int_{\theta_3}^{\theta_4} \int_{\pi/2 - \phi_c + \sin^{-1} \left( \frac{R \sin \theta}{\sqrt{R^2 + H^2 - 2RH \cos \theta}} \right)} \tan \left[ \cos^{-1} \left( \frac{R \sin \theta}{\sqrt{R^2 + H^2 - 2RH \cos \theta}} \right) \right] \, \tan \gamma 
\]

\[
+ \frac{A \cdot B \cdot C (G + F)}{E^2} \int_{\theta_1}^{\theta_4} \int_{\pi/2 - \phi_c + \sin^{-1} \left( \frac{R \sin \theta}{\sqrt{R^2 + H^2 - 2RH \cos \theta}} \right)} \tan \left[ \cos^{-1} \left( \frac{R \sin \theta}{\sqrt{R^2 + H^2 - 2RH \cos \theta}} \right) \right] \, \tan \gamma 
\]

-111-
\[
\frac{\text{PSaR}^2}{\pi} \int_0^{\theta_2} \left[ \theta_4 \int_0^{\pi/2 + \sin^{-1}(\text{ctg} \theta_4 \text{ctg} \theta)} \frac{A \cdot B \cdot C (G + F)}{E^2} \, d\theta \, d\phi \right] + \left[ \frac{\pi}{2} - \phi_c + \sin^{-1} \left( \frac{R \sin \theta}{\sqrt{R^2 + H^2 - 2RH \cos \theta}} \right) \right] \tan \gamma
\]

where \( \theta_4 \) is again determined by Equation 134.

For \( \phi_4 > \pi \), two conditions are again considered. If \( \pi/2 - \theta_S < \theta_1 \), Equation 127 becomes the same as Equation 136 except that the last term is eliminated and the upper limit, \( \theta_3 \), for the fourth term is replaced by \( \theta_0 \). If \( \pi/2 - \theta_S > \theta_1 \), Equation 127 becomes the same as Equation 138 except that the last term is eliminated and the upper limit, \( \theta_3 \), for the fourth term is replaced by \( \theta_0 \).

For the case where the plane of the flat plate intersects the circle defined by \( \theta = \theta_0 \) in two points, \( (\phi_4, \theta_0) \) and \( (\phi_3, \theta_0) \), for \( \pi/2 - \theta_S < \theta_1 \), Equation 127 becomes the same as Equation 136 with the last term eliminated and the upper limits of the third and fourth terms replaced by \( \theta_0 \). For \( \pi/2 - \theta_S > \theta_1 \), Equation 127 becomes the same as Equation 138 with the last term eliminated and the upper limits of the third and fourth terms replaced by \( \theta_0 \).

For \( \gamma > \pi/2 \), a similar step procedure in the integration of Equation 127 must be used which follows the same method set forth for \( \gamma < \pi/2 \). This will not be done here, however.

Some difficulty is encountered in determining when the plane of the flat plate cuts the sunlit region in the vicinity of the terminator. To determine whether intersection of the plane and terminator occurs for a given \( \phi_C \) and \( h \), the \( \gamma_2 \) for the plane with \( \phi_C = 0 \) to be tangent to the terminator was calculated as

\[
\gamma_2 = \cos^{-1} \left( \frac{R \sin \theta_2}{\sqrt{R^2 + H^2 - 2RH \cos \theta_2}} \right)
\]

where

\[
\theta_2 = \frac{\pi}{2} - \theta_S
\]
The maximum possible $Y_0$ without intersection with the sunlit area was then calculated as

$$Y_0 = \theta_0 \quad (141)$$

Corresponding to this point is an angle, $\phi_{co}$, calculated from

$$\phi_{co} = \frac{\pi}{2} - \sin^{-1}(\text{ctg} \theta_S \text{ctg} \theta_o) \quad (142)$$

For a given $\phi_c$, the limiting $Y_{lim}$ for intersection of the plane of the flat plate with the terminator was calculated from

$$Y_{lim} = Y_2 - \left( \frac{Y_2 - Y_0}{\phi_{co}} \right) \phi_c \quad (143)$$

This is not an exact determination of the $Y$ for tangency of the plane of the plate with the terminator circle; however, the error introduced is small.

The heat flux integrals were integrated numerically on an IBM 7090 computer. The results are presented in Appendix B as the geometric factor $(q/PSa)$ as a function of altitude with the three angles, $\theta_S$, $\gamma$, and $\phi_c$, as parameters. Each table is for a constant $\gamma$ and $\phi_c$.

The albedo data for a flat plate is also useful in determining albedo to an irregular surface. The irregular surface may be approximated by a series of flat plates and the albedo input is obtained by summing the individual values for each of the flat plates.
DISCUSSION OF ASSUMPTIONS

SIMPLIFIED SPACE RADIATION ANALYSIS

1. It is assumed that all thermal radiation considered in the analysis is in diffuse form except direct solar radiation. Fortunately, most thermal radiation is in diffuse form, which is relatively simple to analyze when compared with specular radiation.

2. It is assumed that direct solar radiation impinges upon the earth and upon the satellite with parallel rays, due to the great distance between the sun and its planets. Almost zero error is introduced into the analysis by this assumption.

3. In all cases, it is assumed that the earth emits as a black body and is in a state of thermal equilibrium (i.e., the planetary emitted energy is equal to the absorbed solar energy). It is also assumed that the earth emission is a constant at any point on its surface and does not vary from day to night. These are reasonable assumptions because little is known of the actual spectral and local variations in the planetary emitted radiation.

4. The earth reflected solar radiation is assumed to follow the cosine law (i.e., it is a maximum at the subsolar point and decreases to zero at the terminator). This assumption greatly simplifies the analysis and is quite accurate except in the region of the terminator, where a slight error is introduced.

5. In all cases, the planetary albedo is assumed to be constant over the surface of the planet, and the planet is assumed to be a diffuse reflector. This is done because of the complications of the problem and because local variations are almost impossible to define.

6. In all cases, conduction and convection between the satellite and its surroundings were neglected. This is reasonable because orbital heights are usually too far above the atmosphere for thermal effects to appear.

7. It is assumed that the absorptivity to direct solar radiation of the vehicle surface is equal to the absorptivity to the earth reflected solar radiation. This is correct if the spectral quality of the
reflected solar energy is the same as for the direct solar energy. It is felt that only a very small error is introduced by this assumption.

8. No transient heat transfer effects are considered in this analysis. Steady-state conditions are assumed for purposes of simplification.

9. An earth-oriented vertical cylinder is the assumed configuration in all cases for purposes of simplification. The ends of the cylinder are ignored in the analysis. The cylinder wall is assumed to be at a uniform temperature, which is correct for a vertical cylinder spinning on its axis or for a cylinder with a shell of very high thermal conductivity.

10. In the discussion on simplified geometry analysis the earth is assumed to be a flat plate. This, in effect, results in the satellite-to-space configuration factor and the satellite-to-earth configuration factor both being equal to 0.5.

11. In the refined geometry analysis discussion, the earth is assumed to be a sphere. As a result, this analysis is considerably more accurate than the simplified geometry analysis.

IBM 7090 PROGRAM FOR TRANSIENT HEAT TRANSFER ANALYSIS OF ORBITING SPACE VEHICLES

1. It is assumed in this analysis that the earth can be represented gravitationally by the zero-order and second-order spherical harmonics of its potential. The presence of harmonics in the earth's gravitational potential causes periodic and secular variations in several of the orbital elements. Only the secular perturbations which result in regression of the nodes and advance of the perigee position are considered in the analysis. Other periodic changes have negligible effect upon the shadow intersection problem.

2. A rigorous specification of the position at which the satellite enters and exits the earth's true shadow leads to needlessly complicated expressions. For this reason, the following simplifications concerning shadow geometry were assumed:

   a. The earth was assumed spherical with its radius equal to 3960 statute miles.
   b. The earth's shadow was assumed cylindrical and umbral (sun at infinity).
   c. Penumbral effects were ignored.
The error involved is extremely small even when large orbits are considered. For instance, a satellite in a circular orbit with an altitude of 10,000 miles has an orbit period of approximately 560 minutes, with perhaps 50 minutes spent in earth shadow (depending on orbit orientation). By assuming a cylindrical earth shadow and ignoring penumbral effects, the analysis uses an umbral shadow time that is about 50 seconds longer than the true umbral shadow time. This is a negligible error. For a 1000-mile-altitude circular orbit, the negligible error is approximately 18 seconds in an orbit period of 118 minutes. Additionally, it should be mentioned that the assumption of no penumbral effects tends to lessen these errors introduced by the assumption of cylindrical umbral shadow, so that there is almost zero error from a thermal analysis standpoint.

3. It is assumed that all thermal radiation considered in the analysis, except direct solar radiation, is in diffuse form. Fortunately, most thermal radiation is in diffuse form, which is relatively simple to analyze when compared with specular radiation.

4. It is assumed that direct solar radiation impinges upon the earth and upon the satellite with parallel rays, due to the great distance between the sun and its planets. Almost zero error is introduced into the analysis by this assumption.

5. In all cases, it is assumed that the earth emits as a black body and is in a state of thermal equilibrium (i.e., the planetary-emitted energy is equal to the absorbed solar energy). It is also assumed that the earth emission is a constant at any point on its surface and does not vary from day to night. These are reasonable assumptions because little is known of the actual spectral and local variations in the planetary emitted radiation.

6. The earth reflected solar radiation is assumed to follow the cosine law (i.e., it is a maximum at the subsolar point and decreases to zero at the terminator). This assumption greatly simplifies the analysis and is quite accurate except in the region of the terminator, where a slight error is introduced.

7. In all cases, the planetary albedo is assumed to be constant over the surface of the planet, and the planet is assumed to be a diffuse reflector. This is done because of the complications of the problem and because local variations are almost impossible to define.

8. In all cases, conduction and convection between the satellite and its surroundings are neglected. This is reasonable because orbital heights are usually too far above the atmosphere for thermal effects to appear.
9. It is assumed that the absorptivity of the vehicle surface to planetary thermal emission is equal to the emissivity of the vehicle surface. Since the effective temperature of the earth and the temperatures of most vehicle surfaces are nearly the same, this assumption is validated by Kirchhoff's law.

10. Any scattering effects of direct solar radiation upon the satellite due to the earth's atmosphere are ignored. It is felt that this will introduce a negligible error into the analysis.

11. The geometrical configuration factor from the spherical satellite to earth was calculated with the assumption that the satellite is a point source in space. The assumption is valid if the satellite is uniform in temperature; it would be if spinning or if its shell had a very high thermal conductivity.

12. It is assumed that any internally generated heat load is uniformly distributed over the particular vehicle surface specified. Internal heat transfer paths are neglected. This was done in order to simplify the analysis.

SPACE THERMAL ENVIRONMENT STUDY

1. It is assumed that all thermal radiation considered in the analysis, except direct solar radiation, is in diffuse form. Fortunately, most thermal radiation is in diffuse form, which is relatively simple to analyze when compared with specular radiation.

2. It is assumed that direct solar radiation impinges upon the earth and upon the satellite with parallel rays, due to the great distance between the sun and its planets. Almost zero error is introduced into the analysis by this assumption.

3. In all cases, it is assumed that the earth emits as a black body and is in a state of thermal equilibrium (i.e., the planetary emitted energy is equal to the absorbed solar energy). It is also assumed that the earth emission is a constant at any point on its surface and does not vary from day to night. These are reasonable assumptions because little is known of the actual spectral and local variations in the planetary emitted radiation.

4. In all cases, the planetary albedo is assumed to be constant over the surface of the planet, and the planet is assumed to be a diffuse reflector. This is done because of the complications of the problem and because local variations are almost impossible to define.
5. In all cases, conduction and convection between the satellite and its surroundings were neglected. This is reasonable because orbital heights are usually too far above the atmosphere for thermal effects to appear.
Section VI

TECHNIQUES FOR RADIATION HEAT TRANSFER PROBLEM SOLUTION

GENERAL ANALOG HEAT TRANSFER ANALYSIS METHODS

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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</thead>
<tbody>
<tr>
<td>A</td>
<td>Area, sq ft</td>
</tr>
<tr>
<td>CE</td>
<td>Electrical capacitance</td>
</tr>
<tr>
<td>CT</td>
<td>Thermal conductance, Btu/(hr)(°F)</td>
</tr>
<tr>
<td>cp</td>
<td>Specific heat, Btu/(lb)(°F)</td>
</tr>
<tr>
<td>F</td>
<td>Configuration factor</td>
</tr>
<tr>
<td>f</td>
<td>Interchange factor</td>
</tr>
<tr>
<td>hc</td>
<td>Convection heat transfer coefficient, Btu/(hr)(sq ft)(°F)</td>
</tr>
<tr>
<td>hr</td>
<td>Radiation heat transfer coefficient, Btu/(hr)(sq ft)(°F)</td>
</tr>
<tr>
<td>I</td>
<td>Current flow, amp</td>
</tr>
<tr>
<td>k</td>
<td>Thermal conductivity, Btu/(hr)(sq ft)(°F/ft)</td>
</tr>
<tr>
<td>L</td>
<td>Length, ft</td>
</tr>
<tr>
<td>q</td>
<td>Heat flow, Btu/hr</td>
</tr>
<tr>
<td>RE</td>
<td>Electrical resistance, ohms</td>
</tr>
<tr>
<td>RT</td>
<td>Thermal resistance, hr(°F)/Btu</td>
</tr>
<tr>
<td>t</td>
<td>Temperature, °F</td>
</tr>
<tr>
<td>Δt</td>
<td>Temperature difference at time θ</td>
</tr>
<tr>
<td>Δt₀</td>
<td>Temperature difference at time 0</td>
</tr>
<tr>
<td>V</td>
<td>Voltage potential</td>
</tr>
<tr>
<td>V₀</td>
<td>Voltage potential at time 0</td>
</tr>
<tr>
<td>θ</td>
<td>Time, hr</td>
</tr>
<tr>
<td>σ</td>
<td>Stefan-Boltzmann constant = 0.1713 x 10^-8 Btu/(hr)(sq ft)(°R^4)</td>
</tr>
<tr>
<td>ω</td>
<td>Mass, lb</td>
</tr>
</tbody>
</table>
ELECTRIC CIRCUIT ANALOGY

The basic equations governing the flow of electricity are similar to those governing heat flow; therefore, a close analogy exists between the concepts of an electrical circuit and a "thermal circuit." In complicated heat transfer problems it is often necessary to rely upon this analogy to arrive at the solution.

In the thermal circuit, temperature difference is considered analogous to voltage potential and heat flow is considered analogous to current flow. Thus, the analogous equations

\[ I = \frac{\Delta V}{R_E} \]  
(amp) (144)
\[ q = \frac{\Delta t}{R_T} \]  
(Btu/hr) (145)

Thermal resistance \( R_T \) is evaluated with respect to the mode of heat transfer

\[ R_T = \frac{L}{kA} \]  
for conduction (146)
\[ R_T = \frac{1}{h_c A} \]  
for convection (147)
\[ R_T = \frac{1}{h_r A} \]  
for radiation (148)

where

\[ h_r = \sigma f(T_1^2 + T_2^2)(T_1 + T_2) \]

It is often convenient to use the concept of thermal conductance instead of thermal resistance. Conductance is merely the reciprocal of resistance. Thus

\[ C_T = \frac{kA}{L} \]  
for conduction (149)
\[ C_T = \frac{h_c A}{L} \]  
for convection (150)
\[ C_T = \frac{h_r A}{L} \]  
for radiation (151)

STEADY-STATE AND TRANSIENT PROBLEM SOLUTION

An example of a simple steady-state heat transfer problem utilizing the network method of solution is an insulated round wire carrying an electrical current. The heat generated inside the wire is \( i^2R \) watts, which must be dissipated by conduction through the insulation and by
convection and radiation to the environment. The temperature of the wire \( t_w \) and the ambient temperature \( t_a \) are known. The problem is to determine the amount of heat dissipated and the temperature of the surface of the insulation \( t_s \) (Figure 47). It is convenient to combine \( R_C \) and \( R_R \) into a single resistance as shown in Figure 48.

\[
R_2 = \frac{1}{R_C} + \frac{1}{R_R}
\]

Figure 47. Thermal Network for Insulated Wire

Figure 48. Simplified Thermal Network for Insulated Wire
The total heat loss is given by

\[ q = \frac{t_w - t_a}{R_1 + R_2} \]  \hspace{1cm} (152)

and the surface temperature of the insulation is given by

\[ t_s = \frac{C_1 t_w + C_2 t_a}{C_1 + C_2} \]  \hspace{1cm} (153)

It will be noted that the discussion has been limited to steady-state conditions. However, it is often required to analyze heat transfer problems on a transient basis (i.e., temperature versus time). In this case, the effect of heat capacity must be included. The analogous equations for transient conditions are

\[ V = V_0 e^{-\theta/R_T C_p} \]  \hspace{1cm} (154)

\[ \Delta t = \Delta t_0 e^{-\theta/R_T (\omega c_p)} \]  \hspace{1cm} (155)

where

\[ \Delta t_0 = \text{Temperature difference at time 0} = t_a - t_0 \]

\[ \Delta t = \text{Temperature difference at time} \theta = t_a - t_\theta \]

It is evident that the term \( \omega c_p \) is the thermal capacitance. The thermal circuit for a single node, single resistor transient problem (represented in Equation 155) is shown in Figure 49.

\[ \text{Figure 49. Thermal Network for Single Node, Single Resistor Transient Problem} \]
Multiple node transient heat transfer problems are handled by connecting a thermal capacitance between each node (temperature) and ground. This type of circuit is difficult to solve by hand, and usually requires the use of an analog or digital computer. The network for the temperature distribution versus time in a slab might appear as shown in Figure 50.

Figure 50. Thermal Network for Temperature Distribution Versus Time in Slab
Problems concerning radiation heat transfer involve proper accounting of all interreflections between the various objects, shields, and surfaces being investigated. This can be achieved very satisfactorily by utilizing the radiosity analog network method as developed by A. K. Oppenheim of the University of California (Reference 16). The significance of this technique becomes apparent when interreflections with multiple surfaces are considered. Other methods of analysis, at best, can only approximate interreflections for most cases. The radiosity method presents an analytically exact solution, without need for such items as "modified" configuration factors.

The radiosity method is normally restricted to problems concerning gray bodies; however, problems concerning real bodies can be analyzed if the additional effort is warranted. It should be noted, however, that the analysis is limited to diffuse emission and reflection, but radiation from most surfaces is fortunately in diffuse form.
In describing this technique, it is important to define the radiosity of a surface $J$. Radiosity is the sum of all the emitted, reflected, and transmitted radiant energy streaming away from a surface. For a gray opaque surface, radiosity is the sum of the emitted and reflected radiation and is given by

$$J = rG + \epsilon E$$  \hspace{1cm} (156)$$

where

$$E = \sigma T^4$$

Therefore

$$G = J - \epsilon E \frac{r}{r}$$  \hspace{1cm} (157)$$

Also

$$q_{\text{net}} = A(J - G)$$  \hspace{1cm} (158)$$

Substituting

$$\frac{q_{\text{net}}}{A} = J - \frac{J - \epsilon E}{r} = J - \frac{J}{r} + \frac{\epsilon}{r} E$$

$$= \frac{rJ - J}{r} + \frac{\epsilon}{r} E$$

$$= \frac{(r - 1)J}{r} + \frac{\epsilon}{r} E$$

$$= \frac{\epsilon(E - J)}{r}$$

Therefore

$$\frac{q_{\text{net}}}{A} = \left(\frac{\epsilon}{1 - \epsilon}\right)(E - J)$$  \hspace{1cm} (159)$$

Thus, the net radiation leaving or entering a surface is analogous to the current flow when a potential of $E - J$ is applied across a conductance of $\epsilon A/(1 - \epsilon)$. 

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Furthermore, the direct radiation exchange between any two surfaces $A_1$ and $A_2$ can be expressed as

$$q_{12} = (FA)_{12} J_1 - (FA)_{21} J_2 = (FA)_{12} (J_1 - J_2)$$

(160)

It follows, then, that the net radiation exchange between a surface $A_i$ and its surroundings, consisting of $n$ surfaces, is the total energy impinging on $A_i$ minus the total energy leaving $A_i$, or

$$q_{i(\text{net})} = \sum_{k=1}^{n} (FA)_{ik} (J_k - J_i)$$

(161)

Equations 159 and 161 form the basis for a network completely describing radiation exchange between any number of surfaces. Figure 51 is an example for a four-sided enclosure.

It is often convenient, especially with transient radiation problems and combination radiation-convection-conduction problems, to use a conventional analog network, thus eliminating the floating potential nodes $J$. With this approach it is still possible to account for all the interreflections by using an equivalent conductance $(fA)$ which is readily obtained from the radiosity network (Reference 16).

Briefly, it can be stated that the equivalent conductance $f_{1i}A_1$ between any two potential nodes $1$ and $i$ is equal to the current flowing into node $i$ when it is grounded and short-circuited with all the remaining potential nodes, with the exception of node $1$ on which a potential of unity is imposed. As an example, suppose it is desired to represent the four-sided enclosure of Figure 51 with a conventional network. Note that

$$h_{r12}^2 A_1 = \sigma (FA)_{12} (T_1^2 + T_2^2)(T_1 + T_2)$$

(162)

To determine $(fA)_{12}$, for instance, it would be necessary to use the radiosity network of Figure 51, setting $E_1$ equal to 1.0 and $E_2$, $E_3$, and $E_4$ equal to 0. Solving for $q_{12}$ would then give the desired answer as

$$q_{12} = (fA)_{12} = J_2 \left( \frac{A_2 \epsilon_2}{1 - \epsilon_2} \right)$$

(163)
Figure 51. Radiosity Analog Network for Four-Sided Enclosure

Figure 52. Conventional Analog Network for Four-Sided Enclosure
In a like manner, the equivalent conductances \((fA)_{13}, (fA)_{14}, (fA)_{24}, (fA)_{23},\) and \((fA)_{34}\) can be obtained and then used in the network of Figure 52 for the general solution to the problem.

COMMONLY USED METHODS

One of the earliest relationships for the net heat transfer between two bodies is the simplified equation from Hottel (Reference 17).

\[
q_{12} = \sigma F_e F_a A_1 (T_1^4 - T_2^4)
\]

where

\[
F_a = \text{Configuration factor}
\]

\[
F_e = \text{Factor which includes emissivities allowing for departure of source and receiver from complete blackness and which depends upon } \epsilon_1, \epsilon_2, \text{ and configuration of surfaces.}
\]

A second method developed by Hottel (Reference 18) to evaluate the net exchange between two surfaces is expressed by

\[
q_{12} = \sigma f_{12} A_1 (T_1^4 - T_2^4)
\]

where

\[
f_{12} = \frac{1}{F_{12}} + \frac{1}{\epsilon_1 - 1} + \frac{A_1}{A_2} \left( \frac{1}{\epsilon_2 - 1} \right)
\]

and

\[
F_{12} = \text{Configuration factor from surface 1 to surface 2}
\]

Equations 164 and 165 are limited in application with respect to multiple interreflecting surfaces. An attempt has been made to account for reflecting (refractory) surfaces by replacing the geometric configuration factor \(F\) with a modified configuration factor \(F\), which includes both direct and reflected radiation effects. Values of \(F\) are usually obtained from charts or graphs and are rather limited in application because these graphs are available for certain specific configurations only.
COMPARISON OF ANALYTICAL METHODS

At the present time, a variety of techniques is used to analyze radiation heat transfer problems. The radiosity analog network method is an extremely useful technique for obtaining an exact solution for any type of gray body, multiple-surface configuration. The ray tracing method, to be discussed in the following section, also gives quite accurate results. Extreme care must be exercised, however, in choosing the proper technique for a particular problem. Large errors can occur if the proper technique is not used, particularly in problems where there are multiple reflecting surfaces.

The illustrative examples given here show the variation in results obtained by the different techniques.

Problem 1

Two parallel and equal disks of diameter \( d \) are separated by distance \( \ell \). (See Figure 53.) There are no refractory walls. Calculate the net radiant interchange between the disks.

![Figure 53. Parallel Disks](image)

Given

\[
d = 1.0 \text{ ft} \\
\ell = 0.5 \text{ ft} \\
\epsilon_1 = 0.7 \\
\epsilon_2 = 0.3 \\
t_1 = 500 \text{ F}
\]
Solution 1A

From Reference 17 (Equation 164),

\[ q_{12} = \sigma F_e F_a A_1 (T_1^4 - T_2^4) \]

where

\[ F_e = \epsilon_1 \epsilon_2 = 0.21 \text{ (p 56, case 10, Reference 17)} \]

\[ F_a = 0.37 \]

\[ A_1 = \pi r^2 = \pi (0.5)^2 = 0.786 \text{ sq ft} \]

\[ T_1 = 500 + 460 = 960 \text{ °R} \]

\[ T_2 = 100 + 460 = 560 \text{ °R} \]

\[ \sigma = 0.1713 \times 10^{-8} \text{ Btu/(hr)(sq ft)(°R)} \]

Therefore

\[ q_{12} = 0.1713 (0.21)(0.37)(0.786)(9.6^4 - 5.6^4) \]
\[ = 0.1713 (0.21)(0.37)(0.786)(8500 - 983) \]
\[ = 0.1713 (0.21)(0.37)(0.786)(7517) = 78.6 \text{ Btu/hr} \]

Solution 1B

From Reference 18 (Equation 165),

\[ q_{12} = \sigma f_{12} A_1 (T_1^4 - T_2^4) \]

where

\[ f = \frac{1}{F_{12}} + \frac{1}{\epsilon_1} - 1 + \frac{A_1}{A_2} \left( \frac{1}{\epsilon_2} - 1 \right) \]
\[ \epsilon_1 = 0.7 \]
\[ \epsilon_2 = 0.3 \]
\[ F_{12} = 0.37 \]

and where

\[ F = \frac{1}{0.37 + 0.7 - 1 + 1 \left( \frac{1}{0.3} - 1 \right)} \]
\[ = \frac{1}{2.7 + 1.429 - 1 + 3.33 - 1} \]
\[ = \frac{1}{5.462} = 0.183 \]

Therefore

\[ q_{12} = 0.1713 \times (0.183)(0.786)(9.6^4 - 5.6^4) \]
\[ = 0.1713 \times (0.183)(0.786)(7517) = 185.1 \text{ Btu/hr} \]

Solution 1C (Radiosity Network)
As shown in Figure 54,

\[ E_1 = \sigma T_1^4 = 0.1713 \times (9.6^4) = 1456 \]

\[ E_2 = \sigma T_2^4 = 0.1713 \times (5.6^4) = 168.4 \]

\[ C_1 = \frac{1}{R_1} = \frac{\epsilon_1 A_1}{1 - \epsilon_1} = \frac{0.7 \times (0.786)}{1 - 0.7} = 1.833 \]

\[ C_2 = \frac{1}{R_2} = F_{12} A_1 = 0.37 \times (0.786) = 0.2908 \]

\[ C_3 = \frac{1}{R_3} = \frac{\epsilon_2 A_2}{1 - \epsilon_2} = \frac{0.3 \times (0.786)}{1 - 0.3} = 0.3372 \]

\[ C_4 = \frac{1}{R_4} = F_{13} A_1 = 0.63 \times (0.786) = 0.495 \]

\[ C_5 = \frac{1}{R_5} = F_{23} A_2 = 0.63 \times (0.786) = 0.495 \]

Since there are no refractory walls, the irradiation from the surroundings is zero and \( J_3 = 0 \). To calculate \( q_{12} \), it is necessary to determine the equivalent conductance \( (fA)_{12} \). Let \( E_1 = 1.0, E_2 = 0, J_3 = 0 \) (Figure 55).

Figure 55. Radiosity Network for Determining Equivalent Conductance
Solving for $J_1'$ and $J_2'$

\[
C_1 (E_1 - J_1') + C_4 (J_3 - J_1') + C_2 (J_2' - J_1') = 0
\]

\[
C_3 (E_2 - J_2') + C_5 (J_3 - J_1') + C_2 (J_1' - J_2') = 0
\]

\[
1.833 \left(1 - J_1'\right) + 0.495 (0 - J_1') + 0.2908 (J_2' - J_1') = 0
\]

\[
0.3372 (0 - J_2') + 0.495 (0 - J_2') + 0.2908 (J_1' - J_2') = 0
\]

\[
1.833 + 0.2908 J_2' - 2.6188 J_1' = 0
\]

\[
0.2908 J_1' - 1.1230 J_2' = 0
\]

\[
J_1' = 3.86 J_2'
\]

\[
J_2' = 0.1868
\]

Therefore

\[
(fA)_{12} = C_3 (J_2 - 0) = 0.3372 (0.1868) = 0.063
\]

and

\[
q_{12} = \sigma(fA)_{12} \left(T_1^4 - T_2^4\right)
\]

\[
= 0.1713 (0.063) (9.6^4 - 5.6^4) = 81.2 \text{ Btu/hr}
\]

Discussion of Problem 1

If Problem 1 were recalculated for the case where $F_{12}$ was 0.9 instead of 0.37, the following comparison could be made:

<table>
<thead>
<tr>
<th>Method</th>
<th>$F_{12} = 0.37$</th>
<th>$F_{12} = 0.9$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equation 164</td>
<td>78.6 Btu/hr</td>
<td>191 Btu/hr</td>
</tr>
<tr>
<td>Equation 165</td>
<td>185.1 Btu/hr</td>
<td>262 Btu/hr</td>
</tr>
<tr>
<td>Radiosity network</td>
<td>81.2 Btu/hr</td>
<td>231 Btu/hr</td>
</tr>
</tbody>
</table>

As Oppenheim has pointed out in his paper (Reference 16), the radiosity network gives the exact solution to radiant interchange problems, with the basic stipulation that the radiant energy be in diffuse form. Thus it can be stated that the answers obtained by use of the radiosity network for both cases of problem 1 are the correct results. These are presented in the table above as 81.2 and 231 Btu/hour, respectively. Equation 164 is correct for the first case but is about 20 percent in error in the second case. Equation 165 is over 100 percent in error in the first case and about 15 percent in error in the second.
Problem 2

Given

To show the effect of reflecting surfaces, let the configuration of Problem 2 be enclosed with a single reflecting (refractory) surface. It is assumed that the reflecting wall reflects all the incident radiation.

Solution 2A

From Reference 17 (Equation 164),

\[ q_{12} = \sigma F_e F_a A_1 (T_1^4 - T_2^4) \]

where

\[ F_e = \varepsilon_1 \varepsilon_2 = 0.21 \text{ (p 56, case 10, Reference 17)} \]

\[ F_a = \frac{F}{F_a} = 0.64 \text{ (Figure 4-7, p 57, Reference 17)} \]

Therefore

\[ q_{12} = 0.1713 \times 0.21 \times 0.64 \times 0.786 \times (9.6^4 - 5.6^4) \]

\[ = 0.1713 \times 0.21 \times 0.64 \times 0.786 \times 7517 = 136 \text{ Btu/hr} \]

Solution 2B

From Reference 18 (Equation 165),

\[ q_{12} = \sigma f_{12} A_1 (T_1^4 - T_2^4) \]

where

\[ f_{12} = \frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1 + \frac{A_1}{A_2} \left( \frac{1}{\varepsilon_2} - 1 \right) \]

\[ \varepsilon_1 = 0.7 \]

\[ \varepsilon_2 = 0.3 \]

\[ \frac{F}{F_{12}} = 0.64 \]

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Therefore

\[ f_{12} = \frac{1}{0.64 + \frac{1}{0.7} - 1 + \frac{1}{0.3 + 1}} \]

\[ = \frac{1}{1.563 + 1.429 - 1 + 3.333 - 1} = 0.231 \]

and

\[ q_{12} = 0.1713 \times 0.231 \times 0.786 \times 7517 = 234 \text{ Btu/hr} \]

**Solution 2C (Radiosity Network)**

As shown in Figure 56,

\[ E_1 = \sigma T_1^4 = 1456 \]

\[ E_2 = \sigma T_2^4 = 168.4 \]

and

\[ C_1 = 1.833 \]

\[ C_2 = 0.2908 \]

\[ C_3 = 0.3372 \]

\[ C_4 = 0.495 \]

\[ C_5 = 0.495 \]

Since there is no current in \( R_6 \), the radiosity of the reflecting surface \( J_R \) must equal \( E_R \). This shows that the reflectivity of a perfectly insulated reflecting surface is completely ineffective because the addition of a surface resistor such as \( R_6 \) has no effect on the network.
Figure 56. Radiosity Network for Problem 2

\[ E_2 = \sigma T_2^4 \]

\[ E_1 = \sigma T_1^4 \]

\[ R_4 = \frac{1}{C_4} = \frac{1}{0.495} = 2.02 \]

\[ R_5 = \frac{1}{C_5} = \frac{1}{0.495} = 2.02 \]

\[ R_{4,5} = R_4 + R_5 = 4.04 \]

\[ C_{4,5} = \frac{1}{R_{4,5}} = \frac{1}{4.04} = 0.2475 \]

\[ C_{2,4,5} = C_2 + C_{4,5} = 0.2908 + 0.2475 = 0.5383 \]

\[ R_{2,4,5} = \frac{1}{C_{2,4,5}} = \frac{1}{0.5383} = 1.858 \]

\[ R_1 = \frac{1}{C_1} = \frac{1}{1.833} = 0.546 \]
\[ R_3 = \frac{1}{C_3} = \frac{1}{0.3372} = 2.97 \]

\[ R_{\text{total}} = R_1 + R_{2,4,5} + R_3 = 0.546 + 1.858 + 2.97 = 5.374 \]

Therefore

\[ q_{12} = \frac{1}{R_{\text{total}}} (E_1 - E_2) \]

\[ = \frac{1}{5.374} (1456 - 168.4) \]

\[ = \frac{1287.6}{5.374} = 240 \text{ Btu/hr} \]

Discussion of Problem 2

Problem 2 is summarized as follows:

- Equation 164: 136 Btu/hr
- Equation 165: 234 Btu/hr
- Radiosity network: 240 Btu/hr

In the case where interreflecting surfaces are present, it can be seen that Equation 164 is in considerable error even with the use of a modified \( F_a \). In this case, however, Equation 165 is close to the correct answer of 240 Btu/hour.

In reviewing the results of Problems 1 and 2, it is concluded that Equations 164 and 165 are correct only if they are chosen with care to suit the problem at hand. The radiosity network method of analysis, however, is always correct for cases involving diffuse radiation.
RAY TRACING ANALYSIS METHOD

Very accurate results may be obtained from the ray tracing method of heat transfer analysis. Unfortunately, however, the method is difficult to use without a high-speed digital computer because of the lengthy and tedious calculations involved. A method has been developed whereby this technique can be programmed for an IBM 704 or 709 computer (Reference 19), although the programming has not yet been done. The material for this discussion was supplied by the Los Angeles division of North American Aviation.

NOMENCLATURE

\[a\] \hspace{1cm} \text{Area of surface}

\[e\] \hspace{1cm} \text{Monochromatic emissivity power of black surface at particular surface temperature and wavelength}

\[f\] \hspace{1cm} \text{Configuration form factor}

\[q\] \hspace{1cm} \text{Heat flow}

\[u\] \hspace{1cm} \text{Energy emitted by surface}

\[v\] \hspace{1cm} \text{Energy received by surface}

\[W\] \hspace{1cm} \text{Energy absorbed by surface}

\[\epsilon\] \hspace{1cm} \text{Emissivity}

\[\lambda\] \hspace{1cm} \text{Wavelength}

\[\rho\] \hspace{1cm} \text{Reflectance}

RADIANT INTERCHANGE ANALYSIS

This discussion is concerned with an enclosure made up of a finite number of finite surfaces. The enclosure contains a nonabsorbing media. Each of the surfaces of this enclosure is considered to be opaque, homogeneous, diffusely reflecting, uniformly irradiated, and at a uniform temperature. The \(i\)th surface of this \(n\) surface enclosure emits radiant energy in the amount

\[u_i = a_i (1 - \rho_{i,j}) e_{i,j} (\Delta \lambda_j) \quad (j = 1, 2, \ldots, p) \quad (166)\]
where

\[ a_i = \text{Area of } i^{th} \text{ surface} \]

\[ \rho_{i,j} = \text{Reflectance of } i^{th} \text{ surface for radiation of average wavelength } \lambda_j \text{ in narrow wavelength band of } (\Delta \lambda)_j \]

\[ e_{i,j} = \text{Monochromatic emissive power of black surface at temperature of } i^{th} \text{ surface and at wavelength } \lambda_j \]

The term reflectance describes the behavior of a particular specimen, while reflectivity is reserved to describe the behavior of the material itself (i.e., the reflectance of a highly polished specimen of a material is numerically equal to the reflectivity of that material).

The right-hand side of Equation 166 actually represents \( p \) terms where \( p \) is the number of wavelength bands into which the important part of the electromagnetic spectrum has been divided. This notation convention will be used throughout this discussion. That is, whenever a subscript appears two or more times in any product on the right-hand side of an equation and does not appear on the left-hand side of that equation, it is to be understood that the product in question is to be summed on the subscript, as the subscript takes on all of its possible identities.

The \( i^{th} \) surface receives from the \( n \) surfaces directly emitted radiation which has suffered no reflections in passing from the originating surface to the \( i^{th} \) surface. This energy is in the amount

\[ o_{i,j} = u_{k,j} f_{ki} \quad (k = 1, 2 \ldots n) \quad (167) \]

where

\[ f_{ki} = \text{Configuration factor from } k^{th} \text{ to } i^{th} \text{ surface} \]

In Equation 167, the subscript \( o \) denotes the fact that no reflections have taken place in the transfer of the energy.

Of the energy \( o_{i,j} \), the \( i^{th} \) surface absorbs

\[ w_{i,j} = (1-\rho_{i,j}) u_{k,j} f_{ki} \quad (168) \]

where, in the general case,

\[ o_{i,j} = \sum_{j=1}^{P} o_{i,j} \quad (169) \]
Energy which has suffered $\beta$ reflections before reaching the $i^{th}$ surface is

$$\beta^v_{i,j} = u_{k,j}^t P_{k\ell} j t m^\rho_m, j m n^\rho_n, j i = \ldots f_{si}$$  \hspace{1cm} (170)

The amount of this energy absorbed by the $i^{th}$ surface is

$$\beta^w_{i,j} = (u_{k,j}^f P_{k\ell} j t m^\rho_m, j m n^\rho_n, j i = \ldots f_{si})(1 - \rho_{i,j})$$  \hspace{1cm} (171)

An energy balance on the $i^{th}$ surface for radiation of average wavelength $\lambda_j$ is

$$q_{i,j} = u_{i,j} \frac{\sum_{\beta=0}^\infty \beta^w_{i,j}}{\beta}$$  \hspace{1cm} (172)

That is,

$$q_{i,j} = u_{i,j} - (1 - \rho_{i,j}) (u_{k,j}^f P_{k\ell} j t m^\rho_m, j m n^\rho_n, j i = \ldots f_{si})$$

$$+ u_{k,j}^f P_{k\ell} j t m^\rho_m, j m n^\rho_n, j i = \ldots$$  \hspace{1cm} (173)

where the energy $q_j$, which must be added to or removed from the $i^{th}$ surface to take into account the differences between the radiant energy leaving and entering the surface, is

$$q_i = \sum_{j=0}^\infty q_{i,j}$$  \hspace{1cm} (174)

The form of Equation 173 is not suited to computations. Therefore, the procedures are directed toward obtaining forms of the energy balance equation that are more suitable for computation. The terms can be written as a product of certain matrices. For example,

$$\alpha^v_{i,j} = u_{k,j}^f f_{ki} = \left[ u_{1,j}^u u_{2,j} u_{n,j} \right] \left[ \begin{array}{c} f_{1i} \\ f_{2i} \\ \vdots \\ f_{ni} \end{array} \right] = U_j F(l)$$  \hspace{1cm} (175)
and

\[ v_{i,j} = u_{k,j} \rho_{i,k} j_{i,k} \]

\[ = \begin{bmatrix} u_{i,j} u_{2,j} \cdots u_{n,j} \end{bmatrix} \begin{bmatrix} f_{11} & f_{12} & \cdots & f_{1n} \\ f_{21} & f_{22} & \cdots & f_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ f_{n1} & f_{n2} & \cdots & f_{nn} \end{bmatrix} \begin{bmatrix} \rho_{1,j} & 0 & \cdots & 0 \\ 0 & \rho_{2,j} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \rho_{n,j} \end{bmatrix} \begin{bmatrix} f_{1j} \\ f_{2j} \\ \vdots \\ f_{nj} \end{bmatrix} \]

\[ = U_i F R_j F(i) \] (176)

The capital letters are reserved for matrix quantities unless otherwise stated. That is

\[ U_j = \begin{bmatrix} u_{1,j} u_{2,j} \cdots u_{n,j} \end{bmatrix} \] (177)

\[ F = \begin{bmatrix} f_{11} & f_{12} & \cdots & f_{1n} \\ f_{21} & f_{22} & \cdots & f_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ f_{n1} & f_{n2} & \cdots & f_{nn} \end{bmatrix} \] (178)

\[ R_j = \begin{bmatrix} \rho_{1,j} & 0 & \cdots & 0 \\ 0 & \rho_{2,j} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \rho_{n,j} \end{bmatrix} \] (179)

\[ F(i) = \begin{bmatrix} f_{1i} \\ f_{2i} \\ \vdots \\ f_{ni} \end{bmatrix} \] (180)

Equation 173 can be written in the form

\[ q_{i,j} = u_{i,j} - (1 - \rho_{i,j}) \left( U_i F(i) + U_i F R_j F(i) + U_i F R_j F R_j F(i) + \ldots \right) \] (181)
or
\[ q_{i,j} = u_{i,j} - (1 - \rho_{i,j})u_j \left[ I + (FR_j) + (FR_j)^2 + (FR_j)^3 + \ldots \right] F(l) \] (182)

where
\[ I = \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \end{bmatrix} \] (183)

It can be shown that
\[ \left[ I + (FR_j) + (FR_j)^2 + (FR_j)^3 + \ldots \right] = \left[ I - FR_j \right]^{-1} \] (184)

where
\[ \left[ I - FR_j \right]^{-1} \] is the inverse of the matrix \[ I - FR_j \]

Finally, Equation 173 may be written in the form
\[ q_{i,j} = u_{i,j} - (1 - \rho_{i,j})u_j \left[ I - FR_j \right]^{-1} F(l) \] (185)

The total net energy leaving or entering surface \( i \) is
\[ q_i = u_i - (1 - \rho_{i,j})u_j \left[ I - FR_j \right]^{-1} F(l) \] (186)

The matrix equation for the entire system of \( n \) equations is
\[ Q = U - (I - R_j)U_j \left[ I - FR_j \right]^{-1} F \] (187)

where
\[ Q = \begin{bmatrix} q_1 & q_2 & \cdots & q_n \end{bmatrix} \] (188)

and
\[ U = \begin{bmatrix} U_1 & U_2 & \cdots & U_n \end{bmatrix} \] (189)
DIGITAL COMPUTATION

For the purpose of digital computations of heat transfer and temperatures of n surfaces, equations in the form of Equation 186 will be used. Let

\[
C_j = \left[ I - FR_j \right]^{-1} \begin{bmatrix}
C_{11,j} & C_{12,j} & \cdots & C_{1n,j} \\
C_{21,j} & C_{22,j} & \cdots & C_{2n,j} \\
\vdots & \vdots & \ddots & \vdots \\
C_{n1,j} & C_{n2,j} & \cdots & C_{nn,j}
\end{bmatrix}
\]  

(190)

The matrix product in Equation 186 can be shown to be

\[
U_j \left[ I - FR_j \right]^{-1} F(i) = u_{1,j} (C_{11,j} f_{11} + C_{21,j} f_{21} + \cdots + C_{1n,j} f_{1n}) \\
+ u_{2,j} (C_{12,j} f_{12} + C_{22,j} f_{22} + \cdots + C_{2n,j} f_{2n}) \\
\vdots \\
+ u_{n,j} (C_{n1,j} f_{1n} + C_{n2,j} f_{2n} + \cdots + C_{nn,j} f_{nn})
\]

(191)

Planck's equation gives the relationship for monochromatic emissive power of an ideal radiator at temperature T_i.

\[
e_{i,j} = \frac{C_1 \lambda_j^{-5}}{\exp\left(\frac{C_2}{\lambda_j T_i}\right) - 1}
\]

(192)

where \(C_1 = 1.18070 \times 10^8\) Btu (microns)^4/(hour)(square foot) and \(C_2 = 25896\) microns (^°R), where microns is the measure of wavelength.

Let

\[
y_{i,j} = \frac{C_1 \lambda_j^{-5}(\Delta \lambda)_j}{\exp\left(\frac{C_2}{\lambda_j T_i}\right) - 1} \text{ Btu/(hr)(sq ft)}
\]

(193)

Then
\( U_j \left[ I - FR_j \right]^{-1} F(i) = a_1(1 - \rho_1, j)y_1, j (C_{11}, j f_{11} + C_{12}, j f_{21} + \ldots + C_{1n}, j f_{n1}) \\
+ a_2(1 - \rho_2, j)y_2, j (C_{21}, j f_{21} + C_{22}, j f_{22} + \ldots + C_{2n}, j f_{n1}) \\
\vdots \hspace{2cm} \vdots \hspace{2cm} \vdots \\
+ a_n(1 - \rho_n, j)y_n, j (C_{n1}, j f_{n1} + C_{n2}, j f_{21} + \ldots + C_{nn}, j f_{nn}) \\
\) \tag{194}

Let
\[ C_{\epsilon k}, j f_{ki} = \left[ C_{\epsilon 1}, j f_{1i} + C_{\epsilon 2}, j f_{2i} + \ldots + C_{\epsilon n}, j f_{ni} \right] \] \tag{195}
so that
\[ U_j \left[ I - FR_j \right]^{-1} F(i) = a_\epsilon \epsilon, j y_\epsilon, j C_{\epsilon k}, j f_{ki} \left( \begin{array}{c} \epsilon_k \\ \end{array} \right) = 1, 2 \ldots n \] \tag{196}

where
\[ \epsilon_i, j = 1 - \rho_i, j \] \tag{197}

From Equation 186,
\[ q_i = a_i \epsilon_i, j y_i, j - a_i \epsilon_i, j \epsilon_i, j y_i, j C_{\epsilon k}, j f_{ki} \] \tag{198}
or
\[ q_i \epsilon_i, j + a_1 \epsilon_i, j y_1, j C_{\epsilon k}, j f_{ki} + \ldots + a_i \epsilon_i, j y_i, j \epsilon_i, j f_{ki} - 1 \] \tag{199}

The system of n equations may be written in the form
\[ \begin{align*}
q_1 + d_{11}, j y_1, j + \ldots + d_{1n}, j y_n, j & = 0 \\
\vdots & \vdots \\
q_i + d_{i1}, j y_1, j + \ldots + d_{in}, j y_n, j & = 0 \\
\vdots & \vdots \\
q_n + d_{n1}, j y_1, j + \ldots + d_{nn}, j y_n, j & = 0
\end{align*} \] \tag{200}
where

$$d_{a\beta} = a_{\beta} \epsilon_{a, j}(\epsilon_{\alpha, j} C_{\beta k} f_{\gamma a} - \delta_{a \beta})$$  \hspace{1cm} (201)$$

where $\delta_{a \beta}$ is the Kronecker delta and

$$\delta_{a \beta} = \begin{cases} 
1 & \text{if } a = \beta \\
0 & \text{if } a \neq \beta
\end{cases}$$

The quantity $q_i$ may be heat that is conducted or convected to the surface $i$ or it may be that generated internally in the material of surface $i$. Therefore, in general, the system of equations to be solved for the unknown temperatures $T_1, T_2, \ldots, T_i, \ldots, T_n, T_a, T_b, \ldots$ is

$$
\begin{align*}
d_{11,j1,j} + d_{1n,jn,j} + d_{1l} T_1 + \ldots + d_{1n} T_n + d''_{1} T_a + d''_{1b} T_b + \ldots + \eta_1 &= 0 \\
& \vdots \quad \vdots \quad \vdots \\

\end{align*}
$$

$$
\begin{align*}
d_{11,j1,j} + d_{1n,jn,j} + d_{1l} T_1 + \ldots + d_{1n} T_n + d''_{1} T_a + d''_{1b} T_b + \ldots + \eta_1 &= 0 \\
& \vdots \quad \vdots \quad \vdots \\

\end{align*}
$$

$$
\begin{align*}
d_{nn,jn,j} + d_{nn} T_n + \ldots + d''_{nn} T_n + d''_{na} T_a + d''_{nb} T_b + \ldots + \eta_n &= 0 \\
\end{align*}
$$

Other equations containing only $T_s$ to the first power equal zero.  \hspace{1cm} (202)

where $T_a, T_b, \text{ and so forth, are temperatures of elements of the system which are not involved in the radiant energy interchange. All terms having the primed coefficients are reserved, of course, for conduction and convection. This assumes that the conduction and convection of energy can be written in such a manner that only the first powers of the temperatures are involved. The $\eta$ terms are reserved for internal energy generation within elements of the system.}

It should be noted that this analysis has been set up using the assumption that Lambert's cosine law adequately defines the space density of emitted and reflected radiation. Obviously, this is not the physical case. A more exact analysis would include the variation of space density of reflected and emitted radiation. However, because no such data are now available and because such a numerical analysis would be complex for even the most advanced computing machines, it has not appeared necessary that these more accurate descriptions of the actual physical system be included at this time.
The preceding analysis is general for the case of varying values of reflectance with wavelength. Here, again, it would be a major task to actually sum across the spectrum and at the same time solve the required set of nonlinear equations. Therefore, as a first step in probing such solutions, it has been decided that a gray body analysis should be used. This simply means that the quantity \( y \) will be replaced by \( \sigma T^4 \). This assumption, of course, has been used many times in the past even though it often leads to inaccurate solutions. It is not, then, necessary to sum on \( j \) in the expression for \( \bar{d}_\alpha \beta \) in Equation 201.
DISCUSSION OF ASSUMPTIONS

1. The methods of analysis discussed in this section have the common restriction that radiant energy is emitted or reflected in diffuse form, as opposed to specular form. A satisfactory method of handling partly diffuse, partly specular radiation has not yet been devised. Fortunately, most thermal radiation encountered in engineering applications can be considered to be in diffuse form.

2. The radiosity network method is usually applied only to gray body radiation and is so used in this report. Methods have been developed whereby non-gray radiation can be treated, but this is considered beyond the scope of this report.
One of the most difficult areas in the analysis of radiation heat transfer is proper calculation of the geometric configuration factor. Basically, the configuration factor $F_{12}$ from $A_1$ to $A_2$ is defined as the fraction of the total radiant flux leaving $A_1$ that is incident upon $A_2$. The configuration factor from a plane point source to a finite surface (commonly known as a differential-finite configuration factor) is obtained by integration over $A_2$, and the mean configuration factor from a finite source (finite-finite configuration factor) is the average of the point configuration factors over the finite source. The integral expression for the differential-finite configuration factor from $dA_1$ to $A_2$ is given by

$$F(dA_1 - A_2) = \frac{1}{\pi} \int_{A_2} \frac{\cos \theta_1 \cos \theta_2 \, dA_2}{S^2}$$

(203)

The integral expression for the finite-finite configuration factor from $A_1$ to $A_2$ is given in the Section III discussion on radiant heat exchange between surfaces.

$$F_{12} = \frac{1}{A_1 \pi} \int_{A_1} \int_{A_2} \frac{\cos \theta_1 \cos \theta_2}{S^2} \, dA_1 \, dA_2$$

(204)

As an example (from Reference 20) consider the two mutually perpendicular surfaces shown in Figure 57. The left-hand corner of the horizontal surface is assumed to be the origin, with the $x$, $y$, and $z$ axes as shown. The horizontal surface has overall dimensions of $D$ and $W$ while those of the vertical are $H$ and $W$. Thus

$$F_{12} = \frac{1}{WD\pi} \int_{A_1} \int_{A_2} \frac{\cos \theta_1 \cos \theta_2}{S^2} \, dA_1 \, dA_2$$

(205)
where \( \cos \theta_1 = \frac{z}{s} \)

\[ \cos \theta_2 = \frac{D - y}{s} \]

\[ s = \sqrt{(x_2 - x_1)^2 + (D - y)^2 + z^2} \]

and

\[ dA_1 = dx_1 \, dy \]

\[ dA_2 = dx_2 \, dz \]

Figure 57. Geometry for Calculation of Configuration Factor for Two Mutually Perpendicular Surfaces
Integrating Equation 206 yields

\[ F'_{12} = \frac{1}{WD\pi} \left\{ \frac{1}{4} \left[ (D^2 - W^2 + H^2) \ln (D^2 + H^2 + W^2) 
- (D^2 + H^2) \ln (D^2 + H^2) - (D^2 - W^2) \ln (D^2 + W^2) \right] 
- \frac{1}{WD\pi} \left[ \frac{1}{4} \left[ (H^2 - W^2) \ln (H^2 + W^2) - D^2 \ln D^2 - H^2 \ln H^2 + W^2 \ln W^2 \right] 
+ \frac{1}{WD\pi} \left[ HW \tan^{-1} \frac{W}{H} + DW \tan^{-1} \frac{W}{D} - W \sqrt{D^2 + H^2} \tan^{-1} \frac{W}{\sqrt{D^2 + H^2}} \right] \right\} \] (207)

It can be seen that the integration process is often tedious, even for simple shapes such as in the example. In fact, for most cases the integration cannot be solved analytically and other means must be used to obtain the answer. Under these circumstances the following approach can be utilized:

1. If the areas in question can be assumed infinite in one direction, there are several very simple and rapid methods available with which to obtain the configuration factor.

2. If step 1 does not fit the problem, the next step is to use tables and charts which are available for specific configurations. These are discussed in this section and provide solutions to a number of different configurations, with the help of form factor algebra.

3. If the previous steps are not adequate, there is available an IBM program which calculates the configuration factor between any two plane areas if they are in the form of parallelograms.
4. The method that can be used where all other methods prove to be inadequate is called the unit sphere method. This is a highly accurate technique, although unfortunately it is rather tedious. Most mechanical integrators are based on the unit sphere principle.

A most useful method for evaluating the configuration factor between surfaces infinite in one direction is called the "string" method and is presented in Reference 21 (p 66-68).

Consider the enclosure of Figure 58. It is desired to compute the configuration factor from surface $A_1$ to surface $A_2$. A minimum-length line is stretched over the surface connecting edge B of $A_1$ to edge E of $A_2$ (dotted line BCDE) as well as a minimum-length line from edge L of $A_1$ to edge F of $A_2$ (line LKJHGF). A minimum-length line is now stretched from B to F (line BHGF) a second line from L to E (line LKJE). The configuration factor $F_{12}$ can then be obtained from the expression

$$A_1F_{12} = A_2F_{21} = \frac{(LKJE + BHGF) - (BCDE + LKJHGF)}{2}$$

(208)
Equation 208 states that the AF product between two surfaces, per unit of length normal to the sketch of Figure 58, is the sum of the lengths of crossed strings stretched between the ends of the lines representing the two surfaces, less the sum of the lengths of uncrossed strings similarly stretched between the surfaces, all divided by 2.

Another useful method is that which calculates the configuration factor from a differential area to an infinitely long surface (Figure 59). Surface $A_2$ is any surface generated by an infinitely long line moving parallel to itself and to the plane $dA_1$.

$$F(dA_1-A_2) = \frac{1}{2} (\cos \phi - \cos \theta)$$  \hspace{1cm} (209)

Figure 59. Diagram of Differential Area and Infinitely Long Surface

There is some error involved if $A_2$ is not infinitely long in one direction. However, if the length is greater than twice the distance from $A_1$ to $A_2$, the error is less than 10 percent. For small surfaces, the configuration factor can be found for two directions and averaged.

Equation 209 can be applied for several points along a finite surface $A_1$ and then averaged. This results in a fairly small error if sufficient points are taken.

Instead of calculating each point, it is simpler to draw the bodies to scale and use Figure 60, which is a graphical solution of Equation 209. The origin should be placed at several points on one shape to obtain an average configuration factor. Figure 61 also can be utilized in this way.
Figure 60. Differential Area Shape Factor for T
Figure 60. Differential Area Shape Factor for Two-Dimensional Case
Figure 61. Shape Modulus From Differential Area to Lune

\[ F_{dA, L} = \frac{1}{2} (\sin \theta_1 + \sin \theta_2) \]
TABULATED DATA

DATA OF REPORT NACA TN 2836

One of the most widely used sources of tabulated configuration factor data is report NACA TN 2836, "Radiant - Interchange Configuration Factors," D. C. Hamilton and W. R. Morgan of Purdue University, December 1952 (Reference 22). This report includes configuration factor data for the following shapes:

1. A plane point source $dA_1$ and a plane rectangle $A_2$ parallel to the plane of $dA_1$

2. A plane point source $dA_1$ and a plane rectangle $A_2$, the planes of $dA_1$ and $A_2$ intersecting at an angle $\phi (0^\circ < \phi < 180^\circ)$

3. A plane point source $dA_1$ and any surface $A_2$ generated by an infinitely long line moving parallel to itself and to the plane of $dA_1$

4. A plane point source $dA_1$ and any infinite plane $A_2$ with the planes of $dA_1$ and $A_2$ intersecting at an angle $\theta$

5. A spherical point source $dA_1$ and a plane rectangle $A_2$

6. A plane point source $dA_1$ and a plane circular disk $A_2$

7. A plane point source $dA_1$ and a plane disk $A_2$, the planes of $dA_1$ and $A_2$ intersecting at an angle of 90 degrees

8. A plane point source $dA_1$ and a right circular cylinder $A_2$

9. Two concentric cylinders with a point source $dA_1$ on the inside of the large cylinder at one end

10. Same geometry as shape 2 with a triangular area added to the top of $A_2$

11. Same as shape 10 with the triangle reversed

12. An infinitely long cylinder $A_1$ and an infinite plane $A_2$, mutually parallel
13. A line source $dA_1$ and a plane rectangle $A_2$ parallel to the plane of $dA_1$ with $dA_1$ opposite one edge of $A_2$

14. A line source $dA_1$ and a plane rectangle $A_2$ which intersects the plane of $dA_1$ at an angle $\phi$

15. A line source $dA_1$ and a right circular cylinder $A_2$ parallel to $dA_1$

16. Two concentric cylinders with a line source $dA_1$ on the inside of the large cylinder. The outside cylinder is $A_1$, the inside cylinder is $A_2$

17. Same geometry as shape 16, calculates configuration factor from $dA_1$ to the ends of the concentric cylinders

18. Identical, parallel, directly opposed rectangles

19. Two rectangles $A_1$ and $A_2$ with one common edge and an included angle $\phi$ between the two planes

20. Parallel, directly opposed, plane, circular disks

In addition to the graphical and tabular data presented in this report, the integrated equations of many of the shapes are given. Form factor algebra and basic theory are also presented.

DATA OF CONVAIR (FORT WORTH) STUDY

This discussion presents the results of a study conducted by the Fort Worth Division of Convair to determine the configuration factors for various shapes (Reference 23). No attempt has been made to present the derivation of the equations presented herein. A complete development of the equations can be found in Reference 23.

It should be noted that some of the integrations cannot be performed analytically and numerical methods are required.

Parallel Planes

For nodes 1 and 2, as defined in Figure 62, lying on parallel planes, the black body interchange factor is defined by the following equations.
\[ F_{12} = \frac{1}{\pi A_1} \left[ f_1(\beta-b, \delta-c) - f_1(\beta-a, \delta-c) + f_1(a-a, \delta-c) - f_1(a-b, \delta-c) \right. \\
\left. + f_1(a-b, \gamma-c) - f_1(a-a, \gamma-c) + f_1(\beta-a, \gamma-c) \\
- f_1(\beta-b, \gamma-c) + f_1(\beta-b, \gamma-d) - f_1(\beta-a, \gamma-d) + f_1(a-a, \gamma-d) \\
- f_1(a-b, \gamma-d) + f_1(a-b, \delta-d) - f_1(a-a, \delta-d) + f_1(\beta-a, \delta-d) \\
- f_1(\beta-b, \delta-d) \right] \] (210)

where the function \( f_1 \) is defined by

\[ f_1(\nu, \xi) = \frac{1}{2} \left( E \nu \tan^{-1} \frac{\nu}{E} - \xi \sqrt{E^2 + \nu^2} \tan^{-1} \frac{\xi}{\sqrt{E^2 + \nu^2}} \right. \\
- \nu \sqrt{E^2 + \xi^2} \tan^{-1} \left. \frac{\nu}{\sqrt{E^2 + \xi^2}} + \frac{E^2}{2} \ln \frac{E^2 + \nu^2 + \xi^2}{E^2 + \xi^2} \right) \] (211)
For nodes 1 and 2, as defined in Figure 62 with \( \gamma = c = 0 \) and \( \delta = d = \infty \), lying on parallel planes (i.e. infinite strips), the black body interchange factor is defined by

\[
F_{12} = \frac{1}{2(\beta - a)} \left( \sqrt{E^2 + (\beta - a)^2} - \sqrt{E^2 + (\beta - b)^2} \right) + \frac{\sqrt{E^2 + (a-b)^2}}{E^2 + (a-b)^2} \]  

\[ \sqrt{E^2 + (a-b)^2} - \sqrt{E^2 + (a-a)^2} \]  

(212)

- Figure 63. Nodes on Skewed Planes

**Skewed Planes**

For nodes 1 and 2, as defined in Figure 63, lying on nonparallel planes, the black body interchange factor is defined

\[
F_{12} = \frac{1}{\pi A_1} \left( f_2(b-a, d) - f_2(b-a, c) + f_2(b-\beta, c) - f_2(b-\beta, d) + f_2(a-\beta, d) - f_2(a-\beta, c) + f_2(a-a, c) - f_2(a-a, d) \right) 
\]

(213)

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where the function $f_2$ is defined by

$$f_2(\xi, \omega) = \frac{1}{2} \int_{-\infty}^{\infty} \left( \frac{1}{2} \gamma_1 \sin^2 \theta \log \left( \frac{\omega^2 + \gamma_1^2 - 2\omega \gamma_1 \cos \theta}{\omega \gamma_1 \cos \theta} \right) \right) dy_1$$

$$+ (\cos \theta) \sqrt{\xi^2 + \gamma_1^2 \sin^2 \theta} \tan^{-1} \left( \frac{\omega \gamma_1 \cos \theta}{\sqrt{\xi^2 + \gamma_1^2 \sin^2 \theta}} \right) dy_1$$

$$+ \frac{1}{2} \int_{-\infty}^{\infty} \left( \gamma_1 \sin \theta \cos \theta \tan^{-1} \left( \frac{\gamma_1 \cos \theta - \omega}{\gamma_1 \sin \theta} \right) \right) dy_1$$

For the case defined in Figure 63 when $\theta$ is 90 degrees, the black body interchange factor is defined by

$$F_{12} = \frac{1}{\pi A_1} \left[ f_3(b-a, d^2+y^2) - f_3(b-a, c^2+d^2) + f_3(b-a, c^2+\delta^2) \right]$$

$$- f_3(b-a, c^2+y^2) + f_3(b-a, c^2+\gamma^2) - f_3(b-a, c^2+\delta^2)$$

$$+ f_3(b-a, d^2+\delta^2) - f_3(b-a, d^2+\gamma^2) + f_3(a-a, d^2+y^2)$$

$$- f_3(a-a, c^2+\delta^2) + f_3(a-a, c^2+\gamma^2) - f_3(a-a, c^2+\delta^2)$$

$$+ f_3(a-a, c^2+y^2) - f_3(a-a, c^2+\gamma^2) + f_3(a-a, d^2+\delta^2)$$

$$- f_3(a-a, d^2+\gamma^2)$$

where the function $f_3$ is

$$f_3(\xi, \nu) = \left[ \frac{1}{2} \frac{\xi}{\sqrt{\nu}} \tan^{-1} \left( \frac{\xi}{\sqrt{\nu}} \right) + \frac{1}{4} \xi^2 \ln (\xi^2 + \nu) - \frac{1}{8} (\xi^2 + \nu) \ln (\xi^2 + \nu) \right]$$

(216)
For nodes 1 and 2, as defined in Figure 63 with $a = \alpha = 0$ and $b = \beta = \infty$, lying on nonparallel planes (i.e. infinite strips), the black body interchange factor is defined by

$$F_{12} = \frac{1}{2(\delta - \gamma)} \left( \sqrt{\delta^2 + c^2 - 2c \delta \cos \theta} - \sqrt{\delta^2 + d^2 - 2d \delta \cos \theta} + \sqrt{\gamma^2 + d^2 - 2d \gamma \cos \theta} - \sqrt{\gamma^2 + c^2 - 2c \gamma \cos \theta} \right)$$

(217)

**Parallel Disks**

The black body interchange factor between two disks, with radii of $R_1$ and $R_2$, respectively, whose centers lie on a line normal to both disks is given by

$$F_{12} = \frac{1}{2R_1^2} \left[ E^2 + R_1^2 + R_2^2 - \sqrt{(E^2 + R_1^2 + R_2^2)^2 - (2R_1R_2)^2} \right]$$

(218)

where $E$ is the distance between the disks.

**Plane and Parallel Cylinder**

For node 1 lying on the surface of a cylinder and node 2 lying on the surface of a plane (parallel to the cylinder) as defined in Figure 64, the black body interchange factor is defined by

$$\bar{\theta} = \cos^{-1} \frac{x_2}{\sqrt{x_2^2 + y_2^2}}$$

(219)

For $\theta_2 < \bar{\theta} < \theta_1$,

$$F_{12} = \frac{1}{2\pi A_1} \int_a^b \left| f_4(\beta - c, \wedge_1) - f_4(\beta - c, \wedge_2) \right| - \left| f_4(\beta - d, \wedge_1) - f_4(\beta - d, \wedge_2) \right|$$

$$+ \left| f_4(a - d, \wedge_1) - f_4(a - d, \wedge_2) \right| - \left| f_4(a - c, \wedge_1) - f_4(a - c, \wedge_2) \right| \, dx_2$$

(220)
Figure 64. Nodes on $\bar{\rho}$-plane and Parallel Cylinder

For $\theta_1 < \bar{\theta} < \theta_2$,

$$F_{12} = \frac{1}{2\pi A_1} \int_a^b \left[ f_4(\beta-c, \wedge_1) + f_4(\beta-c, \wedge_2) - f_5(\beta-c) \right] - \left[ f_4(\beta-d, \wedge_1) ight]$$

$$+ f_4(\beta-d, \wedge_2) - f_5(\beta-a) \right] - \left[ f_4(\beta-d, \wedge_1) + f_4(\beta-d, \wedge_2) - f_5(\beta-d) \right]$$

$$- \left[ f_4(a-c, \wedge_1) + f_4(a-c, \wedge_2) - f_5(a-c) \right] \ dx_2$$  \hspace{1cm} (221)
where the functions $f_4$ and $f_5$ are defined as

$$f_4(\xi, \eta) = \frac{\xi}{4(y_2^2 + x_2^2)} \left[ \frac{2y_2 \sqrt{\eta} + 2x_2(\epsilon + \eta)}{\sqrt{\eta}} \tan^{-1} \frac{\xi}{\sqrt{\eta}} \right.$$

$$+ \frac{\epsilon x_2}{\xi} \ln \left( \frac{\xi^2 + \eta}{\xi^2 + \eta} \right) + \frac{\epsilon x_2}{\xi} \ln \left( \frac{\eta}{\xi^2 + \eta} \right)$$

$$+ \frac{y_2}{\xi} \sin^{-1} \frac{\eta - \eta}{2 \sqrt{y_2^2 + x_2^2}} - \frac{y_2 \epsilon}{\xi} \sin^{-1} \frac{\eta - \eta}{2 \sqrt{y_2^2 + x_2^2}}$$

$$+ \frac{\sqrt{\xi^4 + 2 \xi^2 \eta + \epsilon^2}}{\xi} \sin^{-1} \frac{\eta + \xi^2 - \xi^2 \eta - \epsilon^2}{2 \rho (\xi^2 + \xi^2) \sqrt{y_2^2 + x_2^2}} \left. \right]$$

$$f_5(\xi) = \frac{\xi}{2(y_2^2 + x_2^2)} \left[ \frac{4x_2 \sqrt{y_2^2 + x_2^2}}{\tan^{-1} \frac{\xi}{\sqrt{y_2^2 + x_2^2} - \rho}} \right.$$

$$+ \frac{\epsilon x_2}{\xi} \ln \left( \frac{\eta + \xi^2 - 2 \rho \sqrt{y_2^2 + x_2^2}}{\eta + \xi^2 - 2 \rho \sqrt{y_2^2 + x_2^2}} \right)$$

$$+ \frac{\eta}{\xi} \ln \frac{\eta - 2 \rho \sqrt{y_2^2 + x_2^2}}{\eta + \xi^2 - 2 \rho \sqrt{y_2^2 + x_2^2}}$$

$$+ \frac{\pi y_2}{2 \xi} \left( \frac{\xi^2 + \epsilon - \sqrt{\xi^4 + 2 \eta \xi^2 + \epsilon^2}}{\xi^2 + \epsilon - \sqrt{\xi^4 + 2 \eta \xi^2 + \epsilon^2}} \right) \right]$$

(222)

(223)
where

\[ \eta = y_2^2 + x_2^2 + \rho^2 \]

\[ \epsilon = y_2^2 + x_2^2 - \rho^2 \]

\[ \chi = 4\rho^2(y_2^2 + x_2^2) - (\nabla - \eta)^2 \]

\[ \wedge_1 = \eta - 2\rho(x_2 \cos \theta_1 + y_2 \sin \theta_1) \]

\[ \wedge_2 = \eta - 2\rho(x_2 \cos \theta_2 + y_2 \sin \theta_2) \]

**Concentric Cylinders**

For node 1 on the outside surface of the inner cylinder and node 2 on the inside of the outer cylinder, as defined in Figure 65, the black body interchange factor is defined by Equations 224 and 225. For \( \theta'_1 > 90^\circ \) or \( \theta'_2 < 90^\circ \),

\[
F_{12} = \frac{\rho_0}{2\pi A_1} \int_{\psi_1}^{\psi_2} \left( |f_6(\beta-c, \wedge_1) - f_6(\beta-c, \wedge_2)| - |f_6(\beta-d, \wedge_1) - f_6(\beta-d, \wedge_2)| + |f_6(a-d, \wedge_1) - f_6(a-d, \wedge_2)| - |f_6(a-c, \wedge_1) - f_6(a-c, \wedge_2)| \right) d\psi \tag{224} \]

For \( \theta'_1 < 90^\circ < \theta'_2 \),

\[
F_{12} = \frac{\rho_0}{2\pi A_1} \int_{\psi_1}^{\psi_2} \left( |f_6(\beta-c, \wedge_1) + f_6(\beta-c, \wedge_2) - f_7(\beta-c)| - |f_6(\beta-d, \wedge_1) + f_7(\beta-d)| + |f_6(a-d, \wedge_1) + f_6(a-d, \wedge_2) - f_7(a-d)| - |f_6(a-c, \wedge_1) + f_6(a-c, \wedge_2) - f_7(a-c)| \right) d\psi \tag{225} \]
where the functions $f_6$ and $f_7$ are defined as

$$f_6(\xi, \lambda) = \frac{\xi}{4\rho_o} \left[ \frac{2\sqrt{X}}{\sqrt{\lambda}} \tan^{-1} \frac{\xi}{\sqrt{\lambda}} + \xi \sin^{-1} \frac{\eta - \lambda}{2\rho\rho_o} ight.$$  

$$- \frac{1}{\xi} \sqrt{\xi^4 + 2\eta \xi^2 + \epsilon^2 \sin^{-1} \frac{\eta + \xi}{2\rho\rho_o} - \eta \xi^2 - \epsilon^2}$$ 

$$- \frac{\epsilon}{\xi} \sin^{-1} \frac{\lambda + \epsilon^2}{2\rho\rho_o} \right]$$  

(226)  

$$f_7(\xi) = \frac{\pi}{4\rho_o} \left[ \xi^2 + \epsilon - \sqrt{\xi^4 + 2\eta \xi^2 + \epsilon^2} \right]$$  

(227)
where

\[ \eta = \rho_0^2 + \rho^2 \]
\[ \epsilon = \rho_0^2 - \rho^2 \]
\[ \lambda = 4 \rho_0^2 \rho^2 - (\eta - \eta)^2 \]
\[ \lambda_1 = \eta - 2 \rho_0 \rho \sin \theta_1' \]
\[ \lambda_2 = \eta - 2 \rho_0 \rho \sin \theta_2' \]

and \( \theta' \) is related to \( \theta \) and \( \psi \) as follows, when \( 0 < \theta \) (or \( \psi \)) < \( 2\pi \),

**For** \( \psi < \pi \),

\[ \theta' = \theta - \psi + \frac{\pi}{2} \text{ for } \theta < (\psi + \pi) \]

\[ \theta' = \theta - \psi - \frac{\pi}{2} \text{ for } \theta > (\psi + \pi) \]

**For** \( \pi < \psi < 2\pi \),

\[ \theta' = \theta - \psi + \frac{5\pi}{2} \text{ for } \theta < (\psi - \pi) \]

\[ \theta' = \theta - \psi + \frac{\pi}{2} \text{ for } \theta > (\psi - \pi) \]

**Parallel Cylinders**

For node 1 on the surface of the cylinder of radius \( \rho \) and node 2 on the surface of the cylinder of radius \( \rho_0 \) as defined in Figure 66, the black body interchange factor is defined by Equations 228 and 229. For \( \theta_1' > 90^\circ \) or \( \theta_2' < 90^\circ \),
Figure 66. Nodes on Parallel Cylinders

\[ F_{12} = \frac{\rho_o}{2nA_1} \int_{\psi_1}^{\psi_2} \left( E \cos \psi - \rho_0 \right) \left[ \left| f_\theta(\beta-c, ^{1}\wedge) - f_\theta(\beta-c, ^2\wedge) \right| - \left| f_\theta(\beta-d, ^1\wedge) - f_\theta(\beta-d, ^2\wedge) \right| + \left| f_\theta(a-d, ^1\wedge) - f_\theta(a-d, ^2\wedge) \right| \right] d\psi \]

For \( \theta_1 < 90^\circ < \theta_2 \):

\[ F_{12} = \frac{\rho_o}{2nA_1} \int_{\psi_1}^{\psi_2} \left( E \cos \psi - \rho_0 \right) \left[ \left| f_\theta(\beta-c, ^1\wedge) + f_\theta(\beta-c, ^2\wedge) \right| - \left| f_\theta(\beta-d, ^1\wedge) + f_\theta(\beta-d, ^2\wedge) - f_\theta(\beta-d) \right| + \left| f_\theta(a-d, ^1\wedge) + f_\theta(a-d, ^2\wedge) - f_\theta(a-d) \right| - \left| f_\theta(a-c, ^1\wedge) + f_\theta(a-c, ^2\wedge) - f_\theta(a-c) \right| \right] d\psi \]
where the functions \( f_8 \) and \( f_9 \) are defined as

\[
f_8(\xi, \wedge) = \frac{\xi}{4Z} \left( \frac{\sqrt{X}}{\sqrt{\wedge}} \tan^{-1} \frac{\xi}{\sqrt{\wedge}} + \xi \sin^{-1} \frac{\eta \wedge - \epsilon^2}{2\rho \wedge} - \frac{\epsilon}{\xi} \sin^{-1} \frac{\eta \wedge - \epsilon^2}{2\rho \wedge} \right)
\]

\[
+ \frac{1}{\xi} \sqrt{\xi^4 + 2\eta \xi^2 + \epsilon^2 \sin^{-1} \frac{\eta \wedge + \xi^2}{2\rho \wedge (\wedge + \xi^2)}}
\]

(230)

\[
f_9(\xi) = \frac{\pi}{4Z} \left( \xi^2 + \epsilon - \sqrt{\xi^4 + 2\eta \xi^2 + \epsilon^2} \right)
\]

(231)

where

\[
Z = \sqrt{E^2 + \rho_o^2 - 2E \rho_o |\cos \psi|}
\]

\[
\eta = Z^2 + \rho^2
\]

\[
\epsilon = Z^2 - \rho^2
\]

\[
X = 4\rho^2 Z^2 - (\wedge - \eta)^2
\]

\[
\wedge_1 = \eta - 2\rho Z \sin \theta_1
\]

\[
\wedge_2 = \eta - 2\rho Z \sin \theta_2
\]

when \( 0 < \psi < 2\pi \) and \( -\pi < \theta < \pi \), \( \theta' \) is related to \( \theta \) and \( \psi \) as

\[
\theta' = \theta + \frac{\pi}{Z} \tan^{-1} \frac{\rho_o \sin \psi}{E - \rho_o |\cos \psi|}
\]

**Cylinder and Skewed Plane**

For nodes 1 and 2, as defined in Figure 67, lying on a cylinder and a plane (which is not parallel to the cylinder), respectively, the black body interchange factor is defined by
Figure 67, Nodes on Cylinder and Skewed Plane

\[
F_{12} = \frac{\rho \sin \psi}{2 \pi A_1} \int_c^d \int_{\theta_1}^{\theta_2} \left[ f_{10}(b, f) - f_{10}(b, e) \right. \\
+ \left. f_{10}(a, e) - f_{10}(a, f) \right] d\theta d\gamma_1
\]

where the function \( f_{10} \) is given by

\[
f_{10}(\xi, \gamma) = \frac{G_1}{2} \ln \left( \gamma^2 - 2 \rho \cos \theta + \delta_2 \right) \\
- \frac{G_2}{2} \ln \left( \gamma^2 - 2 \rho \cos \theta + \delta_1 \right)
\]
\[ + \frac{a_2 (\cos \theta + \rho \cos \theta) + \sqrt{r} \cos \theta (\rho \cos \theta - \delta_1)}{(\delta_1 - \rho^2 \cos^2 \theta) \sqrt{\delta_1 - 2 \rho \cos \theta + \delta_1}} \tan^{-1} \frac{\xi - Z_1}{\sqrt{\delta_1 - 2 \rho \cos \theta + \delta_1}} \]
\[ + \frac{G_1 \rho \cos \theta - G_3}{\sqrt{\delta_2 - \rho^2 \cos^2 \theta}} \tan^{-1} \frac{\cos \theta}{\sqrt{\delta_2 - \rho^2 \cos^2 \theta}} - \]
\[ - \frac{G_2 \rho \cos \theta - G_4}{\sqrt{\delta_1 - \rho^2 \cos^2 \theta}} \tan^{-1} \frac{\cos \theta}{\sqrt{\delta_1 - \rho^2 \cos^2 \theta}} \]

(233)

where

\[ G_1 = \frac{\beta_3 + 2 \rho \cos \theta (a_3 + 2 \rho \cos^2 \theta \cot \psi) - \delta_2 \cos \theta \cot \psi}{\delta_2 - \delta_1} \]
\[ G_2 = \frac{\beta_3 + 2 \rho \cos \theta (a_3 + 2 \rho \cos^2 \theta \cot \psi) - \delta_1 \cos \theta \cot \psi}{\delta_2 - \delta_1} \]
\[ G_3 = \frac{\delta_2 (a_3 + 2 \rho \cos^2 \theta \cot \psi) - \gamma_3}{\delta_2 - \delta_1} \]
\[ G_4 = \frac{\delta_1 (a_3 + 2 \rho \cos^2 \theta \cot \psi) - \gamma_3}{\delta_2 - \delta_1} \]
\[ r = (E - \rho \sin \theta + Z_1 \cot \psi)^2 \]
\[ a_2 = \sqrt{r} \left( (E + Z_1 \cot \psi) \sin \theta - \rho \right) \]
\[ \delta_1 = (\rho \cos \theta)^2 + r \]
\[ \delta_2 = \delta_1 + (Z_1 - \xi)^2 \]
and

\[ \beta_3 = \left( \frac{1}{\delta_1 - \rho^2 \cos^2 \theta} \right) \chi \]

\[ \left\{ (\xi - Z_1) \left( 2a_2 \rho \cos \theta + \rho^2 \cos^3 \theta \sqrt{r} \right) + \delta_1 \right\} \]

\[ \left\{ (\xi - Z_1) \left( E - \rho \sin \theta \right) \cot \psi \cos \theta \right\} \]

\[ \left\{ (\delta_1 - \rho^2 \cos^2 \theta) \cot \psi \cos \theta \right\} \]

\[ \left\{ (\xi - Z_1) \left( E - \rho \sin \theta \right) \cot \psi \right\} \]

\[ a_3 = \left( \frac{1}{\delta_1 - \rho^2 \cos^2 \theta} \right) \left\{ (\xi - Z_1) \right\} \]

\[ \left\{ (\xi - Z_1) \left( a_2 + \rho \cos^2 \theta \sqrt{r} \right) - \left[ 2 \rho \cos^2 \theta \right] \right\} \]

\[ \left\{ (\xi - Z_1) \left( (E + Z_1 \cot \psi) \sin \theta + \rho \right) \left( (\xi - Z_1) \left( (E + Z_1 \cot \psi) \sin \theta + \rho \right) \right\} \]

\[ \left\{ (\xi - Z_1) \left( a_2 + \rho \cos^2 \theta \right) \right\} \]

\[ \left\{ (\xi - Z_1) \left( (E + Z_1 \cot \psi) \sin \theta + \rho \right) \left( (\delta_1 - \rho^2 \cos^2 \theta) \cot \psi \right) \right\} \]

\[ \gamma_3 = \left( \frac{1}{\delta_1 - \rho^2 \cos^2 \theta} \right) \left\{ (\xi - Z_1) \left( a_2 + \rho \cos^2 \theta \right) \right\} \]

\[ \left\{ (\xi - Z_1) \left( (E + Z_1 \cot \psi) \sin \theta + \rho \right) \left( (\xi - Z_1) \left( (E + Z_1 \cot \psi) \sin \theta + \rho \right) \right\} \]

\[ \left\{ (\xi - Z_1) \left( (E + Z_1 \cot \psi) \sin \theta + \rho \right) \left( (\xi - Z_1) \left( a_2 + \rho \cos^2 \theta \right) \right\} \]

\[ \left\{ (\xi - Z_1) \left( (E + Z_1 \cot \psi) \sin \theta + \rho \right) \left( (\delta_1 - \rho^2 \cos^2 \theta) \cot \psi \right) \right\} \]
Cylinder (Internal)

For the case of two nodes lying on the inside of the same cylinder, as defined in Figure 68, the black body interchange factor is defined by

\[
F_{12} = \frac{1}{\pi A_1} \int_{\theta_c}^{\theta_o} \left\{ f_{11} (b-c, \theta B) - f_{11} (b-c, \theta A) + f_{11} (b-d, \theta A) - f_{11} (b-d, \theta B) + f_{11} (a-d, \theta B) + f_{11} (a-c, \theta A) - f_{11} (a-c, \theta B) \right\} d\theta_1
\]

(234)

where the function \( f_{11} \) is given by
\[ f_{11}(\xi, \wedge) = \frac{\xi^2 (\wedge - \theta_1)}{8} - \frac{\xi}{4} \sqrt{\xi^2 + 4 \rho^2} \tan^{-1} \left( \frac{\sqrt{\xi^2 + 4 \rho^2} \tan \left( \frac{\wedge - \theta_1}{2} \right)}{\xi} \right) \]

\[-\frac{\xi \rho}{2} \cos \left( \frac{\wedge - \theta_1}{2} \right) \tan^{-1} \left( \frac{\xi}{2 \rho \sin \left( \frac{\wedge - \theta_1}{2} \right)} \right) \tag{235}\]

Plane and Sphere

The black body interchange factor between node 1 on a plane and node 2 on a sphere, as defined in Figure 69 is given by

\[ F_{12} = \frac{1}{\pi a_1} \int \int \int \int \frac{\rho^2 \sin \psi (E - \rho \eta) (\epsilon - \rho)}{(X_1^2 + 2 + E^2 + (y_1')^2 - 2 \rho \epsilon)^2} d\theta d\psi dx_1 dy_1 \] \tag{236}

where

\[ \eta = \sin \psi \sin \theta \sin \phi + \cos \psi \cos \phi \]

\[ \epsilon = x \sin \psi \cos \theta + E \eta + y_1' (\sin \psi \sin \theta \sin \phi - \cos \psi \sin \phi) \]

Equation 236 is not integrated analytically because the resulting IBM computation routine is more complicated than the case wherein all four integrations are done numerically.

Internal Symmetrical Radiation

For the case where a node is defined as a ring around some symmetrical body, computation of the black body interchange factors is greatly simplified. The black body interchange factors between the various nodes of the sphere-cone-cylinder configuration of Figure 70 are given by the following equations.
NOTE: $\psi$ IS MEASURED IN $yz$ PLANE

Figure 69. Nodes on Plane and Sphere
For nodes on a cylinder,

\[
F(n, n') = \left\{ \frac{1}{4\rho_2(a_n - a_{n-1})} \right\} \left\{ f_{12}(a_n - a_{n-1}) - f_{12}(a_{n-1} - a_{n-1}) \right\} \\
+ f_{12}(a_{n-1} - a_{n'}) - f_{12}(a_{n-1} - a_{n'-1})
\]

where

\[
\xi_{12}(\xi) = \xi^2 - |\xi| \sqrt{\xi^2 + 4\rho^2} + 2\rho |\xi|
\]

For nodes on a sphere,

\[
F(m, m') = \frac{1}{2} (\cos \theta_{m'-1} - \cos \theta_m)
\]
For nodes on a cone,

\[
\mathcal{F}(\ell, \ell') = \left[ \frac{1}{2} \sin \psi \right] \left[ 2 (b_\ell - b_{\ell-1}) (b_{\ell'} - b_{\ell'-1}) \right] + f_{13}(b_\ell, b_{\ell'}) - f_{13}(b_{\ell-1}, b_{\ell'}) + f_{13}(b_{\ell'-1}, b_{\ell'-1}) \]

(240)

where the function \( f_{13} \) is given by

\[
f_{13}(\xi, \omega) = \left[ \left( \xi - \omega \right)^2 + \left( \rho_1 - \frac{\xi}{\tan \psi} \right)^2 + \left( \rho_1 + \frac{\omega}{\tan \psi} \right)^2 \right]^{\frac{1}{2}}
\]

(241)

For a node on a sphere to a node on a cylinder,

\[
\mathcal{F}(m, n) = \left\{ \frac{1}{4} \frac{\zeta_0^2}{\cos \theta_{m-1} - \cos \theta_n'} \right\} \left[ \rho \cos (a_n - a_{n-1}) (\cos \theta_{m-1} - \cos \theta_m) \right] + f_{14}(a_{n-1}, \theta_{m-1}) - f_{14}(a_{n-1}, \theta_m) + f_{14}(a_n, \theta_m) - f_{14}(a_n, \theta_{m-1}) \]

(242)
where

\[ f_{14}(\xi, \omega) = \left[ \left( \xi + \rho_o (\cos \omega - \cos \psi) \right)^2 + \rho_1^2 + \rho_o^2 \sin^2 \omega \right]^{\frac{1}{2}} - \left( 2 \rho_o \rho_2 \sin \omega \right)^2 \]  

(243)

and \( \rho_o \) (radius of sphere) is given by

\[ \rho_o = \frac{\rho_1}{\sin \psi} \]  

(244)

For a node on a sphere to a node on a cone,

\[ F_{(m, l)} = \left\{ \frac{1}{4 \rho_o^2 (\cos \theta_{m-1} - \cos \theta_m)} \right\} \left\{ 2 \rho_o (b_{l-1} - b_{l-1}')(\cos \theta_{m-1} - \cos \theta_m) \right\}^{\frac{1}{2}} + f_{15}(b_{l-1}, \theta_{m-1}) - f_{15}(b_{l}, \theta_m) + f_{15}(b_{l}, \theta_m) - f_{15}(b_{l-1}, \theta_{m-1}) \]  

(245)

where \( \rho_o \) is defined by Equation 244 and

\[ f_{15}(\xi, \omega) = \left[ \left( \xi + \rho_o (\cos \omega - \cos \psi) \right)^2 + \left( \rho_1 + \frac{\xi}{\tan \psi} \right)^2 + \rho_o^2 \sin^2 \omega \right]^{\frac{1}{2}} - \left[ 2 \rho_o \sin \omega \left( \rho_1 + \frac{\xi}{\tan \psi} \right) \right]^2 \]  

(246)
For a node on a cone to a node on a cylinder,

\[
F(\ell, n) = \left[ \frac{1}{2} \sin \psi \right] \left[ \frac{(b_\ell)^2 - (b_{\ell-1})^2}{2 \rho_1 (b_\ell - b_{\ell-1}) + \frac{\tan \psi}{\tan \psi}} \right] ^2 \left( b_\ell - b_{\ell-1} \right) (a_n - a_{n-1})
\]

\[
+ f_{16} (a_{n-1}, b_{\ell-1}) - f_{16} (a_n, b_\ell) \]

\[
+ f_{16} (a_n, b_\ell) - f_{16} (a_n, b_{\ell-1}) \]

where \( f_{16} \) is defined by

\[
f_{16} (\xi, \omega) = \left\{ \left[ (\xi - \omega)^2 + \rho_2^2 + (\rho_1 + \frac{\omega}{\tan \psi})^2 \right] ^2 - \left[ 2\rho_2 (\rho_1 + \frac{\omega}{\tan \psi}) \right] ^2 \right\} ^{1/2}
\]

For the configuration of Figure 71, the black body interchange factor between two nodes (\( n \) and \( n' \)) is given by

\[
F(n, n') = \left[ \frac{1}{m(b + d) (a_n - a_{n-1})} \right] \left[ f_{17} (a_n - a_{n'-1}) \right. \\
- f_{17} (a_{n-1} - a_{n'-1}) + f_{17} (a_{n-1} - a_n) \\
\left. - f_{17} (a_n - a_{n'}) \right]
\]

(249)
where $f_{17}$ is

$$f_{17}(\xi) = b \sqrt{\xi^2 + d^2} \tan^{-1} \frac{b}{\sqrt{\xi^2 + d^2}} - b \xi \tan^{-1} \frac{b}{\xi}$$

$$+ d \sqrt{\xi^2 + b^2} \tan^{-1} \frac{d}{\sqrt{\xi^2 + b^2}} - d \xi \tan^{-1} \frac{d}{\xi}$$

$$+ \frac{\xi^2}{2} \ln \left( \frac{(\xi^2 + b^2) (\xi^2 + d^2)}{\xi^2 (\xi^2 + b^2 + d^2)} \right)$$

(250)

Figure 7. Rectangular Box Configuration
The configuration factors for various cylindrical shapes presented here were published by H. Leuenberger and R. A. Person in Paper 56-A-144 of the American Society of Mechanical Engineers (Reference 24).

Directly Opposed Parallel Disks

\[
F_{b, 2} = \frac{1}{2} \left( 1 - \frac{\rho^2 - R^2 + L^2}{\sqrt{(\rho^2 + R^2 + L^2)^2 - 4\rho^2R^2}} \right)
\] (251)

\[
F_{a, 2} = F_{12} = \frac{1}{2} \left[ 1 + \frac{R^2 + L^2}{R^2} - \sqrt{\left(1 + \frac{R^2 + L^2}{R^2}\right)^2 - 4 \frac{R^2}{R^2}} \right]
\] (252)

when \( R = r \),

\[
F_{12} = 1 - \frac{1}{2} \left( \frac{L}{R} \sqrt{4 + \frac{L^2}{R^2} - \frac{L^2}{R^2}} \right)
\]
The limiting values are

\[
\begin{align*}
L \to 0 & \quad F_{12, 1} = 1 & \quad R \geq r \\
F_{12, 2} = \frac{R^2}{r^2} & \quad R \leq r \\
L \to \infty & \quad F_{12, 1} = 0 \\
R \to 0 & \quad F_{12, 2} = 0 \\
R \to \infty & \quad F_{12, 1} = 1 \\
r \to 0 & \quad F_{12, 2} = \frac{R^2}{(L^2 + R^2)} \\
r \to \infty & \quad F_{12, 2} = 0
\end{align*}
\]

Cylinder

1. TOP OF CYLINDER
2. BOTTOM OF CYLINDER
3. CURVED SURFACE OF CYLINDER
R. RADIUS OF CYLINDER
L. HEIGHT OF CYLINDER
a. DIFFERENTIAL VERTICAL STRIP OF 3
b. DIFFERENTIAL ELEMENT OF a
z. DISTANCE BETWEEN b & 2

\[
F_{b, 2} = \frac{Z^2 + 2R^2}{2R \sqrt{Z^2 + 4R^2}} - \frac{Z}{2R}
\]

\[
F_{b, 3} = 1 + \frac{L}{2R} - \frac{Z^2 + 2R^2}{2R \sqrt{Z^2 + 4R^2}} - \frac{(L - Z)^2 + 2R^2}{2R \sqrt{(L - Z)^2 + 4R^2}}
\]

\[
F_{13} = F_{23} = \frac{1}{2} \left( \frac{L}{R} \sqrt{4 + \frac{L^2}{R^2}} - \frac{L^2}{R^2} \right)
\]
The limiting values are

\[
\begin{align*}
L \to \infty & \quad F_{13} = 1 \quad Z \to 0 & \quad F_{b, 2} = \frac{1}{2} \\
& \quad F_{33} = 1 & \quad F_{b, 3} = \frac{1}{2} + \frac{L}{2R} - \frac{L^2 + 2R^2}{2R \sqrt{L^2 + 4R^2}} \\
L \to 0 & \quad F_{13} = 0 & \\
& \quad F_{33} = 0 & \\
R \to \infty & \quad F_{13} = 0 & \\
& \quad F_{33} = 0 & \\
R \to 0 & \quad F_{13} = 1 & \\
& \quad F_{33} = 1 &
\end{align*}
\]

Directly Opposed Parallel Annuli

\[
F_{a, 2} = F_{32}
\]
\[
F_{a, 3} = F_{33} = 1 - \frac{1}{2} \left( \sqrt{4 + \frac{L^2}{R^2}} - \frac{L}{R} \right)
\]

Directly Opposed Parallel Annuli

1. INNER DISK CONTAINED BY TOP ANNULUS
2. TOP ANNULUS
3. INNER DISK CONTAINED BY BOTTOM ANNULUS
4. BOTTOM ANNULUS
r. INNER RADIUS OF ANNULUS
R. OUTER RADIUS OF ANNULUS
L. DISTANCE BETWEEN ANNULI
\(R_2 > r_1, R_4 > r_3\)

\[
F_{14} = \frac{1}{2} \left[ \frac{R_4^2 - r_3^2}{r_1^2} - \sqrt{\left(1 + \frac{R_4^2}{r_1^2}\right)^2 - 4 \frac{R_4^2}{r_1^2}} \right]
\]
\[
+ \sqrt{\left(1 + \frac{r_3^2}{r_1^2}\right)^2 - 4 \frac{r_3^2}{r_1^2}} \right]
\]

(256)

(257)

(258)
\[ F_{24} = \frac{1}{2(R_2^2 - r_1^2)} \left[ \sqrt{(R_2^2 + r_3^2 + L^2)^2 - (2r_3R_2)^2} \right. \\
\left. - \sqrt{(R_2^2 + R_4^2 + L^2)^2 - (2R_2R_4)^2} + \sqrt{(r_1^2 + R_4^2 + L^2)^2 - (2r_1R_4)^2} \right. \\
\left. - \sqrt{(r_1^2 + r_3^2 + L^2)^2 - (2r_1r_3)^2} \right] \]  

\[ (259) \]

When \( R_2 = R_4 = R \) and \( r_1 = r_3 = r \),

\[ F_{14} = \frac{1}{2} \left[ \frac{R_2^2 - r^2}{r^2} - \sqrt{\left(1 + \frac{R_2^2 + L^2}{r^2}\right)^2 - 4\left(\frac{R}{r}\right)^2} + \frac{L}{R} \sqrt{4 + \frac{L^2}{R^2}} \right] \]  

\[ (260) \]

\[ F_{24} = \left(\frac{R_2^2}{R_2^2 - r^2}\right) \left[ \sqrt{\left(1 + \frac{r_3^2 + L^2}{R_2^2}\right)^2 - 4\left(\frac{r_3}{R}\right)^2} - \frac{L}{2R} \left( \sqrt{4 + \frac{L^2}{R^2}} + \sqrt{\frac{r_3^2}{R_2^2} + \frac{L^2}{R_2^2}} \right) \right] \]  

\[ (261) \]

The limiting values are

When \( L \rightarrow \infty \),

\[ F_{14} = 0 \]

When \( L \rightarrow \infty \),

\[ F_{24} = 0 \]

When \( L \rightarrow 0 \),

\[ F_{14} = 0 \]

\[ R_4 > r_1 > r_3 \]

\[ \frac{r_3^2}{r_1^2} = 1 - \frac{r_3^2}{r_1^2} \]

\[ r_1 > R_4 \]

\[ \frac{R_4^2 - r_3^2}{r_1^2} \]
\[ L \to 0 \quad F_{24} = 0 \quad r_3 > R_2 \text{ or } r_1 > R_4 \]
\[ = \frac{R_2^2 - r_3^2}{R_2^2 - r_1^2} \quad R_4 > R_2 > r_3 > r_1 \]
\[ = 1 \quad R_4 > R_2 \text{ and } r_1 > r_3 \]
\[ = \frac{R_4^2 - r_1^2}{R_2^2 - r_1^2} \quad R_2 > R_4 \text{ and } r_1 > r_3 \]

\[ R_2 \to r_1 \quad F_{24} = \frac{1}{2} \left[ \frac{r_1^2 - r_3^2 + L^2}{\sqrt{r_1^2 + r_3^2 + L^2}} - \frac{r_1^2 - R_4^2 + L^2}{\sqrt{r_1^2 + R_4^2 + L^2}} \right] \]

\[ r_1 \to 0 \quad F_{44} = \frac{R_4^2}{L^2 + R_4^2} - \frac{r_3^2}{L^2 + r_3^2} \]
Cylinder and Annulus Contained in Top

1. DISK CONTAINED IN CYLINDER TOP
2. ANNULUS IN CYLINDER TOP
3. BOTTOM OF CYLINDER
4. CURVED SURFACE OF CYLINDER

r = INNER RADIUS OF ANNULUS
R = RADIUS OF CYLINDER
L = HEIGHT OF CYLINDER

\[
F_{24} = \frac{1}{2} \left[ 1 + \left( \frac{1}{R^2 - r^2} \right) \left( L \sqrt{4R^2 + L^2} - \sqrt{r^2 + R^2 + L^2} - (2Rr)^2 \right) \right]
\]

(262)

\[
F_{14} = \frac{1}{2} \left[ 1 - \frac{R^2 + L^2}{r^2} + \sqrt{\left( 1 + \frac{R^2 + L^2}{r^2} \right)^2 - 4 \frac{R^2}{r^2}} \right]
\]

(263)

The limiting values are

\[
r \to R \quad F_{24} = \frac{1}{2} \left( 1 + \frac{L}{\sqrt{4R^2 + L^2}} \right)
\]
Two Concentric Cylinders of Equal Radii (One Above Other)

\[ F_{14} = \frac{1}{4} \left[ \left( \frac{L_1 + L_2}{L_1} \right) \sqrt{4 + \left( \frac{L_1 + L_2}{R} \right)^2} - \frac{L_1 + 2L_2}{R} - \frac{L_2}{L_1} \sqrt{4 + \frac{L_2^2}{R^2}} \right] \]  \hspace{1cm} (264)

\[ F_{12} = \frac{L_2}{2R} + \frac{1}{4} \left[ \sqrt{4 + \frac{L_1^2}{R^2}} + \frac{L_2}{L_1} \sqrt{4 + \frac{L_2^2}{R^2}} - \left( \frac{L_1 + L_2}{L_1} \right) \sqrt{4 + \left( \frac{L_1 + L_2}{R} \right)^2} \right] \]  \hspace{1cm} (265)

when \( L_1 = L_2 = L_0 \),

\[ F_{14} = \frac{1}{4} \left[ 4 \sqrt{1 + \frac{L^2}{R^2}} - \frac{3L}{R} - \sqrt{4 + \frac{L^2}{R^2}} \right] \]  \hspace{1cm} (266)

\[ F_{12} = \frac{1}{2} \left[ \frac{L}{R} + \sqrt{4 + \frac{L^2}{R^2}} - 2 \sqrt{1 + \frac{L^2}{R^2}} \right] \]  \hspace{1cm} (267)
The limiting values are

\[ L_1 \to 0 \quad F_{14} = \frac{L_2^2 + 2R^2}{2R\sqrt{L_2^2 + 4R^2}} - \frac{L_2^2}{2R} \]

\[ F_{12} = \frac{1}{2} + \frac{L_2^2}{2R} - \frac{L_2^2 + 2R^2}{2R\sqrt{L_2^2 + 4R^2}} \]

Two Concentric Cylinders of Equal Length (One Contained Within Other)

1 CURVED EXTERIOR SURFACE OF INNER CYLINDER
2 CURVED INTERIOR SURFACE OF OUTER CYLINDER
3 BOTTOM ANNULUS CONTAINED BETWEEN 1 & 2
4 TOP ANNULUS CONTAINED BETWEEN 1 & 2
R RADIUS OF OUTER CYLINDER
r RADIUS OF INNER CYLINDER
L HEIGHT OF CYLINDERS
a DIFFERENTIAL VERTICAL STRIP OF 1
b DIFFERENTIAL ELEMENT OF a
c DIFFERENTIAL VERTICAL STRIP OF 2
d DIFFERENTIAL ELEMENT OF c
z DISTANCE BETWEEN b & 3
W DISTANCE BETWEEN d & 3

\[ F_{d,1} = \frac{r}{R} \left[ 2 - \frac{1}{\pi} \left\{ \cos^{-1} \frac{W^2 - R^2 + r^2}{W^2 + R^2 - r^2} + \cos^{-1} \frac{(L - W)^2 - R^2 + r^2}{(L - W)^2 + R^2 - r^2} \right\} - \frac{W}{r} \left( \frac{W^2 + R^2 + r^2}{\sqrt{(W^2 + R^2 + r^2)^2 - 4r^2R^2}} \right)^{\cos^{-1} \frac{r(W^2 - R^2 + r^2)}{R(W^2 + R^2 - r^2)}} \right] \]

\[ - \frac{r}{R} \left[ 2 - \frac{1}{\pi} \left\{ \left( \frac{L - W}{r} \right)^2 \frac{(L - W)^2 + R^2 + r^2}{\sqrt{(L - W)^2 + R^2 + r^2}^2 - 4r^2R^2} \right\} X \right] \]

(268)
\[
\cos^{-1} \left[ \frac{r \left( (L - W)^2 - R^2 + r^2 \right)}{R \left( (L - W)^2 + R^2 - r^2 \right)} \right] + \frac{r}{R} \left[ 2 - \frac{1}{\pi} \left( \frac{L}{r} \cos^{-1} \frac{r}{R} \right) \right] \\
F_{d, 2} = 2 \left( 1 - \frac{r}{R} \right) + \frac{L}{2R} - \frac{W^2 + 2R^2}{2R \sqrt{4R^2 + W^2}} - \frac{(L - W)^2 + 2R^2}{2R \sqrt{4R^2 + (L - W)^2}} \\
F_{d, 3} = \frac{1}{2} - (F_{d, 1}^* + F_{d, 2}^*)
\]

*Evaluated with \( L \) replaced by \( W \)

\[
F_{b, 3} = \frac{1}{2\pi} \left\{ \cos^{-1} \frac{Z^2 - R^2 + r^2}{Z^2 + R^2 - r^2} - \frac{Z}{r} \left[ \frac{Z^2 + R^2 + r^2}{\sqrt{(Z^2 + R^2)^2 - 4R^2r^2}} \right] \right\} \\
F_{b, 2} = 1 - (F_{b, 3} + F_{b, 4})
\]

-195-
\[F_{21} = F_{c, 1} = \frac{r}{R} \left[ 1 - \frac{1}{\pi} \left\{ \cos^{-1} \left( \frac{L^2 - R^2 + r^2}{L^2 + R^2 - r^2} \right) \right. \right. \]
\[\left. \left. - \frac{1}{2rL} \left( \sqrt{(L^2 + R^2 + r^2)^2 - (2Rr)^2} \cos^{-1} \frac{r(L^2 - R^2 + r^2)}{R(L^2 + R^2 - r^2)} \right. \right. \]
\[\left. \left. + (L^2 - R^2 + r^2) \left( \sin^{-1} \frac{r}{R} - \frac{\pi}{2} (L^2 + R^2 - r^2) \right) \right] \right] \] (273)

\[F_{22} = F_{c, 2} = 1 - \frac{r}{R} \frac{1}{\pi} \left\{ \frac{2r}{L} \tan^{-1} \frac{2 \sqrt{R^2 - r^2}}{L} \right. \right. \]
\[\left. \left. - \frac{L}{2R} \left( \frac{\sqrt{4R^2 + L^2}}{L} \sin^{-1} \frac{4(R^2 - r^2) + L^2}{R^2} \right) \right. \right. \]
\[\left. \left. - \sin^{-1} \frac{R^2 - 2r^2}{R^2} + \frac{\pi}{2} \left( \frac{\sqrt{4R^2 + L^2}}{L} - 1 \right) \right] \right] \] (274)

Values calculated from Equations 273 and 274 are in agreement with values obtained by approximate numerical methods by Hamilton and Morgan (Reference 22).

\[F_{23} = F_{c, 3} = \frac{1}{2} (1 - F_{21} - F_{22}) \quad (275)\]

\[F_{34} = 1 - \left( \frac{L}{R^2 - r^2} \right) [r - R (F_{22} + 2F_{21} - 1)] \quad (276)\]
Figure 72. Form Factor From Outer Cylinder to Inner Cylinder

Figure 73. Form Factor From Outer Cylinder to Itself
The limiting values are

\[
\begin{align*}
L \to 0 & & F_{21} = 0 & & F_{21} = 0 \\
F_{22} = 0 & & F_{22} = 1 - \frac{1}{2}\left(\sqrt{4 + \frac{L^2}{R^2}} - \frac{L}{R}\right) \\
F_{23} = 1/2 & & F_{23} = \frac{1}{2}\left(\sqrt{4 + \frac{L^2}{R^2}} - \frac{L}{R}\right) \\
F_{34} = 1 & & F_{34} = 1 - \frac{1}{2}\left(\frac{L}{R}\sqrt{4 + \frac{L^2}{R^2}} - \frac{L^2}{R}\right)
\end{align*}
\]

\[
\begin{align*}
L \to \infty & & F_{21} = \frac{r}{R} \\
F_{22} = 1 - \frac{r}{R} & & F_{22} = 0 \\
F_{23} = 0 & & F_{23} = 0 \\
F_{34} = 0 & & F_{34} = 0
\end{align*}
\]

\[
\begin{align*}
r \to R & & F_{21} = 1 \\
F_{22} = 0 & & F_{22} = 0 \\
F_{23} = 0 & & F_{23} = 0 \\
F_{34} = 0 & & F_{34} = 0
\end{align*}
\]

\[
\begin{align*}
W \to L & & F_{d, 1} = \frac{r}{R} \left[ 1 - \frac{1}{\pi} \left\{ \cos^{-1} \frac{L^2 - R^2 + r^2}{L^2 + R^2 - r^2} \right\} \right] \\
& & - \frac{L}{r} \left[ \frac{L^2 + R^2 + r^2}{\sqrt{L^2 + R^2 + r^2}^2 - 4r^2R^2} \right] x \\
& & \cos^{-1} \left( \frac{r(L^2 - R^2 + r^2)}{R(L^2 + R^2 - r^2)} \right) - \cos^{-1} \left( \frac{r}{R} \right)
\end{align*}
\]
\[ F_d, \theta = 1 - \frac{r}{R} + \frac{L}{2R} - \frac{L^2 + 2R^2}{2R \sqrt{L^2 + 4R^2}} \]
\[ + \frac{1}{\pi} \left[ 2 \frac{R}{R} \tan^{-1} \frac{\sqrt{R^2 - r^2}}{L} + \frac{L}{R} \sin^{-1} \left( 1 - \frac{2r^2}{R^2} \right) \right] \]
\[ - \frac{L^2 + 2R^2}{R \sqrt{L^2 + 4R^2}} \sin^{-1} \left( 4 \left( R^2 - r^2 \right) + \frac{L^2}{R} \left( R^2 - 2r^2 \right) \right) \frac{L^2 + 4 \left( R^2 - r^2 \right)}{L^2 + 4 \left( R^2 - r^2 \right)} \]

**Cylinder and Plane of Equal Length Parallel to Cylinder Axis (Plane Outside Cylinder)**

1. CURVED SURFACE OF CYLINDER
2. PLANE
3. ONE-HALF OF PLANE
4. RADIUS OF CYLINDER
5. HEIGHT OF CYLINDER & PLANE
6. DISTANCE FROM CYLINDER AXIS TO PLANE
7. LENGTH OF PLANE
8. VERTICAL DIFFERENTIAL STRIP OF \( \theta \)
9. DIFFERENTIAL ELEMENT OF \( a \)
10. DISTANCE FROM \( a \) TO CENTER OF \( \theta \)
11. DISTANCE FROM BOTTOM EDGE OF PLANE TO \( b \)
12. \( S = R \)
\[ F_{b,1} = \frac{SR}{S^2 + x^2} \left[ 2 - \frac{1}{\pi} \left( \cos^{-1} \left( \frac{y^2 - S^2 - x^2 + R^2}{y^2 + S^2 + x^2 - R^2} \right) \right) \right] \]

\[ + \cos^{-1} \left( \frac{(L-y)^2 - S^2 - x^2 + R^2}{(L-y)^2 + S^2 + x^2 - R^2} \right) \]

\[ - \frac{y}{R} \left[ \frac{y^2 + S^2 + x^2 + R^2}{\sqrt{(y^2 + S^2 + x^2 - R^2)^2 + 4y^2R^2}} \right] X \]

\[ \cos^{-1} \left( \frac{R(y^2 - S^2 - x^2 + R^2)}{\sqrt{y^2 + S^2 + x^2 - R^2}} \right) \]

\[ - \frac{SR}{S^2 + x^2} \left[ 2 - \frac{1}{\pi} \left( \frac{L-y}{R} \right) \sqrt{\left( \frac{L-y}{R} \right)^2 + \frac{(L-y)^2 + S^2 + x^2 + R^2}{\left( (L-y)^2 + S^2 + x^2 - R^2 \right)^2 + 4(L-y)^2R^2}} \right] X \]

\[ + \frac{L}{R} \cos^{-1} \left( \frac{R}{\sqrt{S^2 + x^2}} \right) \]

\[ F_{a,1} = \frac{SR}{S^2 + x^2} \left[ 1 - \frac{1}{\pi} \left( \cos^{-1} \left( \frac{L^2 - S^2 - x^2 + R^2}{L^2 + S^2 + x^2 - R^2} \right) \right) \right] \]

\[ - \frac{1}{2RL} \left[ \sqrt{(L^2 + S^2 + x^2 + R^2)^2} + 4L^2R^2 \right] X \]

\[ \cos^{-1} \left( \frac{R(L^2 - S^2 - x^2 + R^2)}{\sqrt{S^2 + x^2} \left( L^2 + S^2 + x^2 - R^2 \right)} \right) \]

\[ + (L^2 - S^2 - x^2 + R^2) \sin^{-1} \left( \frac{R}{\sqrt{S^2 + x^2}} \right) \]

\[ - \frac{\pi}{2} (L^2 + S^2 + x^2 - R^2) \]
\[ F_{21} = F_{31} = \frac{2}{T} \int_{0}^{T/2} F_{a, 1} \, dx \]  

The limiting values are

\[ y \to 0 \]  or  \[ y \to L \]

\[ F_{b, 1} = \frac{SR}{S^2 + x^2} \left[ 1 - \frac{1}{\pi} \left( \cos^{-1} \left( \frac{L^2 - S^2 - x^2 + R^2}{L^2 + S^2 + x^2 - R^2} \right) - \cos^{-1} \left( \frac{R}{\sqrt{S^2 + x^2}} \right) \right) \right] \]

\[ \frac{L^2 + S^2 + x^2 + R^2}{\sqrt{(L^2 + S^2 + x^2 - R^2)^2 + 4L^2R^2}} \]

\[ \frac{R(\frac{L^2 - S^2 - x^2 + R^2)}{\sqrt{S^2 + x^2}(L^2 + S^2 + x^2 - R^2)}}{\sqrt{L^2 + S^2 + x^2 - R^2}} \]

\[ L \to \infty \]

\[ F_{b, 1} = \frac{RS}{S^2 + x^2} \]

\[ F_{a, 1} = \frac{RS}{S^2 + x^2} \]

\[ F_{21} = F_{31} = \frac{2P}{T} \tan^{-1} \frac{T}{2S} \]

\[ T \to 0 \]

\[ F_{21} = F_{a, 1} \]  where  \[ F_{a, 1} \]  is evaluated at  \[ x = 0 \]

\[ S \to \infty \]

\[ F_{b, 1} = 0 \]

\[ F_{a, 1} = 0 \]

\[ F_{21} = 0 \]
$$S \rightarrow R \quad F_{b, 1} = \left( \frac{R^2}{R^2 + x^2} \right) \left[ \frac{1}{\pi} \left( \int \frac{\cos^{-1} \frac{y^2 - x^2}{y^2 + x^2}}{y^2 + x^2} \right) \right]$$

$$+ \cos^{-1} \left( \frac{(L - y)^2 - x^2}{(L - y)^2 + x^2} \right) - \frac{y}{R} \left[ \int \frac{\sqrt{y^2 + x^2 + 2R^2}}{(y^2 + x^2) - 4y^2R^2} \right] \xi$$

$$\cos^{-1} \left( \frac{R(y^2 - x^2)}{\sqrt{R^2 + x^2} (y^2 + x^2)} \right)$$

$$- \frac{L - y}{R} \left[ \frac{(L - y)^2 + x^2 + 2R^2}{\sqrt{(L - y)^2 + x^2} - 4(L - y)^2R^2} \right] \xi$$

$$\cos^{-1} \left( \frac{R \frac{(L - y)^2 - x^2}{[L - y)^2 + x^2]}{\sqrt{R^2 + x^2} \left[ (L - y)^2 + x^2 \right]} \right)$$

$$+ \frac{L}{R} \cos^{-1} \left( \frac{R}{\sqrt{R^2 + x^2}} \right)$$

$$S \rightarrow R \quad F_{a, 1} = \frac{R^2}{R^2 + x^2} \left[ 1 - \frac{1}{\pi} \left[ \cos^{-1} \frac{L^2 - x^2}{L^2 + x^2} \right. \right.$$

$$- \frac{1}{2RL} \left[ \int \frac{\sqrt{L^2 + x^2} + 4L^2R^2 \cos^{-1} \frac{R(L^2 - x^2)}{\sqrt{L^2 + x^2} (L^2 + x^2)}}{R^2 + x^2} \right] \xi$$

$$+ (L^2 - x^2) \sin^{-1} \left( \frac{R}{\sqrt{R^2 + x^2}} - \frac{\pi}{2} \frac{L^2 + x^2}{R^2 + x^2} \right) \right] \right]$$
Cylinder and Plane of Equal Length Parallel to Cylinder Axis (Plane Inside Cylinder)

1. VERTICAL INNER SURFACE OF CYLINDER
2. SIDE OF PLANE FACING 1
3. ONE-HALF OF PLANE
R. RADIUS OF CYLINDER
L. HEIGHT OF CYLINDER & PLANE
S. DISTANCE FROM CYLINDER AXIS TO PLANE (TAKEN POSITIVE AS SHOWN)
a. VERTICAL DIFFERENTIAL STRIP OF 2
x. DISTANCE FROM a TO CENTER OF PLANE

\[
F_{a,1} = 1 - \frac{1}{\pi} \left[ \tan^{-1} \frac{\sqrt{R^2 - S^2} + x}{L} + \tan^{-1} \frac{\sqrt{R^2 - S^2} - x}{L} \right] + \frac{x (R^2 - S^2 - x^2)}{4L (x^2 + S^2)} \ln \left[ \frac{\left( \frac{\sqrt{R^2 - S^2} + x}{\sqrt{R^2 - S^2} - x} \right)^2 + L^2}{\left( \frac{\sqrt{R^2 - S^2} + x}{\sqrt{R^2 - S^2} - x} \right)^2 + L^2} \right] + \frac{xL}{4(x^2 + S^2)} \ln \frac{\left( \frac{\sqrt{R^2 - S^2} + x}{\sqrt{R^2 - S^2} - x} \right)^2 + L^2}{\left( \frac{\sqrt{R^2 - S^2} + x}{\sqrt{R^2 - S^2} - x} \right)^2 + L^2} \left[ \frac{L^2}{R} \left( \frac{\sqrt{R^2 - S^2}}{R} + \frac{\sqrt{R^2 - S^2}}{R} \right) + \cos^{-1} \frac{S^2 + x}{R \sqrt{S^2 + x^2}} - \frac{2\pi}{2} \right] \right] X + \left[ \frac{\sqrt{(L^2 + R^2 + S^2)^2 - 4R^2 (x^2 + S^2)}}{R^2 + S^2} \right] X \cos^{-1} \frac{2R^2 S^2 + S^2 (R^2 - S^2 - x^2 - L^2) + x (R^2 + S^2 + x^2 + L^2) \sqrt{R^2 - S^2}}{R \sqrt{S^2 + x^2} \left( \frac{\sqrt{R^2 - S^2 + x}}{\sqrt{R^2 - S^2 + x}} \right)^2 + L^2} \right]
\]

(280)
The limiting values are

\[ F_{21} = F_{31} = \frac{1}{\sqrt{R^2 - S^2}} \int_0^{\sqrt{R^2 - S^2}} F_{a,1} \, dx \]  

(281)

\[ x \to 0 \quad F_{a,1} = 1 - \frac{2}{\pi} \left\{ \tan^{-1} \frac{\sqrt{R^2 - S^2}}{L} + \frac{1}{4LS} \left[ \frac{L^2 + R^2 + S^2}{R^2 - S^2} \cos^{-1} \frac{S}{R} \right. \right. \]

\[ - \left. \left. \frac{\pi L^2 + \sqrt{(L^2 + R^2 + S^2)}^2 - 4R^2 S^2}{R(R^2 - S^2 + L^2)} \right] \left. \frac{\cos^{-1} \frac{S(R^2 - S^2 - L^2)}{R(R^2 - S^2 + L^2)}}{4} \right\} \]

\[ S \to 0 \quad F_{a,1} = 1 - \frac{1}{\pi} \left\{ \tan^{-1} \frac{R + x}{L} + \tan^{-1} \frac{R - x}{L} \right. \]

\[ + \frac{R^2 - x^2}{4Lx} \ln \left[ \frac{(R + x)^2}{(R - x)^2 + L^2} \right] \left( (R - x)^2 + L^2 \right) \]

\[ + \frac{L}{4x} \ln \left( \frac{(R - x)^2 + L^2}{(R + x)^2 + L^2} \right) \]

\[ x \to 0 \quad \text{and} \quad S \to R \quad F_{a,1} = \frac{1}{4} \left( \frac{\sqrt{L^2 + 4R^2} - \frac{L}{R}}{R} \right) \quad L \to \infty \quad F_{a,1} = 1 \]

\[ F_{21} = 1 \]
Two Concentric Cylinders of Unequal Radii (One Atop Other)

For

\[
\frac{L_2}{L_1} \leq \frac{1}{2} \left( \frac{R}{r} - 1 \right) \quad (2 \text{ receives no direct radiation from 3})
\]

\[
F_{12} = \frac{r}{4L_1} \left[ 1 - \frac{R^2 + L_2}{r^2} + \sqrt{\left( \frac{R^2 + L_2}{r^2} \right)^2 - 4 \frac{R^2}{r^2}} \right] \quad (262)
\]

\[
F_{14} = \frac{1}{4} \left( \sqrt{4 + \frac{L_1^2}{r^2}} - \frac{L_1}{r} \right) - \frac{r}{4L_1} \left[ 1 - \frac{R^2 + L_2^2}{r^2} + \sqrt{\left( \frac{R^2 + L_2^2}{r^2} \right)^2 - 4 \frac{R^2}{r^2}} \right] \quad (283)
\]
For
\[
\frac{L_2}{L_1} = \frac{1}{2} \left( \frac{R}{r} - 1 \right)
\]

\[
F_{b, 4} = \frac{1}{n} \left[ \frac{Z^2 + 2r^2}{r \sqrt{Z^2 + 4r^2}} \tan^{-1} \frac{\sqrt{Z^2 + 4r^2}}{\sqrt{r^2 (2L_2 + Z)^2 - R^2 Z^2}} \right] + \frac{1}{n} \left( \frac{Z + L_2}{2r} \right) \left( \frac{R^2 + r^2 + (Z + L_2)^2}{\sqrt{\left[ (Z + L_2)^2 + R^2 + r^2 \right]^2 - 4R^2 r^2}} \right)
\]

(284)

\[
- \frac{Z \sin^{-1} \left( \frac{Z \sqrt{R^2 - r^2}}{2r \sqrt{L_2 (L + Z)}} \right)}{2r \sqrt{L_2 (L + Z)}} + \frac{1}{n} \left( \frac{Z + L_2}{2r} \right) \left( \frac{R^2 + r^2 + (Z + L_2)^2}{\sqrt{\left[ (Z + L_2)^2 + R^2 + r^2 \right]^2 - 4R^2 r^2}} \right) \cos^{-1} \left( \frac{2r^2 L_2 \left[ R^2 - r^2 - (Z + L_2)^2 \right] + Z \left( R^2 - r^2 \right) \left[ R^2 - r^2 + (Z + L_2)^2 \right]}{2Rr (Z + L_2) \left[ L_2 (Z + L_2) + R^2 - r^2 \right]} \right)
\]

(285)

\[
F_{14} = F_{a, 4} = \frac{\int_0^{L_1} F_{b, 4} dZ}{L_1}
\]

\[
F_{12} = \frac{1}{4} \left[ \sqrt{\frac{L_1^2}{R^2} - \frac{L_1}{R}} \right] - F_{a, 4}
\]

(286)
The limiting values are

\[ F_{b,4} = \frac{1}{\pi} \left[ \tan^{-1} \frac{\sqrt{R^2 - r^2}}{L_2} + \frac{L_2}{2r} \left( \frac{R^2 + r^2 + L_2^2}{\sqrt{(L_2^2 + R^2 + r^2)^2 - 4R^2r^2}} \right) \right] \]

\[ \left( \cos^{-1} \frac{r(R^2 - r^2 - L_2^2)}{R(L_2^2 + R^2 - r^2)} - \cos^{-1} \left( -\frac{r}{R} \right) \right) \]

\[ Z \to 0 \quad F_{b,4} = \frac{L_2^2 + 2R^2}{2R\sqrt{L_2^2 + 4R^2}} - \frac{L_2}{2R} \]

\[ r \to R \quad F_{14} = \frac{1}{4} \left[ \left( \frac{L_1 + L_2}{L_1} \right)^2 \sqrt{4 + \frac{(L_1 + L_2)^2}{R^2}} - \frac{L_1 + 2L_2}{R} \right. \]

\[ - \frac{L_2}{L_1} \sqrt{4 + \frac{L_2^2}{R^2}} \]
Two Concentric Cylinders of Unequal Length (One Enclosed by Other)

1. EXTERIOR SURFACE OF TOP INNER CYLINDER
2. EXTERIOR SURFACE OF MIDDLE INNER CYLINDER
3. EXTERIOR SURFACE OF BOTTOM INNER CYLINDER
4. INTERIOR SURFACE OF TOP OUTER CYLINDER
5. INTERIOR SURFACE OF MIDDLE OUTER CYLINDER
6. INTERIOR SURFACE OF BOTTOM OUTER CYLINDER
7. ANNULUS BETWEEN TOPS OF 1 & 4
8. ANNULUS BETWEEN BOTTOMS OF 3 & 6
9. ANNULUS BETWEEN BOTTOMS OF 1 & 4
10. ANNULUS BETWEEN BOTTOMS OF 2 & 5

R = RADIUS OF OUTER CYLINDERS
r = RADIUS OF INNER CYLINDERS
L₁ = HEIGHT OF TOP CYLINDERS
L₂ = HEIGHT OF MIDDLE CYLINDERS
L₃ = HEIGHT OF BOTTOM CYLINDERS

9 & 10 ARE USED FOR CALCULATION PURPOSES ONLY & DO NOT SHIELD RADIATION BETWEEN CYLINDERS

\[
F_{2, (4 + 5 + 6)} = 1 - \frac{R^2 - r^2}{2rL_2} \left[ F_{7, (1 + 2)} + F_{8, (2 + 3)} - F_{71} - F_{83} \right]
\]  
(287)

\[
F_{5, (1 + 2 + 3)} = F_{52} + \frac{1}{RL_2} \left[ r(L_1F_{19} + L_3F_{3, 10}) \right.
\]
\[
- \left( \frac{R^2 - r^2}{2} \right) (F_{10, (1 + 2)} - F_{9, (2 + 3)} - F_{10, 2} - F_{92}) \]
\]  
(288)

The F's on the right-hand side of Equations 287 and 288 may be evaluated from data given for two concentric cylinders of equal length.
DISCUSSION

To permit full utilization of the foregoing tabulated data, a summary of configuration factor properties and a discussion of some useful techniques follows (from Reference 25).

Reciprocity

The reciprocity relationship for the configuration factor from \( A_1 \) to \( A_2 \) is

\[
A_1 F_{12} = A_2 F_{21}
\]  
(289)

This relationship often allows a great simplification in the analysis of configuration factors; \( F_{21} \) can be obtained directly from \( F_{12} \) and the areas of the surfaces.

Sum Equals Unity

By definition, the sum of the configuration factors to all surfaces seen by a given surface is unity. This relationship is often written as

\[
\sum_{n=2}^{n=m} F(1, n) = 1.0
\]  
(290)

where

\( m = \text{Total number of surfaces} \)

Yamauti Modified Reciprocity Relationship

A modified reciprocity relationship, given by Yamauti, is also useful. (A general proof of this relationship is given in Reference 26, p. 336-337). This relationship in terms of the areas of Figure 74 is

\[
F_{14} A_1 = F_{32} A_3 = F_{23} A_2 = F_{41} A_4
\]  
(291)

-209-
The relations of Equation 291 assume perfectly diffusing surfaces of uniform radiant intensity located as shown in Figure 74. As indicated, areas $A_1$ and $A_3$ lie on one plane, and areas $A_2$ and $A_4$ lie on another plane. In addition, the width $W_3$ of $A_3$ and $A_4$ is the same as is the width $W_1$ of $A_1$ and $A_2$. As long as these geometrical conditions hold, the modified reciprocity relationship of Equation 291 is applicable and can be applied to planes at any other angle, including planes that are parallel. This relation is especially useful in dealing with rectangular areas.

**Application of Configuration Factor Properties to Problem**

Consider the infinitely long enclosure of Figure 75. Suppose that the configuration factor $F_{32}$ is known and that the problem is to determine the remaining configuration factors in the enclosure. An obvious solution is to use the string method (page 156). However, for purposes of demonstration, the following solution will utilize several of the special properties described above.
Figure 75. Diagram of Infinitely Long Enclosure

The enclosure of Figure 75 is symmetrical in that $A_1 = A_4$ and $A_2 = A_3$. Because of this symmetry, the following configuration factor relationship can be written as

\[ F_{41} = F_{14} \]
\[ F_{32} = F_{23} \]  
\[ F_{31} = F_{34} = F_{21} = F_{24} \]  

Assuming that $F_{34}$ is desired, apply Equation 290 to area $A_3$,

\[ F_{32} + F_{31} + F_{34} = 1.0 \]  

Using the relations of Equation 292 in Equation 293 yields an expression for $F_{34}$ in terms of the known configuration factor $F_{32}$.

\[ F_{34} = \frac{1 - F_{32}}{2} \]  

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Once \( F_{34} \) is known, the remaining configuration factors for Figure 75 can be determined by the reciprocity relationship. For example, the configuration factor \( F_{43} \) is given by

\[
F_{43} = F_{34} \frac{A_{3}}{A_{4}}
\]  

(295)

**Configuration Factor Algebra**

In many instances it becomes necessary to determine configuration factors which cannot be found directly from the tabulated data. For example, consider the case of a surface \( A_{3} \), which is perpendicular to a second surface \( A_{2} \), and the two surfaces do not have a common edge as shown by diagram 2 of Figure 76. The configuration factor \( F_{32} \) for this configuration is desired.

As is evident from the geometry of diagram 2 (Figure 76), \( F_{32} \) cannot be evaluated directly from the graphical data.

A convenient technique for evaluating \( F_{32} \) is to consider the flux transfer between a fictitious source consisting of surfaces \( A_{3} \) and \( A_{1} \) and the area \( A_{2} \). Denote the flux received by area \( A_{2} \) from \( A_{1} + A_{3} \) as \( \phi_{12} \). From this must be subtracted the flux \( \phi_{12} \) due to the source \( A_{1} \) yielding

\[
\phi_{32} = \phi_{12} - \phi_{12}
\]  

(296)

The total flux leaving an area \( A_{n} \) which is incident on an area \( A_{m} \) is given by

\[
\phi_{(n,m)} = J_{n} F_{(n,m)} A_{n}
\]  

(297)

where

\[ J_{n} = \text{Radiosity or total flux per unit area streaming away from surface } n \]

Substituting Equation 297 into Equation 296 yields

\[
J_{3} F_{32} A_{3} = J_{1} F_{(1 + 3, 2)} A_{(1 + 3)} - J_{1} F_{12} A_{1}
\]  

(298)

Assuming that \( J_{3} = J_{1} = 1.0 \), Equation 298 becomes

\[
F_{32} A_{3} = F_{(1 + 3, 2)} A_{(1 + 3)} - F_{12} A_{1}
\]  

(299)
Basic perpendicular configuration (for F_{21} or F_{12} use configuration factor graphs)

\[ A_{3}^{F}32 = A_{2}^{F}23 \]

\[ = A_{(1+3)}^{F}(1+3, 2) - A_{1}^{F}12 \]

\[ A_{1}^{F}14 = A_{4}^{F}41 \]

\[ = 1/2 \left[ A_{(1+3)}^{F}(1+3, 2+4) - A_{1}^{F}12 - A_{3}^{F}34 \right] \]

\[ A_{1}^{F}(1, 2+4) = A_{(2+4)}^{F}(2+4, 1) \]

\[ = 1/2 \left[ A_{(1+3)}^{F}(1+3, 2+4) - A_{3}^{F}34 + A_{1}^{F}(12) \right] \]

\[ A_{3}^{F}(3, 2+4+6) = A_{(2+4+6)}^{F}(2+4+6, 3) \]

\[ = 1/2 \left[ A_{(1+3)}^{F}(1+3, 2+4) + A_{(3+5)}^{F}(3+5, 4+6) - A_{1}^{F}12 - A_{5}^{F}56 \right] \]

Figure 76. Diagrams of Configuration Factor Algebra (Sheet 1 of 2)
Basic parallel configuration ($A_1 = A_2$) (for $F_{12}$ or $F_{21}$ use configuration factor graphs)

\[ A_1 F_{(1, 2+4)} = A_{(2+4)} F_{(2+4, 1)} = 1/2 \left[ A_{(1+3)} F_{(1+3, 2+4)} + A_{12} F_{12} - A_{34} F_{34} \right] \]

\[ A_1 F_{(1, x)} = A_{x} F_{(x, 1)} = A_{(1+3+5+7)} F_{(1+3+5+7, 2+4+6+8)} + A_{78} F_{78} \]

\[ A_{(3+7)} F_{(3+7, 4+8)} - A_{(5+7)} F_{(5+7, 6+8)} \]

Figure 76. Diagrams of Configuration Factor Algebra (Sheet 2 of 2)
Solving for $F_{32}$ from Equation 299 yields

$$F_{32} = \frac{1}{A_3} \left[ F_{(1 + 3, 2)}^A (1 + 3) - F_{12}^A A_1 \right] \quad (300)$$

Equation 300 expresses the shape modulus $F_{32}$ in terms of two shape moduli which can be obtained directly from graphical information available in NACA TN 2836 (Reference 22).

As a second example, consider finding $F_{14}$ for diagram 3. Applying the same technique as for the first example yields

$$\phi_{14} = \phi_{(1 + 3, 2 + 4)} - \phi_{12} - \phi_{34} - \phi_{32} \quad (301)$$

Now, if all surfaces have uniform emittance, Yamauti's modified reciprocity theorem can be applied, yielding

$$\phi_{14} = \phi_{32} = \phi_{23} = \phi_{41} \quad (302)$$

Substituting Equation 302 into Equation 301 and combining terms,

$$\phi_{14} = \frac{1}{2} \left[ \phi_{(1 + 3, 2 + 4)} - \phi_{12} - \phi_{34} \right] \quad (303)$$

Equation 297 is now substituted into Equation 303. The resulting equation is solved for $F_{14}$. This operation gives

$$F_{14} = \frac{1}{2} A_1 \left[ F_{(1 + 3, 2 + 4)}^A (1 + 3) - F_{12}^A A_1 - F_{34}^A A_3 \right] \quad (304)$$

Equation 304 is a relation for $F_{14}$ in terms of configuration factors which can be evaluated graphically.

A similar procedure can be used to derive the configuration factor for almost any configuration in terms of configuration factors which can be evaluated directly. A number of the more common cases are summarized in Figure 76, which was obtained from Reference 26 (Table 38).

**Finite Configuration Factor Conversion**

An important technique for the evaluation of finite-finite configuration factors is called the area weighted method. Briefly, the finite-finite
configuration factor can be obtained from a knowledge of the differential-finite configuration factor at every point or, as in this method, at certain well chosen intervals.

Recalling the basic equation for a finite-finite configuration factor,

\[ F_{12} = \frac{1}{\pi A_1} \int_{A_1} \int_{A_2} \frac{\cos \theta_1 \cos \theta_2}{S^2} \, dA_1 \, dA_2 \]  

(305)

If \( A_1 \) is relatively small, the kernel \( (\cos \theta_1 \cos \theta_2 / S^2) \) of this integral of the above equation is effectively independent of \( dA_1 \) or essentially constant and can be removed from the integral when integrating over \( A_1 \). Thus

\[ F(\Delta A_1 - A_2) = \left( \frac{\Delta A_1}{A_1} \right) \left( \frac{1}{\pi} \right) \int_{A_2} \frac{\cos \theta_1 \cos \theta_2}{S^2} \, dA_2 \]  

(306)

which is the same as

\[ F(\Delta A_1 - A_2) = \frac{\Delta A_1}{A_1} F(dA_1 - A_2) \]  

(307)

The quantity \( \Delta A_1 \) is a smaller finite area that forms some part of the larger area \( A_1 \). The configuration factor \( F(dA_1 - A_2) \) is taken from the center of \( \Delta A_1 \), to the whole of \( A_2 \). By summing up terms such as given in Equation 307, the total shape modulus \( F_{12} \) is obtained.

\[ F_{12} = \sum_{A_1} \left( \frac{\Delta A_1}{A_1} \right) F(dA_1 - A_2) \]  

(308)
IBM 7090 PROGRAM (GEOMETRIC CONFIGURATION FACTORS)

An IBM 7090 program (Reference 27) which calculates geometric configuration factors is now in final preparation. The program is limited to the calculation of the geometric configuration factor between two planes which must be parallelograms, including the special cases of squares, rectangles, and rhombi.

The method of calculation is a numerical approximation of the integral form of the configuration factor equation from a plane in space to any other plane. Under control of certain input data the two planes are divided into a number of incremental areas. The expression for the configuration factor from an incremental area in plane 1 to another in plane 2 is

\[ F(dA_1 - \Delta A_2) = \frac{\cos \theta_1 \cos \theta_2 \Delta A_2}{n r^2} \]  

(309)

where

\( \theta = \) Angle between the normal to plane 1 and line connecting center points of two incremental areas

\( \theta_2 = \) Same angle for plane 2

\( \Delta A_2 = \) Incremental area in plane 2

\( r = \) Length of line connecting center points of two incremental areas

This calculation is repeated for all the incremental areas in plane 2, and the summation of these is the configuration factor from the incremental area \( \Delta A_1 \) to the total second area. (Note that the calculated individual \( F(dA_1 - \Delta A_2) \) takes the form of a differential area to finite area configuration factor. This is calculated from the midpoint of \( \Delta A_1 \), and is assumed to be the average over \( \Delta A_1 \).)

The foregoing process is then repeated for each incremental area in plane 1. An integrated average of the configuration factors from all the \( \Delta A_1 \) to \( A_2 \) is equivalent to the configuration factor from plane 1 to plane 2.
UNIT SPHERE METHOD (DIFFERENTIAL-FINITE CONFIGURATION FACTOR)

An extremely useful method for the development of the differential-finite configuration factor is known as the unit sphere or solid angle projection method. This is discussed in some detail in Reference 26 (p 294-298).

Briefly, it can be stated that the configuration factor from \( dA_1 \) to \( A_2 \), in Figure 77 can be obtained as follows:

1. A hemisphere is drawn over \( dA_1 \) of radius \( R \).
2. The area \( A_2' \) cut on the spherical surface by the solid angle from \( dA_1 \) to \( A_2 \) is obtained by central projection.
3. The projected area \( A_2' \) must then be projected once more by normal projection to the plane of the radiating surface \( dA_1 \). The area of the second projection is \( A_2'' \) in Figure 77.
4. The configuration factor \( F(dA_1-A_2) \) is given by the ratio of \( A_2'' \) to the area of the circle. Thus,

\[
F(dA_1-A_2) = \frac{A_2''}{\pi R^2}
\]  

(310)

It can be seen that \( A_2 \) need not be a plane surface as long as the perimeter of the surface is defined (i.e., \( A_2 \) could easily have been concave or convex and the same value of \( F(dA_1-A_2) \) would have been obtained).

To determine the configuration factor from a finite surface \( A_1 \) to a finite surface \( A_2 \), the surface \( A_1 \) must be divided into small areas of equal size and the unit sphere method must be used for the centers of every one of these areas. The average of these is the finite-finite configuration factor \( F_{12} \).

The unit sphere method is often useful when the other methods of configuration factor analysis cannot be readily used. However, it is a somewhat tedious method. There are several ways in which to attack the problem:

1. **Descriptive geometry.** This is essentially a "brute force," hand calculation method, which employs ordinary descriptive geometry techniques.

2. **Mechanical integrators.** Several mechanical integrators have been built based on the unit sphere method (References 22 and 29 through 32). These usually require the use of models because they are employed by tracing the outline of the shape under consideration.
Figure 77. Diagram of Unit Sphere Method for Determining Configuration Factor
3. **Photography.** Considerable work has been done at the University of California at Los Angeles and elsewhere, based on a point source light being placed in the center of a milk-glass hemisphere. A model of the area $A_2$ is then placed inside the hemisphere in the proper position with respect to the point source $dA_1$. It is projected by the point source lamp as a shadow to the milk-glass hemisphere. When this hemisphere is photographed from a considerable distance, the ratio of the shadow of the model area to the area of the circle representing the glass sphere is the configuration factor (Reference 28, p 214-215).
DISCUSSION OF ASSUMPTIONS

When configuration factors are determined, the basic assumption is made that the thermal radiation involving these configuration factors exists in diffuse form. The complications produced by an attempted analysis of a partly diffuse, partly specular radiation problem are so great that a satisfactory method of analysis for this condition has not yet been devised.
This section of the report is concerned with the variables which influence satellite shell temperature and their effect on the cyclic temperature during each orbit revolution. Each parameter is independently varied by choosing various values within a realistic range of values. The evaluation studies point out the thermal problems associated with space vehicles and demonstrate the necessity for a large amount of analytical thermal prediction work required during design of a space vehicle.

These evaluation studies were completed through use of the IBM 7090 program, "Program for Determining Temperatures of Orbiting Space Vehicles" (Reference 33). This program is also discussed in Section V of this report.

NOMENCLATURE

\begin{align*}
    a & \quad \text{Earth albedo} \\
    e & \quad \text{Eccentricity} \\
    h & \quad \text{Orbital height, mi} \\
    i & \quad \text{Inclination, deg} \\
    Q & \quad \text{Internal heat load, watt/sq ft of surface area} \\
    S & \quad \text{Solar constant, Btu/(hr)(sq ft)} \\
    a & \quad \text{Absorptivity} \\
    a/\varepsilon & \quad \text{Ratio of absorptivity to emissivity} \\
    \varepsilon & \quad \text{Emissivity} \\
    \omega & \quad \text{Mass, lb/sq ft of surface area}
\end{align*}

VARIABLES SELECTED

The variables that were considered are those listed in Table 6. Simple configurations are used in evaluating the effects of the variables on the cyclic surface temperature and include a rotating sphere, an earth-oriented flat plate, an inertially oriented flat plate, and an eight-sided, earth-oriented prism.

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### Table 6. Study Variables for Rotating Sphere

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbital height</td>
<td>Distance from planet, miles</td>
<td>150 to 2000</td>
</tr>
<tr>
<td>Orbital plane</td>
<td>Inclination from plane of ecliptic, degrees</td>
<td>0 to 80</td>
</tr>
<tr>
<td>Surface finish</td>
<td>Ratio of solar absorptivity to emissivity</td>
<td>0.1 to 20.0</td>
</tr>
<tr>
<td>Internal heat load</td>
<td>Watts per square foot of surface area</td>
<td>1.0 to 20.0</td>
</tr>
<tr>
<td>Mass</td>
<td>Pounds per square foot of surface area</td>
<td>0.25 to 10.0</td>
</tr>
<tr>
<td>Solar Constant</td>
<td>Near earth solar constant, Btu/(hr)(sq ft)</td>
<td>433 to 453</td>
</tr>
<tr>
<td>Albedo</td>
<td>Earth's albedo</td>
<td>0.2 to 0.8</td>
</tr>
</tbody>
</table>

### ROTATING SPHERE EVALUATION

#### Variation of Orbital Height

The cyclic variation in temperature for a rotating sphere is shown in Figure 78 as a function of orbital height. The orbital height in miles was varied from 150 to 2000 miles. The fixed parameters for the sphere were as follows:

- Absorptivity $\alpha$: 0.7
- Emissivity $\epsilon$: 0.5
- Mass $\omega$: 1.5 lb/sq ft
- Earth albedo $\alpha$: 0.35
- Solar constant $S$: 443 Btu/(hr)(sq ft)
- Orbital inclination $\theta$: 33.0 deg

The results point out the influence of increasing height on increasing percentage of time in sunlight and the influence of decreasing earth-emitted and solar-reflected energy with increasing height. The maximum temperatures for the 150- and 500-mile height are similar while the maximum temperature for the 250-mile orbit is higher, and the peak temperatures for the 1000- and 2000-mile orbits are lower. Due to the
Figure 78. Variation of Orbital Height for Rotating Sphere
choice of fixed parameters, the time in direct sunlight is being opposed by the reduction in energy from the earth as the height increases.

The orbital period, percent of time in sunlight, and earth emitted form factor are listed in Table 7 for the various orbits.

Table 7. Variation of Orbital Height for Rotating Sphere

<table>
<thead>
<tr>
<th>Orbital Height (mi)</th>
<th>Orbital Period (min)</th>
<th>Sun time (percent)</th>
<th>Earth-Emitted Form Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>88.89</td>
<td>57</td>
<td>0.37</td>
</tr>
<tr>
<td>250</td>
<td>92.17</td>
<td>58</td>
<td>0.33</td>
</tr>
<tr>
<td>500</td>
<td>100.52</td>
<td>61</td>
<td>0.27</td>
</tr>
<tr>
<td>1000</td>
<td>117.92</td>
<td>72</td>
<td>0.199</td>
</tr>
<tr>
<td>2000</td>
<td>155.4</td>
<td>100</td>
<td>0.127</td>
</tr>
</tbody>
</table>

Variation of Orbital Plane

Using the same parameters as for the orbital height study and holding the orbital height at 250 miles, the effect of orbital plane on cyclic temperature variation was investigated. As shown in Figure 79 the inclination of the plane of the orbit to the plane of the ecliptic was varied from 0 to 80 degrees. Also, the year day from 1 January 1961 was chosen from the data in Figures 80 through 84 to give the maximum sun time for each orbit plane.

The results are as expected. The increase in sun time with increasing orbit plane raises the mean temperature and reaches a maximum when the vehicle is in the sun 100 percent of the time. The effect of launch day can be determined through comparison of the curve for 250 miles (Figure 78) compared with the curve for 33 degrees (Figure 79), because all parameters are the same except the year day.

Variation of Surface Finish

A primary consideration in any space vehicle temperature control system is the external surface finish. The amount of radiant energy received and the amount of heat radiated to space are direct functions of the external condition of the surface. For some space vehicles, where the internal heat loads are low and the equipment temperature tolerance fairly broad, complete control can be attained by the selection of the proper emissivity and solar absorptivity combination.
Figure 79. Variation of Orbital Inclination for Rotating Sphere
In the parametric study described here, the cyclic temperature variation was calculated for various combinations of absorptivity $\alpha$ and emissivity $\epsilon$, with no association given to specific materials or coatings. (Unfortunately, although there are several coatings that have desirable thermal characteristics, these materials do not appear too practical for space application.) The same fixed parameters for the sphere were used.

The results of the study are shown in Figures 80 through 82. In each plot, solar absorptivity was held constant but emissivity varied over a wide range. To point out some of the trends, it is helpful to look at Table 8 where the $\alpha/\epsilon$ ratio is tabulated along with the maximum and minimum temperatures.

Table 8. Variation of Surface Finish for Rotating Sphere

<table>
<thead>
<tr>
<th>Solar Absorptivity</th>
<th>$\alpha/\epsilon$ Ratio</th>
<th>Temperature (F)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Maximum</td>
</tr>
<tr>
<td>0.1</td>
<td>0.1</td>
<td>-81</td>
</tr>
<tr>
<td>0.1</td>
<td>0.125</td>
<td>-75</td>
</tr>
<tr>
<td>0.1</td>
<td>0.20</td>
<td>-59</td>
</tr>
<tr>
<td>0.3</td>
<td>0.33</td>
<td>-33</td>
</tr>
<tr>
<td>0.3</td>
<td>0.375</td>
<td>-14</td>
</tr>
<tr>
<td>0.5</td>
<td>0.5</td>
<td>13</td>
</tr>
<tr>
<td>0.5</td>
<td>0.72</td>
<td>42</td>
</tr>
<tr>
<td>0.5</td>
<td>1.0</td>
<td>53</td>
</tr>
<tr>
<td>0.5</td>
<td>1.0</td>
<td>74</td>
</tr>
<tr>
<td>1.0</td>
<td>1.0</td>
<td>93</td>
</tr>
<tr>
<td>1.0</td>
<td>1.11</td>
<td>104</td>
</tr>
<tr>
<td>1.0</td>
<td>1.25</td>
<td>117</td>
</tr>
<tr>
<td>0.7</td>
<td>1.40</td>
<td>120</td>
</tr>
<tr>
<td>1.0</td>
<td>1.43</td>
<td>133</td>
</tr>
<tr>
<td>0.5</td>
<td>1.66</td>
<td>130</td>
</tr>
<tr>
<td>0.1</td>
<td>2.0</td>
<td>126</td>
</tr>
<tr>
<td>0.5</td>
<td>5.0</td>
<td>285</td>
</tr>
<tr>
<td>0.5</td>
<td>10.0</td>
<td>399</td>
</tr>
<tr>
<td>1.0</td>
<td>20.0</td>
<td>576</td>
</tr>
</tbody>
</table>

As the $\alpha/\epsilon$ ratio increases, the mean temperature increases. Also, at a ratio of 1.0 for various values of solar absorptivity, the temperature spread (between maximum and minimum) decreases with decrease in solar absorptivity. This is due to the mass of the surface, where at low-energy transfer the storage term is more dominant than at high-energy transfer associated with high solar absorptivity. For the particular sphere used...
Figure 80. Variation of Emissivity for Rotating Sphere (Absorptivity 0.10)
Figure 81. Variation of Emissivity for Rotating Sphere (Absorptivity 0.50)
Figure 82. Variation of Emmissivity for Rotating Sphere (Absorptivity 1.0)
in these studies with absorptivity of 0.7 and emissivity of 0.5, the maximum and minimum temperatures of 120 F and 18 F, respectively, would be quite tolerable for most equipment.

**Variation of Mass**

The cyclic temperature variation of a space vehicle surface is a function of the mass of that surface. As shown in Figure 83, the mass for the rotating sphere was varied from 0.25 to 10 pounds per square foot. The same fixed parameters were used.

The results point out, as expected, that as the mass of the surface increases the temperature excursion is decreased. Also, as the mass is increased, the calculated mean temperature increases to the limiting temperature, which for any mass is a function of the fourth root of the average of the temperature extremes to the fourth power. In Table 9, the calculated mean temperature and the maximum and minimum temperatures are tabulated.

**Table 9. Variation of Mass for Rotating Sphere**

<table>
<thead>
<tr>
<th>Mass (lb/sq ft)</th>
<th>Temperature (F)</th>
<th>(4 \sqrt{\frac{T_{\text{max}}^4 + T_{\text{min}}^4}{2}})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Maximum</td>
</tr>
<tr>
<td>0.25</td>
<td>44</td>
<td>154</td>
</tr>
<tr>
<td>0.75</td>
<td>62</td>
<td>139</td>
</tr>
<tr>
<td>1.5</td>
<td>67</td>
<td>118</td>
</tr>
<tr>
<td>3.0</td>
<td>71</td>
<td>100</td>
</tr>
<tr>
<td>10.0</td>
<td>72</td>
<td>84</td>
</tr>
</tbody>
</table>

For any given orbit revolution, the energy input must equal the energy loss and, therefore, the total radiative power loss or input must be a constant, regardless of the mass of this particular vehicle. However, the mass regulates the thermal lag of the surface and determines the cyclic temperature excursion between the limits of equilibrium temperature with no mass and the limiting equilibrium temperature with a very large mass.
Figure 83. Variation of Mass for Rotating Sphere

ROTATING SPHERE
ECCENTRICITY $e$ 0.0
INCLINATION $i$ 33.0 DEG
ORBITAL HEIGHT $h$ 250 MI
EARTH ALBEDO $a$ 0.35
MASS $\omega$ AS NOTED
SOLAR CONSTANT $S$ 443 BTU/(HR)(SQ FT)
ABSORPTIVITY $\alpha$ 0.7
EMISSIVITY $\epsilon$ 0.5
INTERNAL HEAT LOAD $Q$ 0.0
Variation of Internal Heat Load

The cyclic variation in temperature for a rotating sphere is shown in Figure 84 as a function of internal heat load, with the same fixed parameters assumed. The internal heat load was varied from 1.0 to 20 watts per square foot. The results indicate, as expected, that the outer shell temperature increases as the internal heat load increases. The results at 1.0 watt per square foot show a maximum temperature of 125 F and a minimum temperature of 22 F. For the case with an internal heat load of 20 watts per square foot, the maximum temperature increases to 212 F and the minimum temperature is 121 F.

Variation of Earth Albedo

In the calculation of the cyclic temperature variation of a satellite in orbit, it is necessary to know the planet's albedo to properly account for the planet emission and reflected solar energy. As discussed in Section IV on the space thermal environment, the earth albedo varies because of the planet's surface, scattering by clouds and dust in the atmosphere, and molecular scattering by the atmospheric gases.

To determine the effect of various values of the earth's albedo on the cyclic temperature variation, an analysis was made on the rotating sphere. Four values of the earth albedo \( a \) were chosen: 0.2, 0.35, 0.5 and 0.8. For each value, various values of the \( a/c \) ratio were chosen for each satellite.

The results of the analysis for earth albedos of 0.2, 0.5, and 0.8 are shown in Figures 85 through 87, with the same fixed parameters assumed.

A summary of the results is shown in Table 10, where the maximum and minimum temperatures are tabulated for the various ratios of \( a/c \). As the earth albedo is increased, the reflected solar energy from the earth that is incident on the vehicle is increased; however, the earth's emitted energy incident on the vehicle is decreased because the effective earth temperature is decreased. The maximum temperature is shown to increase, while the minimum temperature decreases for an increase in albedo. Also, the magnitude of the change increases with increase in \( a/c \) ratio.

Variation of Solar Constant

To determine the effect on the cyclic temperature variation of changes in the solar constant, an analysis was made using 433, 443, and 453 Btu/(hour)(square foot) as values for the solar constant. For each value, various values of the \( a/c \) ratio were chosen for each satellite. The same fixed parameters were used as in the previous runs.
Table 10. Variation of Earth Albedo for Rotating Sphere

<table>
<thead>
<tr>
<th>Surface Characteristics</th>
<th>Temperature (F)</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Albedo 0.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Albedo 0.35</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Albedo 0.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Albedo 0.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$a/\epsilon$</td>
<td>$a$</td>
<td>$\epsilon$</td>
<td>Max</td>
<td>Min</td>
<td>Max</td>
<td>Min</td>
<td>Max</td>
<td>Min</td>
</tr>
<tr>
<td>0.5</td>
<td>0.5</td>
<td>1.0</td>
<td>13</td>
<td>-51</td>
<td>13</td>
<td>-58</td>
<td>13</td>
<td>-66</td>
</tr>
<tr>
<td>1.0</td>
<td>0.5</td>
<td>0.5</td>
<td>70</td>
<td>0</td>
<td>74</td>
<td>-2</td>
<td>80</td>
<td>-4</td>
</tr>
<tr>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>85</td>
<td>-32</td>
<td>93</td>
<td>-38</td>
<td>100</td>
<td>-44</td>
</tr>
<tr>
<td>1.43</td>
<td>1.0</td>
<td>0.7</td>
<td>121</td>
<td>0</td>
<td>133</td>
<td>-4</td>
<td>144</td>
<td>-7</td>
</tr>
<tr>
<td>1.67</td>
<td>0.5</td>
<td>0.3</td>
<td>122</td>
<td>51</td>
<td>130</td>
<td>52</td>
<td>140</td>
<td>53</td>
</tr>
</tbody>
</table>

Table 11. Variation of Solar Constant for Rotating Sphere

<table>
<thead>
<tr>
<th>Surface Characteristics</th>
<th>Temperature (F)</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Solar Constant</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>433 Btu/(Hr)(Sq Ft)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>443 Btu/(Hr)(Sq Ft)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>453 Btu/(Hr)(Sq Ft)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$a/\epsilon$</td>
<td>$a$</td>
<td>$\epsilon$</td>
<td>Max</td>
<td>Min</td>
<td>Max</td>
<td>Min</td>
<td>Max</td>
<td>Min</td>
</tr>
<tr>
<td>0.5</td>
<td>0.5</td>
<td>1.0</td>
<td>11</td>
<td>-60</td>
<td>13</td>
<td>-58</td>
<td>17</td>
<td>-57</td>
</tr>
<tr>
<td>1.0</td>
<td>0.5</td>
<td>0.5</td>
<td>71</td>
<td>-4</td>
<td>74</td>
<td>-2</td>
<td>76</td>
<td>0</td>
</tr>
<tr>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>89</td>
<td>-40</td>
<td>93</td>
<td>-38</td>
<td>96</td>
<td>-36</td>
</tr>
<tr>
<td>1.43</td>
<td>1.0</td>
<td>0.7</td>
<td>130</td>
<td>-5</td>
<td>133</td>
<td>-4</td>
<td>138</td>
<td>-2</td>
</tr>
<tr>
<td>1.67</td>
<td>0.5</td>
<td>0.3</td>
<td>126</td>
<td>50</td>
<td>130</td>
<td>52</td>
<td>134</td>
<td>54</td>
</tr>
</tbody>
</table>
Figure 84. Variation of Internal Heat Load for Rotating Sphere
Figure 85. Variation of Absorptivity-to-Emissivity Ratio for Rotating Sphere
(Earth Albedo 0.2)
Figure 8o. Variation of Absorptivity-to-Emissivity Ratio for Rotating Sphere (Earth Albedo 0.5)

- Rotating Sphere
- Eccentricity e
- Inclination i
- Orbital Height h
- Earth Albedo a
- Mass \( \omega \)
- Solar Constant \( S \)
- Absorptivity-to-Emissivity Ratio, \( \alpha/\epsilon \)
- Internal Heat Load, \( Q \)

- 0.0
- 33.0 DEG
- 250 MI
- 0.5
- 1.5 LB/SQ FT
- 443 BTU/(HR)(SQ FT)
- AS NOTED

- 1.0 (1.0/1.0)
- 0.5
- 1.0 (0.5/0.5)
- 1.43
- 1.67

Variation in shell temperature (F) as a function of orbital position (degrees).
Figure 87. Variation of Absorptivity-to-Emissivity Ratio for Rotating Sphere (Earth Albedo 0.8)
The results of the analysis for 433 and 453 Btu/(hour)(square foot) are shown in Figures 88 and 89. A summary of the results is shown in Table 11, where the maximum and minimum temperatures are tabulated for the various ratios of \( \alpha/\epsilon \). As expected, the cyclic temperature level is increased as the value of the solar constant is increased. The magnitude of the increase, for the set of conditions assumed for the sphere, appears to be approximately 0.4 to 0.9 percent in temperature level for a 2.0 percent change in solar constant.

**COMPARISON OF ROTATING SPHERE AND FLAT PLATE**

The cyclic variation in shell temperature for a rotating sphere was compared with inertially oriented and earth-oriented flat plates, as shown in Figure 90. The following parameters were used for the three surfaces:

- Absorptivity \( \alpha \) = 0.7
- Emissivity \( \epsilon \) = 0.5
- Mass \( \omega \) = 1.7 lb/sq ft
- Earth albedo \( \alpha \) = 0.35
- Solar constant \( S \) = 443 Btu/(hr)(sq ft)
- Orbital inclination \( \iota \) = 33.0 deg
- Orbital height \( h \) = 250 mi
- Internal heat load \( Q \) = 0

Also, the back faces of the flat plates were assumed to be perfectly insulated.

The earth-oriented flat plate shows a slight increase in temperature at 20 and 170 degrees. This is due to the plate's receiving direct solar energy for a short time, just after passing the terminator and before going into the earth's shadow, and again when leaving the earth's shadow just before passing over the terminator. The temperature level, in general, is higher than that of the inertially oriented plate because the geometric form factor for the earth-emitted energy is constant at approximately 0.88 for the earth-oriented plate. The form factor for the inertially oriented plate varies from 0 at 20 degrees to 0.88 at 185 degrees, where the surface is facing the earth and parallel to the orbit path, and then decreases to 0 again at 335 degrees.
Figure 88. Variation of Absorptivity-to-Emissivity Ratio for Rotating Sphere
[Solar Constant 433 Btu/(Hour)(Square Foot)]
Figure 89. Variation of Absorptivity-to-Emissivity Ratio for Rotating Sphere
[Solar Constant 453 Btu/(Hour)(Square Foot)]
Figure 90. Comparison of Rotating Sphere and Flat Plate
CYCLIC TEMPERATURE VARIATION OF EIGHT-SIDED PRISM

A space vehicle configuration, consisting of an eight-sided prism with two ends, was considered in order to study the effects of cyclic temperature variation of the various sides. The vehicle was assumed to be earth-oriented so that the vehicle axis was on the orbital path. A retrograde orbit of 96.6-degree inclination was used in conjunction with an orbital height of 225 miles. The orientation of the vehicle surfaces in relationship to the earth and sun is shown in Figure 91. The bottom surfaces are 1, 4, and 10, and the top surfaces are 6, 2, and 8; the sides are 5 and 9, and the ends are 3 forward and 7 aft. The fixed parameters used for the prism were as follows:

- Absorptivity $a = 0.7$
- Emissivity $\epsilon = 0.5$
- Mass $\omega = 0.5 \text{ lb/sq ft}$
- Earth albedo $a = 0.35$
- Solar constant $S = 443 \text{ Btu/(hr)(sq ft)}$

The cyclic temperature variation for each surface is shown in Figure 92. To summarize the results and to point out the effects of changing the surface characteristics and increasing the mass of the individual surfaces, the maximum and minimum temperatures are tabulated in Table 12. The mass of the surfaces for the second case was 1.5 pounds per square foot.

Table 12. Maximum and Minimum Temperatures for Eight-Sided Prism

<table>
<thead>
<tr>
<th>Surface</th>
<th>Surface Finish</th>
<th>Temperature (F)</th>
<th>Surface Finish</th>
<th>Temperature (F)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$a$</td>
<td>$\epsilon$</td>
<td>Min</td>
<td>Max</td>
</tr>
<tr>
<td>Bottom</td>
<td>1</td>
<td>0.7</td>
<td>0.5</td>
<td>160</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.7</td>
<td>0.5</td>
<td>116</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.7</td>
<td>0.5</td>
<td>116</td>
</tr>
<tr>
<td>Top</td>
<td>2</td>
<td>0.7</td>
<td>0.5</td>
<td>315</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.7</td>
<td>0.5</td>
<td>253</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.7</td>
<td>0.5</td>
<td>258</td>
</tr>
<tr>
<td>Sides</td>
<td>5</td>
<td>0.7</td>
<td>0.5</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>0.7</td>
<td>0.5</td>
<td>22</td>
</tr>
<tr>
<td>Ends</td>
<td>3</td>
<td>0.7</td>
<td>0.5</td>
<td>323</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>0.7</td>
<td>0.5</td>
<td>323</td>
</tr>
</tbody>
</table>
Figure 91. Diagram of Earth-Oriented Eight-Sided Prism
Figure 92. Cyclic Temperature Variation of Earth-Oriented Eight-Sided Prism (Sheet 1 of 2)
The effect of mass in reducing the temperature spread between maximum and minimum temperatures is shown by surface 1 (the bottom surface which always faces the earth) when compared with the earth-oriented flat plate in Figure 90. For the case with extremely small surface mass, surface 1 reaches the shadow side equilibrium temperature of -17 F. When the mass is increased to 1.5 pounds per square foot and absorptivity and emissivity are changed to 0.4 and 0.3, respectively, the maximum and minimum temperatures are 101 and 37 F. With the proper choice of surface finish and a reasonable structural mass, these particular vehicle surfaces can be maintained within reasonable temperature limits.

DISCUSSION OF ASSUMPTIONS

1. It is assumed in this analysis that the earth can be represented gravitationally by the zero-order and second-order spherical harmonics of its potential. The presence of harmonics in the earth's gravitational potential causes periodic and secular variations in several of the orbital elements. Only the secular perturbations which result in regression of the nodes and advance of the perigee position are considered in the analysis. Other periodic changes have negligible effect upon the shadow intersection problem.

2. A rigorous specification of the position at which the satellite enters and exits the earth's true shadow leads to needlessly complicated expressions. For this reason the following simplifications concerning shadow geometry are assumed:

a. The earth is spherical with its radius equal to 3960 statute miles.
b. The earth's shadow is cylindrical and umbral (sun at infinity).
c. Penumbral effects are ignored.

The error involved is extremely small even when large orbits are considered. For instance, a satellite in a circular orbit with an altitude of 10,000 miles has an orbit period of approximately 560 minutes, with perhaps 50 minutes spent in earth shadow (depending on orbit orientation). By assuming a cylindrical earth shadow and ignoring penumbral effects, the analysis uses an umbral shadow time that is about 50 seconds longer than the true umbral shadow time. This is a negligible error. For a 1000-mile-altitude circular orbit, the negligible error is approximately 18 seconds in an orbit period of 118 minutes. Additionally, it should be mentioned that the assumption of no penumbral effects tends to lessen the above errors introduced by the assumption of cylindrical umbral shadow, so that there is almost zero error from a thermal analysis standpoint.

3. It is assumed that all thermal radiation considered in the analysis, except solar radiation, is in diffuse form. Fortunately most thermal radiation is in diffuse form, which is relatively simple to analyze when compared with specular radiation.
4. It is assumed that direct solar radiation impinges upon the earth and upon the satellite with parallel rays, due to the great distance between the sun and its planets. Almost zero error is introduced into the analysis by the assumption.

5. In all cases, it is assumed that the earth emits as a black body and is in a state of thermal equilibrium (i.e., the planetary emitted energy is equal to the absorbed solar energy). It is also assumed that the earth emission is a constant at any point on its surface and does not vary from day to night. These are reasonable assumptions because little is known of the actual spectral and local variations in the planetary emitted radiation.

6. The earth reflected solar radiation is assumed to follow the cosine law (i.e., it is a maximum at the subsolar point and decreases to zero at the terminator). This assumption greatly simplifies the analysis and is quite accurate except in the region of the terminator, where a slight error is introduced.

7. In all cases, the planetary albedo is assumed to be constant over the surface of the planet, and the planet is assumed to be a diffuse reflector. This is done because of the complications of the problem and because local variations are almost impossible to define.

8. In all cases, conduction and convection between the satellite and its surroundings are neglected. This is reasonable because orbital heights are usually too far above the atmosphere for these types of thermal effects to appear.

9. It is assumed that the absorptivity of the vehicle surface to planetary thermal emission is equal to the emissivity of the vehicle surface. Since the effective temperature of the earth and the temperatures of most vehicle surfaces are nearly the same, this assumption is validated by Kirchhoff's law.

10. Any scattering effects of direct solar radiation upon the satellite due to the earth's atmosphere are ignored. It is felt that this will introduce a negligible error into the analysis.

11. The geometrical configuration factor from the spherical satellite to earth was calculated with the assumption that the satellite is a point source in space. The assumption is valid if the satellite is uniform in temperature, which it would be if spinning or if its shell had a very high thermal conductivity.
CONCLUSIONS

ANALYSIS TECHNIQUES

This report has reviewed the basic principles of thermal radiation and has presented several available methods of radiation heat transfer analysis, with emphasis upon the situation encountered by a vehicle in space.

An IBM 7090 program has been written (Section V) with which it is possible to obtain space vehicle shell temperatures and the incident radiant energy impinging upon the vehicle from its space environment. The significance of this program is that it will accurately simulate any elliptical or circular orbit into which a satellite may be placed.

In the field of general radiation heat transfer analysis, a comparison has been made between various methods of analysis in which the accuracy and versatility of the radiosity analog network method is pointed out. It is hoped that a more widespread use of this relatively new technique will occur in industry.

One of the most difficult areas in the analysis of radiation heat transfer is the proper calculation of the geometric configuration factor. A considerable amount of tabulated data is presented in this report (Section VII), some of which has been heretofore unpublished. In conjunction with this report, an IBM 7090 program (Reference 27) has been written which will calculate the configuration factor between two plane areas in any orientation with respect to each other. While presently limited in scope, this program has promise of being developed into an extremely valuable tool for the heat transfer engineer.

PROBLEM AREAS

Thermal Analysis of Nondiffuse Radiation

A problem area which came to light in the preparation of this report and which needs further investigation concerns the thermal analysis of nondiffuse radiation. Presently used methods of analysis make the basic assumption that all radiant energy is diffuse, whereas, in actuality, radiant energy usually exists in partly diffuse, partly specular form. Data pertaining to directional emissive properties are very limited, almost not
available. Fortunately, the majority of radiant energy does exist in essentially diffuse form, so that presently available analytical methods are usually applicable. There are many occasions, however, when this is not true, and the engineer is forced to make questionable approximations.

Calculation of Geometric Configuration Factors

Another problem area concerns the calculation of geometric configuration factors, an essential part of radiation heat transfer analysis. This is probably the most tedious and time consuming job encountered in the analysis. Although much work has been done in this area, data are still limited. For other than simple shapes, numerical or mechanical integrators must be utilized, and this is a time consuming process. As mentioned, there is hope that an IBM program can be developed to aid in this area.

Measurement and Presentation of Data

The accurate thermal analysis of space vehicles depends heavily on the availability of accurate data on the thermal properties of materials, including solids, liquids, and gases. These properties include absorptivity, emissivity, conductivity, and specific heat, and they should be known for the entire temperature range of interest and as a function of wave length, angle, and pressure, as applicable. Much of the published data on thermal properties, however, are subject to serious question; handbook-type data generally represent only average values over a narrow range of conditions. The common practice of not differentiating between normal and hemispherical emissivity can lead to serious errors in temperature prediction.

The lack of accurate information on thermal properties jeopardizes the accuracy of thermal analyses and probably will lead to in-flight failures. With the multiplicity of data collecting and publishing agencies, the inconsistencies and contradictions between published data on the same materials creates increasing confusion. So it is concluded that standardized methods of measuring and presenting data on the thermal properties of materials are needed.

Effects of Space Environment on Space Vehicles

It is generally accepted that space vehicles will be subjected to deteriorating influences in a space environment. In some cases, the magnitude of these external influences is known. In almost every case, however, the effect of these influences on space vehicle materials is either incompletely known or totally unknown. The data from actual satellites are very meager and are being accumulated too slowly to support current needs.
Although the accumulation of data relative to the effects in materials of some of the components of the space environment is progressing on many fronts, the present lack of data casts doubt on the current designs of space vehicles. One factor that seems to be receiving little experimental attention is the effect of micrometeorite erosion on the absorptivity and emissivity of surface coatings. The short-term effects may reasonably be neglected; but for long durations, the deterioration may become quite pronounced. Comparative data on absorptivity and emissivity before and after a multiplicity of simulated micrometeorite impacts on representative coatings are needed as a guide for future vehicle designs.

The lack of accurate and complete information on the effects of the space environment on the absorptivity and emissivity of surface coatings makes the design of passive temperature control systems very questionable for long-duration vehicles. To compensate for unknown variations, it may be necessary to resort to semipassive or active temperature control systems.

The effect of the low-pressure environment encountered in space is known to cause a significant increase in thermal resistance across structural joints, whether they be bolted, riveted, or spot-welded. This thermal resistance is almost impossible to predict accurately, and it must be eliminated in conduction cooling paths and other thermally significant structures. At the present time, there is available a vacuum-resistant silicone type grease, often called "space grease," which seems to offer great promise in reducing contact resistance when applied to a structural joint. There are other materials, such as aluminum foil, that might also prove to be effective upon investigation. Although some work has been done in this area, further effort is needed.
Section X

ANNOTATED BIBLIOGRAPHY

This annotated bibliography was prepared as a result of a literature survey conducted by the reference staff of the Technical Information Center of S&ID.

PERIODICALS

Advances in Astronautical Sciences

Temperature equilibrea in space vehicles. R. Cornog.

The equilibrium temperature reached within a space vehicle moving within the solar system is discussed. The effects of vehicle configuration, vehicle attitude, surface properties, and internal heat release are evaluated. Particular attention is given to methods of vehicle design whereby the range of equilibrium temperatures can be set at some desired value.

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L. D. Wing.

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The problems associated with the behavior of materials in space, including passive temperature control are discussed.
Aero/Space Sciences, Journal of the

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Vol 27, February 1960, p 146-147.
The minimum-weight straight fin of triangular profile radiating to space. E. N. Nilson and R. Curry.

A basic property of the nonlinear differential equation expressing the radiation of waste heat from a spacecraft yields a method of solution which is an extension of the solution of the problem of determining the triangular fin of optimum shape for discharging such heat by convection.

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ARS Journal

Thermostatic temperature control of satellites and space vehicles. R. A. Hanel.

The temperature of satellites and space vehicles varies considerably with orbital conditions. To achieve greater reliability and
efficiency in long-life instruments, an automatic temperature control is highly desirable; a radiation thermostat performing this function is discussed. The suggested method regulates temperature by adjusting the effective absorptivity and emissivity. Bimetallic strips automatically move a light shield which exposes surfaces with high and low absorptivity-to-emissivity ratios. No internal power source is needed. Calculations demonstrate the effectiveness of the radiation thermostat. The temperature of the satellite's instruments can be kept constant within a few degrees of the design value, regardless of orbital conditions, internally dissipated power, and some erosion of skin coatings.

Vol 30, April 1960, p 344-352.
Thermal control of the Explorer satellites. G. Heller.

Thermal control of the Explorer satellites is discussed. The theoretical studies that were made prior to the launching of these satellites are described, and examples of relationships are presented in graphs. The lower limit of the instrument temperature was 0 C (determined by the efficiency of the chemical batteries). The upper limit was specified as 65 C (based on long-time temperature limits of transistors in the electronic package). This paper relates some of the studies, describes the measuring results of telemetered temperatures, and evaluates expected and obtained data.

Vol 30, May 1960, p 479-484.
Solar heating of a rotating cylindrical space vehicle. A. Charnes and S. Raynor.

Solar heating in a space vehicle idealized as a thin-walled circular cylinder rotating with uniform velocity about its geometric axis is studied for a situation in which heat transfer by convection and heat exchange within the cylinder is negligible. The nonlinear problem is approximated through a perturbation analysis, and detailed estimates are made of the parameters of interest for various ranges of speed of rotation. An estimate of the error between the exact and perturbational approach is made in the case of an illustrative example which might be expected to entail an extreme deviation.
Temperature equilibrea in space vehicles. R. A. Cornog.

The equilibrium temperature reached within a space vehicle moving within the solar system is discussed. The effects of vehicle configuration, vehicle attitude, surface properties and internal heat release are evaluated. Particular attention is given to methods of vehicle design whereby the range of equilibrium temperatures can be set at some desired value.

Thermal protection of space vehicles. P. E. Glaser.

The near-steady heating conditions encountered in long-term space flight have sparked development of integrated systems designed to protect the vehicle while combining maximum insulating effectiveness and low weight.

Thermal control in a space vehicle. P. E. Sandroff and J. S. Prigge.

Use of the equation of hydrostatic equilibrium in determining the temperature distribution in the outer solar atmosphere. S. R. Pottasch.

The purpose of this paper is to use the observed variation of electron density between 3000 kilometers and 20 solar radii and, assuming hydrostatic equilibrium, to derive a distribution of electron temperature in this region. The plausibility of the temperatures derived in this way is discussed.

Radiometric observations of Mars. W. Sinton and J. Strong.

How to find thermal equilibrium in space. R. E. Hess and A. E. Weller.
IRE Transactions on Military Electronics

Problems concerning the thermal design of Explorer satellites.
G. B. Heller.

The thermal design of the Explorer VII satellite is described. A thermal testing program conducted in the vacuum chamber with a prototype of Explorer VII is described, and some preliminary results of temperature measurements of the Explorer VII are given.

Iron Age

Vol 182, 6 November 1958, p 105-107.
How metals help control satellite's temperature. P. M. Unterweiser.

Case histories are considered concerning two small Navy satellites. The problem of controlling the temperature of the satellite's magnesium shell, which was subjected to periodic variations, was solved by gold plating its surface and covering it with an evaporated layer of silicon monoxide. This coating was then overlaid with opaque film of evaporated aluminum for high reflectivity.

Izvestiya Akademii Nauk SSSR, Seriya Geofizicheskaya

Vol 4, April 1957, p 527-533.
Temperature regime of an artificial earth satellite. A. G. Karpenko and M. I. Lidov.

Jet Propulsion

Vol 27, October 1957, p 1079-1083.
Skin temperatures of a satellite. C. M. Schmidt and A. J. Hanawalt.

The need for a workable artificial earth satellite has been established both for reconnaissance and as a prerequisite for space travel. An attendant problem in the design of such a vehicle is the control, and therefore the prediction, of temperatures that will exist in flight. Previous papers on this topic have brought out many salient features of such predictions, but have not been entirely realistic. The present paper attempts to improve on these assumptions and gives numerical computations for a particular configuration considered feasible for a satellite design. The example investigated is a nonrotating cylindrical
shell with one end point earthward. The problem of analysis is largely one of geometry, involving spacewise as well as timewise variations in skin temperature. The skin temperatures that will exist are very dependent on the properties of the surface, particularly emissivity and absorptivity, large values producing the widest range in surface temperatures. By proper choice of these parameters, this range can be greatly controlled. In particular, the mean temperature of the satellite skin is primarily a function of ol/e. For the specific configuration considered herein, nominal limits on the skin temperatures are -200 and +400 F.

Optical Society of America, Journal of the
Optical problems of the satellite. R. Tousey.

Vol 49, September 1959, p 918-924.

Report of NRL Progress
May 1958, p 1-7.
Satellite temperature control. L. F. Drummeter, Jr., and M. Schoch.

Science
Temperatures of a close earth satellite due to solar and terrestrial heating.

See Aero/Space Engineering, Vol 17, No. 10, October 1958, p 104.

SAE Journal
January 1959, p 54-55.
Water and ammonia evaporators show promise in cooling orbital space vehicles. J. S. Tupper.

The temperature equilibrium of a space vehicle. J. E. Navgle.

The equilibrium temperature of a space vehicle is considered. In space, away from the earth, the vehicle will come into radiative equilibrium with the sun's radiation. The skin temperature of the vehicle will rise until the amount of energy radiated by the vehicle is equal to the sum of the energy absorbed from the sun and that produced in the vehicle itself. The absorbed solar energy is in the visible portion of the spectrum, whereas the emitted energy is in the far infrared. Equilibrium temperatures attainable with existing materials are too high; the basic problem is one of keeping the vehicle cool. The problem of interest is the effect of the environment on the surface of such vehicle. Additional research is needed both as to the nature of the environment to be encountered and as to the effect of this environment on the surface.

Coatings for space vehicles. J. L. Snell.

At Jet Propulsion Laboratory, California Institute of Technology, ordinary types 430 and 410 stainless steels, used to encase delicate instrument capsules, were made to have thermal characteristics not yet possible in metal alone. Discussed are the techniques for temperature control, fabrication of the final assembly, and application of special process coatings of Rokide A by Cooper Development Corporation, Monrovia.

The temperature of an object above the earth's atmosphere. M. H. Seavey.

The equilibrium temperature of an object above the earth's atmosphere is calculated by considering the thermal radiation balance for the object.
American Rocket Society

Skin temperatures of a satellite. C. M. Schmidt and J. S. Prigge.

Army Ballistic Missile Agency

Thermal problems of satellites. G. Heller.

California Institute of Technology

EP-481
Satellite temperature measurements for 1958 Alpha - Explorer I.

External Publication 514, 2 June 1958.
Scientific results from the Explorer satellites. A. R. Hibbs.

A brief history of Explorer satellite launchings is given, together
with a description of payload instrumentation. Results of experi-
ments made in the areas of tempera. tures of both case and internal
instrumentation, micrometeorite activity, and cosmic ray
intensity are summarized. The results of preliminary analyses
of these various measurements are reported, and their implications for future
measurements of this type are discussed.

External Publication 647, 7 May 1959.
Temperature control in the Explorer satellites and Pioneer space
probes. E. P. Bulvalda and others.

The Jet Propulsion Laboratory participated in the Explorer and
Juno II programs in the areas of payload design and method of
achieving temperature control. This publication describes the
basic theory for the passive temperature control of satellites and
space probes and the application of this process to the Explorer
and Pioneer III and IV vehicles. Some results of in-flight
temperature measurements are also presented.

Radiative properties of surfaces considered for use on the Explorer
satellites and Pioneer space probes.

Spectral reflectance data in graphical form and tabular absorptance-
emittance data are presented for surface materials considered
for use on the Explorer satellites and Pioneer space probes. The
surfaces ranged from bare aluminum, titanium, and stainless
steel to painted coatings, coatings of Rokide A, and anodized and plated coatings. A brief review of the temperature control problem is presented as background information.

The temperature of an orbiting missile. A. R. Hibbs.

The successful operation of radio equipment carried in an orbiting missile requires fairly close control over the temperatures to which the equipment is subjected. This temperature is controlled by two factors. First, the temperature of the outer shell of the missile depends on radioactive transfer between the missile and its environment (sun, earth, and empty space). Secondly, the temperature of the equipment inside the missile depends on heat transfer from the shell (directly by radiation and through the structure by conduction). The analysis presented shows how the average temperature of the outer shell can be controlled (for a given missile shape, orientation, and trajectory) by a correct choice of surface coatings. It also indicates that the limits of temperature variation of the enclosed equipment can be held to within a few degrees of this average shell temperature by adequate insulation. Numerical calculations indicate the necessary characteristics of the coating and insulating materials.

Progress Report 20-319, 11 April 1957.
Evaluation of the absorptivities of surface materials to solar and terrestrial radiation, with plots of the reflectances (at wave-lengths of 0.4 to 2.5 m) for 10 sample materials including 2 types of fibrous-glass reinforced plastic. W. S. Shipley.

Contributions of the Explorer to space technology. J. E. Froehlich and A. R. Hibbs.

The philosophy of the Explorer programs is presented and demonstrated in the description of missile design and flight operation of the Explorer vehicles. Scientific measurements of cosmic ray intensity, temperature environment, and micrometeorite densities are described, and the significance of these measurements is discussed.
A method is presented for determining the thermal irradiance upon a space vehicle as a result of direct radiation, planetary thermal radiation, and planetary albedo. From this information, the temperature of a space vehicle can be obtained. Calculations can be made for various space vehicle altitudes above a planet and for various solar angles with respect to both the planet and space vehicle. The planets and natural satellites considered are the earth, moon, Mars, and Venus.

A procedure is presented for determining the radiation incident upon a satellite in an elliptical orbit. The satellite is treated as a set of plane areas, each area identified by the direction cosines of its outward normal with respect to a satellite coordinate system. This system is based on orbit orientation. Radiation emitted by and reflected by the parent body is computed by integrating over the spherical cap seen by the satellite. Solar radiation is considered constant. The method is applied to a hypothetical satellite in orbit. Comparisons of incident radiation have been made between rotating and nonrotating satellites in the same orbit. This type of comparison might be used to decide whether or not satellite rotation is desirable, and if so, to what extent. It is also possible to compare different orbits for the same satellite to optimize radiation to its surface.

Paper No. 4, 1 May 1958.
Satellite temperature measurements for 1958 Alpha - Explorer I.
E. P. Buwalda and A. R. Hibbs.
Internation Astronautical Federation

September 1956.

National Academy of Sciences, National Research Council. Materials Advisory Board

Materials problems associated with the thermal control of space vehicles.

National Aeronautics and Space Administration

TND-357, June 1960.
Determination of the internal temperature in satellite 1959 Alpha (Vanguard II). V. R. Simar and others.

Satellite 1959 Alpha was equipped so that accurate measurement of the mini-track beacon frequency (with the doppler component removed) was sufficient to determine the satellite's internal temperature. To provide a precise measurement of this frequency, a sensitive receiving system, utilizing a highly stable but tunable first local oscillator and a noise-eliminating tracking filter, was developed. In addition to the temperature determination, other information such as roll rate and rocket performance was obtained from the observations.

North American Aviation, Los Angeles Division

NA-54-586, 2 July 1954.
A proposed research and development program directed toward reliable temperature prediction of aircraft structural components: part IV. radiation effects. M. R. Kinsler.

NA-56-68, 12 April 1957.
Performance specifications for a versatile spectrophotometer for thermal radiation measurements. E. L. Goodenow and M. W. Peterson.

NA-56-69, 12 April 1957.
Possible designs for a versatile spectrophotometer for thermal radiation measurements. E. L. Goodenow and M. W. Peterson.

NA-57-41, 12 April 1957.

-265-
NA-57-707, 28 June 1957.
Control of external skin temperatures by use of selective finishes.
G. C. Frey.

NA-57-330, 23 July 1957.
Spectral and total radiation data of various aircraft materials.

NA-57-707-1, 5 February 1958.
Emissivity and reflectance of selected surface coatings. R. E. Klemm.

NA-58-525, March 1958. (Secret)
Thermo considerations for the design of satelloid vehicles.

NA-58-1599, 15 December 1958. (Secret)
Preliminary thermo analysis of extensive surfaces protection system requirements for B-70 air vehicle. P. Ohlsen and A. Nusenow.

NA-59-102, 11 August 1959. (Secret)
Preliminary thermodynamic analysis of I. R. seekers for B-70.

NA-59-53, 1959. (Secret)
Thermal radiation characteristics of B-70 weapon system.
R. Klemm and others.

NA-59-53-1, 31 July 1959. (Secret)
Thermal radiation characteristics of B-70 weapon system.
R. Klemm and others.

NA-59-1887. (Secret)
B-70 infra-red radiation and radar X-section. W. Kemp.

Office of Naval Research

Temperature stabilization of Vanguard satellites, theory and practice.
L. F. Drummete and G. H. Hass. (Chapter referenced is unclassified)

The temperature of an orbiting satellite depends on radiation balancing and on the parameters which control the radiation environment. The latter include orbital characteristics and the surface properties of the satellite skin. The surface properties are absorptance for extraterrestrial sunlight and hemispheric emittance, and the governing parameter is the ratio of these. Adjustment of the surface parameters permits a passive system of temperature stabilization and is used in the Vanguard program. For visibility reasons, the Vanguard
devices had to have specular reflecting surfaces with high visible reflection. For satisfactory temperatures, the infrared properties had to be modified to increase the surface emittance. The solution consisted of overcoating polished metal with a vacuum coating of partially oxidized SiO. This material is transparent in the visible but has infrared absorption between 8 and 12 microns. A film 0.54 micron thick has an emittance of 0.13 at 20°C; the emittance increases to 0.40 for a film 1.2 microns thick. Satellite coating is done in a 72-inch evaporator in a special rotating jig designed to provide relatively uniform thickness.

Oklahoma State University, Engineering Experiment Station


The material in this report was presented as a lecture series. The basic principles of radiation are reviewed. The most important aspects of thermal control and solar power generation for spacecrafts and satellites are covered, as are methods for determining radiation properties with special emphasis on selective surfaces. Radiation processes in an enclosure (such as a cavity receiver of a solar powerplant or the interior of a space platform), important energy sources in the solar system (sun and planets), and the atmosphere of the earth are discussed. The fundamentals of solar powerplant design for spacecraft are given.

University of Wisconsin


The radiation energy budget of the earth is determined by the magnitude of three radiation currents: (1) the direct radiation from the sun, (2) the fraction of this that is diffusely reflected by the earth, the clouds, and the atmosphere, and (3) the fraction that is converted into heat and is ultimately reradiated back to space in the far infrared portion of the spectrum. On Explorer VII, three radiation currents are measured with simple bolometers in the form of hollow silver hemispheres. The hemispheres are thermally isolated from, but in close proximity to, specially aluminized mirrors. The image of the hemisphere, which appears in the mirror, makes the sensor look like a full sphere. Two of the hemispheres have a black coating which makes them respond about equally to solar and terrestrial
radiation. Another hemisphere, coated white, is more sensitive to terrestrial radiation than to solar radiation. A fourth has a gold metal surface which makes it more sensitive to solar than to terrestrial radiation. The information telemetered to the earth's surface is the sensor temperatures. The radiation currents are obtained by using these temperatures in heat-balance equations. Sample calculations are given and results are described.

Wright Aeronautical Development Division

WADD TR 54-42, 1954.
Total normal emissivities and solar absorptivities of materials.
G.B. Wilkes.

BOOKS
Clauss, F.J., Editor

Surface effects on spacecraft materials. Wiley, 1960, p 3-54.

The satellite thermal problem is reviewed. Satellite temperatures are shown to depend upon exterior thermal radiation characteristics, external environment, orbit geometry, and internal power generation. A method is presented for estimating uncertainties in the predicted temperatures brought about by uncertainties in the determining variables. Graphs and formulas necessary for application of the method are included in appendices. A survey is made of the origins of uncertainties in the determining variables. Uncertainties in radiation characteristics of surfaces are shown to arise from lack of precision in measurements, lack of control in manufacturing processes, and lack of surface finish stability. Numerical examples clearly illustrate the importance of the uncertainties in radiation characteristics. Methods of reducing uncertainties in internal satellite temperatures through careful selection of surface finishes are given, and active control systems are discussed.

Temperature control of the Explorers and Pioneers. T.O. Thosten and others.

The Jet Propulsion Laboratory participated in the launching of the Explorer satellites and the Juno II space probes (Pioneers III and IV). This participation included payload design and the method of achieving temperature control. This paper describes the basic theory for the passive temperature control of satellites
and space probes and the application of this process to the Explorer and Pioneer III and IV vehicles. Some results of in-flight temperature measurements are also presented.


Coatings for space vehicles. J. C. Raymond.

Six general types of coatings and some of their properties of interest for spacecraft applications are discussed: organic coatings, electrodeposited coatings, phosphate-bonded ceramic coatings, porcelain enamels, high-temperature frit-refractory ceramic coatings, and flame-sprayed ceramic coatings. The four types of ceramic coatings are discussed in detail. A brief description of metal preparation, application and firing of coatings, and coating properties is included. Values for total hemispherical and normal spectral emittance are given where available.


Vanguard emittance studies at NRL. L. F. Drummeter, Jr., and E. Goldstein.

The general problem of passive control of temperature in the Vanguard devices involved many problem areas. This paper presents procedures and results associated with one phase of the thermal work—the studies of emittance. The total hemispherical emittances of several materials were measured by coating them on sample bodies, suspending the bodies in an evacuated chamber, and heating them. The emittances of Al₂O₃ and SiO coated on aluminum, gold, and silver surfaces, of polished tungsten carbide, and of silicon solar cells were measured.


Some methods used at the National Bureau of Standards for measuring thermal emittance at high temperatures. J. C. Richmond.

At the National Bureau of Standards, the Radiometry Section of the Atomic and Radiation Physics Division and the Enameled Metals Section of the Mineral Products Division are concerned with thermal emittance measurements. The investigations of the Radiometry Section include absorption of radiation and the interpretation of absorption spectra (including infrared absorption spectra), accurate evaluation of materials for use in wavelength calibration of spectrometers, and calibration of standards of spectral radiation and standards for total radiant energy. The Enameled Metals Section is engaged in developing instrumentation and procedures for determining total hemispherical emittance,
normal spectral emittance, and spectral reflectance of a wide variety of materials, including ceramics and ceramic-coated metal.

Hynek, J. A., Editor

Astrophysics, a topical symposium. 1951, p 259-301.
The sun and stellar radiation (chapter 6).

Radiation and stars from the sun are discussed, including the spectral energy curve of the sun and the solar constant. The various sources of heat in the photosphere are described. These include radiation from stars and planets, radiation from variable stars, and planetary heat. Radiation properties of the moon are also taken up.

Kuiper, G. P., Editor

Albedo, color and polarization of the earth. A. Dajon.

Malone, T. F., Editor

Solar radiant energy, its modification by the earth and its atmosphere. S. Fritz.

Van Allen, J., Editor

Isolation of the upper atmosphere and of a satellite. P. R. Gast.

The temperature of a satellite is the resultant of the sum of radiations from three sources: directly from the sun, solar radiation returned from the atmosphere and the earth (both 6000 K radiation), and low-temperature (250 K) radiation from the earth. Assuming various characteristics for the model of the satellite (absorptivity of the surface, shape, mass, specific heat) and orbit trajectories (distance of perigee and apogee, duration of insolation, and duration in shadow of the earth), the ranges of maximum and minimum temperatures may be calculated. For one possible elliptical trajectory the mean temperatures for an 0.8-meter, 100-kilogram spherical satellite are not far from 0 C. As the satellite in its orbit passes from sunlight into the shadow
of the earth, the temporary maximum temperatures in the sunlight range from 13 to 3 C and the temporary minimum temperatures in the shadow range from -3 to 5 C. The highest maximum temperature is with the sun in line with the projected major axis and the illuminated satellite at a perigee of 300 miles, and the lowest minimum temperature with the sun in the same position and the satellite at an apogee of 1000 miles. Measurements of insolation freed from difficulties of atmospheric attenuation and measurements of the albedo of the earth will be possible from a satellite vehicle. To achieve the required accuracy, however, rather precise knowledge of the orientation of detectors is essential. Hazards which are unique to the environment may be encountered in attempting measurements from a satellite. These include the effects of the vacuum ultraviolet irradiation and of accumulation of micrometeorites on surfaces of detectors, windows, and satellite skin.


The radiative heat transfer of planet earth. J. J. F. King.

A method is developed for obtaining the vertical temperature distribution of a planetary atmosphere from the law of darkening of the planet's emission spectrum. The intensity of the radiation emerging from a planet is directly dependent on the vertical thermal structure of its atmosphere. For the monochromatic case, the emergent intensity is simply the Laplace transform of the Planck intensity considered as a function of optical depth. Now, for a given wavelength the Planck intensity is a single-valued function of temperature. Thus, in principle, a complete knowledge of the variation of the emergent intensity with zenith angle (law of darkening) suffices to determine the thermal structure of the accessible optical depth. In practice, to find the Planck intensity it is necessary to obtain the inverse Laplace transform, which is mathematically tantamount to solving a Fredholm integral equation of the first kind. An approximate solution to the problem is obtained using the Volterra method, which replaces the integral equation by a set of linear simultaneous equations with the Planck intensity expressed as a series of step functions. A sample calculation shows that as few as three values of the limb-darkening function yield quantitative information on the vertical temperature distribution. Alterations in the theory necessitated by considerations of band, rather than monochromatic, intensity measurements are indicated. A lightweight, rugged instrument which appears capable of such thermal measurements is discussed. This is the far infrared filter photometer currently being developed by Johns Hopkins University under Air Force contract AF 19(604)-949.
Scientific use of earth satellites. 2nd ed, c1958, p 69-72.
Experiments for measuring the temperature, meteor penetration and surface erosion of a satellite vehicle. H. E. LaGow.

White, C. S. and Benson, O. O., Editors

Thermal aspects of travel in the aeropause, problems of thermal radiation.
Section XI

REFERENCES

1. "Emissivity and Emittance, What Are They?," Defense Metals Information Center, Battelle Memorial Institute, OTS PB 161222 (DMIC Memorandum 72), 10 November 1960.


APPENDIX A

TABLES OF EMISSIVITY AND ABSORPTIVITY

This appendix was supplied by the AiResearch Manufacturing Division of the Garrett Corporation. The data presented are incomplete and will be expanded in the first revision of the basic report.

INTRODUCTION

Because radiative heat transfer is a surface phenomenon, it is usually desirable to coat the heat transfer surface to accomplish the desired radiative exchange. The properties of these surface coatings are of importance in the design of space heat rejection systems, because radiation is the only means of dissipating heat other than expelling large masses from the vehicle. The radiator may be exposed to radiation from the sun, nearby planets, and other parts of the vehicle.

Considerable work has been done in recent years in developing coatings, particularly those which are spectrally selective. Some of the applications and the desired types of coatings are listed in Table 1.

NOMENCLATURE

\( \alpha \) Total absorptivity
\( \alpha_s \) Total absorptivity to solar radiation
\( \alpha_\lambda \) Monochromatic absorptivity
\( \epsilon \) Total emissivity
\( \epsilon_T \) Total emissivity of radiator surface
\( \epsilon_\lambda \) Monochromatic emissivity
\( \lambda \) Wavelength, microns
\( \mu \) Microns (1.0 micron = 10^{-4} \text{ centimeters})
### Table 1. Coatings and Their Application

<table>
<thead>
<tr>
<th>Application</th>
<th>Desired Coating</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorber for heat engine using solar energy</td>
<td>High solar absorptivity, low thermal emissivity</td>
<td>High-energy absorption, high temperature</td>
</tr>
<tr>
<td>Photovoltaic cell</td>
<td>High solar absorptivity for cell sensitivity range, high thermal emissivity</td>
<td>High-energy absorption, low temperature</td>
</tr>
<tr>
<td>Infrared detector window</td>
<td>High solar reflectivity, high thermal transmittance</td>
<td>Infrared detection, low temperature</td>
</tr>
<tr>
<td>Low-temperature radiator</td>
<td>Low solar absorptivity, high thermal emissivity</td>
<td>High heat rejection per unit area</td>
</tr>
<tr>
<td>High temperature</td>
<td>High thermal emissivity (low solar absorptivity desirable as long as $\epsilon_T$ is high)</td>
<td>High heat rejection per unit area</td>
</tr>
<tr>
<td>Solar concentrators</td>
<td>High solar reflectivity</td>
<td>High-efficiency concentrator</td>
</tr>
<tr>
<td>Passive temperature control system</td>
<td>Variable $a_s/\epsilon_T$ to accommodate solar flux and internal heat load changes</td>
<td>Constant internal temperature</td>
</tr>
<tr>
<td>Ultraviolet protective coating for organic materials</td>
<td>Reflective or absorbing</td>
<td>Reflection or conversion of ultraviolet into another form to protect organic materials</td>
</tr>
</tbody>
</table>

**SELECTIVE ABSORPTION OR EMISSION**

The use of spectrally selective coatings is often desirable to control energy flux. There are many materials whose total emissivity varies with temperature, and these can often be used to achieve the proper energy balance. Figure 1 shows, in general, how total emissivity varies with
Figure 1. Typical Variation of Surface Absorptivity and Emissivity With Temperature
temperature for metals and nonmetals. For example, \( \alpha_s / \varepsilon_T \) is shown to be greater than unity for polished metals and less than unity for nonmetals.

By use of the principles outlined in the body of this report, selective radiation surfaces can be fabricated by depositing multiple layers of coating material on the surface. Interference films, cavity absorption, absorbing undercoatings, Fresnel (or dielectric) films can be utilized.

For example, a gold smoke film evaporated from a tungsten filament in the presence of small amounts of nitrogen and oxygen has the property of being almost completely transparent to radiations above 2 microns. About 97 percent is transmitted, whereas only 20 percent of the visible spectrum is transmitted with 2 to 3 percent reflection, using a heat source of 120 F, Reference 1.

A polished copper surface may be assumed to be 75 percent reflective in the visible and 98 percent in the infrared range. Thus, if the gold smoke film were deposited on this copper surface, 92 percent of the radiation above 2 microns and only 5 percent of the visible radiation would be reflected due to the double absorption. However, at elevated temperatures the structure and optical properties of the film is affected and stability becomes a factor.

Because emissivity is strongly dependent on surface characteristics, it is necessary that the surface be maintained in a condition most closely approximating the operating environmental conditions during emissivity measurements. In the case of space radiators, high vacuum is most important. Grease, dust, impurities or absorbed gases can materially affect the expected response of a surface.

SPECTRAL CHARACTERISTICS OF COATINGS

The spectral characteristics of some coatings which may be applicable for space radiators are given here. The values for total emissivity are taken from several sources. These totals are only indicative of coating emissivity, because substrate preparation and method of deposition greatly influences the spectral characteristics.

The spectral characteristics of some enamels and pure oxides are shown in Figures 2 through 7 (Reference 2). These characteristics are presented as indicative of the type of information which can be found in the literature.
Figure 2. Monochromatic Normal Emissivity Versus Wavelength for Aluminum Oxide
Figure 3. Monochromatic Normal Emissivity Versus Wavelength for Lead Carbonate and Aluminum Oxide
Figure 4. Monochromatic Normal Emissivity Versus Wavelength for Calcium Oxide and Zirconium Dioxide
Figure 5. Monochromatic Normal Emissivity Versus Wavelength for Magnesium Carbonate and Zinc Oxide
Figure 6. Cupric Oxide on Sodium Chloride
Figure 7. Transmission Versus Wavelength for Molybdenum Oxide and Nickel Oxide on Pyrex
ORGANIC COATINGS

Considerable effort is being directed toward development of organic coatings with high thermal emittance at relatively low temperature (from room temperature to 200 or 300 F). These coatings must be characterized by high resistance to ultraviolet and nuclear radiation, good thermal stability, and high molecular weight to minimize boiloff losses. Preliminary work indicates that organic coatings can be developed with a thermal emissivity greater than 0.95. At the present time, no organic coating can be recommended which will meet all the environmental requirements. Some work on protective ultraviolet absorbers is producing encouraging results, indicating that a high-emissivity coating which is sensitive to ultraviolet may be successfully protected. These organic protective coatings include 1, 1'-ferrocane dicarboxylic acid, 2(2'-hydroxy 5'-methyl phenyl) benzotriazole, and 2 hydroxy 4 methoxy benzophenone.

INORGANIC COATINGS

Because pure metals are generally reflective at temperatures from 100 to 1200 F, they are not suitable for radiator coatings. However, there may be related components which require high thermal reflectance. Typical reflectivity values for vacuum-deposited gold on flat organic substrates are 0.95 for the near and far infrared regions. Aluminum, copper, and silver are also reflective from 0.90 to 0.95 for the same region (Reference 3). Care is required to prevent surface oxidation.

Metallic oxides have relatively high emissivities in the infrared region and low absorptivity for solar irradiation. The emissivities of some coatings as reported by various references are summarized in Table 2, which also lists some of the physical properties.

Information received from other sources and from tests conducted at AirResearch indicate that an emissivity of at least 0.85 at 100 to 200 F can easily be obtained for some of these oxides using flame spraying. The values of 0.93 to 0.97 at the low temperatures listed in Figure 1 can be obtained only under ideal conditions.

The dependence of emissivity on temperature for some other materials is given in Figure 8. Sheet 2 of Figure 8 shows that $\epsilon_T$ will be of the order of 0.8 and 0.9 while $\alpha_s$ should be in the range 0.1 to 0.2. If the coatings are roughened, $\epsilon_T$ and $\alpha_s$ should both increase.

The emittance of two ceramic coatings prepared by the National Bureau of Standards is shown in Figure 9. These coatings are barium silicate glass containing mixtures of quartz, aluminum oxide, chrome oxide, cerium oxide, and other oxides. They are sprayed on stainless steel
Table 2. Materials Having Desirable Radiation Characteristics for Space Radiators

<table>
<thead>
<tr>
<th>Material</th>
<th>Specific Gravity</th>
<th>Melting Point (F)</th>
<th>Boiling Point (F)</th>
<th>Total Normal Emissivity</th>
<th>Application and Stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum oxide</td>
<td>3.5 to 3.9</td>
<td>3700</td>
<td>4080</td>
<td>0.98 0.79 0.16</td>
<td>Good</td>
</tr>
<tr>
<td>Zirconium silicate</td>
<td>4.56</td>
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<td>7800</td>
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</tr>
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<td>subl 3270</td>
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<td>Fair to bad, too soluble in water</td>
</tr>
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<td>Anodized aluminum</td>
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<td>4080</td>
<td>0.77 0.49 0.15</td>
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<tr>
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<td>3700</td>
<td>4080</td>
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Figure 8. Emissivity Versus Temperature for Various Substances
(Sheet 1 of 2)
Figure 8. Emissivity Versus Temperature for Various Substances
(Sheet 2 of 2)
Figure 9. Total Hemispherical Emissivity Versus Wavelength for Type 430 Stainless Steel Coated With Two Ceramic Coatings
samples and then cured at elevated temperatures. Most of these coatings are spectrally selective with $a / \epsilon_T$ approximately 0.1 to 0.3. Conservative values of emissivities for low-temperature radiation are of the order of 0.85 to 0.90. Higher thermal emissivities are desirable, however, for high-temperature radiators such as required for space power systems. It is believed that for high temperature radiators, black iron oxide or nickel oxide coating (nickel penetrate) have emissivities near 0.95.

Total normal emissivity characteristics of various materials are shown in Figures 10 and 11.

COMPUTATION OF TOTAL EMISSIVITY OR ABSORPTIVITY

The methods used to predict radiation heat transfer require knowledge of the total emissivities of the surfaces involved as well as the total absorptivities. Much of the data published to date are in the form of monochromatic reflectivity or absorptivity as a function of wavelength. Thus, it is often necessary to calculate the total emissivity or absorptivity when only the spectral information is available. Basically, this is done by calculating the black body characteristics as given by Planck's Law. The actual power emitted or absorbed is then obtained by taking the product of the black body radiant power and the emissivity at each wavelength. The total emissivity is determined by integrating this product over all wavelengths and dividing by the black body energy over the same wavelengths.

To obtain the value of total emissivity or absorptivity, over all wavelengths ordinarily requires very tedious hand calculations and lengthy graphical integrations. Fortunately, there is available an IBM 7090 program which mechanizes the calculation and integration procedures such that accurate total emissivities and total absorptivities can be obtained very rapidly for any given temperature conditions and material properties. This program is titled "Total Emissivity and Absorptivity Program," and a complete description of the theory involved and usage of the program is available (Reference 7).
Figure 10. Total Normal Emissivity Versus Temperature for Titanium Dioxide and Cobalt Enamels
Figure 11. Total Normal Emissivity Versus Temperature for Aluminum Oxide
REFERENCES


APPENDIX B

PLANETARY THERMAL EMISSION AND PLANETARY REFLECTED SOLAR RADIATION INCIDENT TO SPACE VEHICLES

This appendix was supplied by the Astronautics Division of Convair (General Dynamics Corporation), San Diego, California.

DESCRIPTION AND DEFINITIONS

1 PLANETARY THERMAL EMISSION

The planetary thermal radiation incident to a vehicle surface may be computed by the general equation

\[ q = F A E_t \]  \hspace{1cm} (1)

where

- \( q \) = thermal radiation rate incident to the vehicle surface, BTU/hr.
- \( A \) = characteristic area defining the surface, ft².
- \( E_t \) = total energy rate emitted per planet unit area, BTU/hr-ft².
- \( F \) = geometric factor for radiation from the planet to the vehicle surface, dimensionless.

The value of \( E_t \) is tabulated for the planets in Table I. The geometric factors have been computed for standard vehicle surface geometries with respect to the earth and tabulated as a function of altitude from the earth. These geometric factors may also be used for vehicles in the vicinity of other planets or moons if the geometric factor is used which corresponds to the adjusted equivalent altitude determined by multiplying the altitude of the vehicle from the planet by the ratio of the radius of the earth to the radius of the planet. These radius ratios are tabulated for the planets in Table I.

(1) SPHERE:

Figure 1 describes the configuration for planetary thermal radiation to a sphere. The geometric factor is defined on the basis of the characteristic area \( A = \frac{4}{3} \pi r^2 \),
where \( r \) is the radius of the sphere. Then

\[
F = q \sqrt{\frac{\pi r^2 E_t}{r}}
\]  

(2)

The geometric factor for a sphere with respect to the earth is tabulated in Table 2 as a function of altitude.

(2) CYLINDER

Figure 2 describes the configuration for planetary thermal radiation to the convex surface of a cylinder. Because of lack of three-dimensional symmetry an attitude parameter, \( \gamma \), is required and is the angle between the cylinder axis and the vertical to the vehicle. The geometric factor is defined on the basis of the characteristic area, \( A = DL \), where \( D \) and \( L \) are the diameter and length, respectively, in feet for the cylinder. Then

\[
F = q \sqrt{DLE_t}
\]  

(3)

The geometric factor for a cylinder with respect to the earth is tabulated in Table 3 as a function of altitude with the attitude angle, \( \gamma \), as the parameter.

(3) HEMISPHERE

Figure 3 describes the configuration for planetary thermal radiation to the convex surface of a hemisphere. The geometric factor is defined on the basis of the characteristic area, \( A = \pi r^2 \), where \( r \) is the radius of the hemisphere. Then

\[
F = q \sqrt{\pi r^2 E_t}
\]  

(4)

The geometric factor for a hemisphere with respect to the earth is tabulated in Table 4 as a function of altitude with the attitude angle, \( \gamma \), as parameter.
(4) FLAT PLATE

Figure 4 describes the configuration for planetary thermal radiation to one side of a flat plate. The angle, $\theta$, between the normal to the plate and the vertical to the vehicle defines the attitude of the plate with respect to the planet. The geometric factor is defined on the basis of the characteristic area, $A = P$, the area of one side of the plate. Then

$$ F = \frac{q}{PE_t} $$

The geometric factor for a flat plate with respect to the earth is tabulated in Table 5 as a function of altitude with the attitude angle, $\theta$, as parameter.

It should be noted that the flat plate thermal radiation solution may be used to approximate the thermal radiation incident to any generally convex vehicle surface by dividing the surface into a series of flat plate elements and summing the thermal radiation incident to each of these flat plates.

II PLANETARY REFLECTED SOLAR RADIATION

The planetary albedo incident to a vehicle surface may be computed from the general equation:

$$ q = FASa $$

where $q$ = albedo heat flux rate incident to the vehicle surface, BTU/hr.

$A$ = characteristic area defining the surface, ft$^2$

$S$ = solar heat flux or "constant", BTU/hr.-ft$^2$

$a$ = average reflectivity of the planet's surface, dimensionless

$F$ = geometric factor which accounts for reflected energy distribution on the planetary surface and the geometry, dimensionless

The geometric factor for a sphere is independent of attitude due to
three dimensional symmetry. In the case of all surfaces the location of the vehicle with respect to the sun is defined by the zenith distance between the surface and sun, \( \Theta_s \). The zenith distance is the angle between the earth-vehicle vector and the earth-sun vector. In the case of surfaces lacking spherical symmetry, the attitude of the surface is defined by two angles. One is the angle, \( \phi^a \), between the axis of the cylinder or hemisphere or normal to the flat plate and the vertical to the vehicle. The other is the angle, \( \phi_c \), of rotation of the axis or normal about the vertical to the vehicle from the planet. The datum \( \phi_c = 0 \) occurs when the axis or normal lies in the plane defined by the earth-vehicle vector and the earth-sun vector.

The value of \( S \) and \( a \) are tabulated for the planets in Table I.

The geometric factors for albedo have been computed for standard vehicle surface geometries with respect to the earth and tabulated as a function of altitude from the earth. Again, as described for thermal radiation, these geometric factors may be applied to other planets by using the ratio of the radius of the earth to the radius of the planet tabulated in Table I.

(1) SPHERE

Figure 5 shows the configuration for albedo incident to a sphere. The geometric factor is defined on the basis of the characteristic area, \( A = \pi r^2 \), where \( r \) is the radius of the sphere, then

\[
F = \frac{q}{\pi r^2 Sa}
\]

The geometric factor for albedo incident to a sphere from the earth is shown in Table 6 as a function of altitude in nautical miles with zenith distance, \( \Theta_s \), as parameter.

(2) CYLINDER

Figure 6 shows the configuration for albedo to the convex surface of a cylinder. For a cylinder the geometric factor is defined on the basis...
of the characteristic area, \( A = DL \). Then

\[
F = \frac{q}{DLSa} \tag{8}
\]

where \( D \) = diameter of cylinder, ft.

\( L \) = length of cylinder, ft.

The geometric factor for albedo incident to a cylinder from the earth is tabulated in Tables 7 through 28 as a function of altitude in nautical miles with \( \theta_s, \gamma, \) and \( \phi_c \) as parameters. Each table is for a constant \( \gamma \) and \( \phi_c \), i.e., particular attitude with respect to the earth.

(3) HEMISPHERE

Figure 7 shows the configuration for albedo to the convex surface of a hemisphere. For a hemisphere the geometric factor is computed on the basis of the characteristic area, \( A = \pi r^2 \). Then

\[
F = \frac{q}{\pi r^2 Sa} \tag{9}
\]

where \( r \) = radius of hemisphere, ft.

The geometric factor for albedo incident to a hemisphere from the earth is tabulated in Tables 29 through 65, as a function of altitude in nautical miles with \( \theta_s, \gamma, \) and \( \phi_c \) as parameters. Each table is for a constant \( \gamma \) and \( \phi_c \), i.e., particular attitude.

(4) FLAT PLATE

Figure 8 shows the geometry for albedo to one side of a flat plate. For a flat plate the geometric factor is computed on the basis of the characteristic area, \( A = P \). Then

\[
F = \frac{q}{PSa} \tag{10}
\]

where \( P \) = area of one side of the flat plate, ft.\(^2\)
The geometric factor for albedo incident to one side of a flat plate from the earth is tabulated in Tables 66 through 101 as a function of altitude in nautical miles with \( \Theta_s \), \( \alpha \), and \( \phi_c \) as parameters. Each table is for a constant \( \lambda \) and \( \phi_c \), i.e., particular attitude.

The flat plate albedo solution may also be used to approximate albedo heating of any generally convex satellite or satellite surface by dividing this surface into a series of flat plates and summing the albedo heating for each of these flat plates.
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29-65 Geometric Factor for Reflected Solar to a Hemisphere

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66-101  Geometric Factor for Reflected Solar to a Flat Plate

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*To use the albedo and thermal radiation curves and tabular data for a planet other than the earth, an equivalent earth altitude for the planet must be found. This may be done by multiplying the planetary altitude under consideration by the altitude correction factor given in the above table. The abscissa of the curves should then be entered with this corrected altitude.

Example: Thermal radiation to a sphere 200 naut mi above the surface of Mars.

\[ 200 \times 1.916 = 383.2 \text{ naut mi} \]

From Fig. 3, \( q / \pi r^2 E_t = 1.12 \)

Using \( E_t \) for Mars gives \( q / \pi r^2 = 45.3 \text{ Btu/hr-ft}^2 \)
Figure 1. Geometry for Planetary Thermal Emission to a Sphere

Geometric Factor, \( F = \frac{q}{\iint r^2 E_t} \)
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Figure 2. Geometry for Planetary Thermal Radiation to a Cylinder

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Figure 3. Geometry for Planetary Thermal Emission to a Hemisphere

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Figure 4. Geometry for Planetary Thermal Radiation to a Flat Plate

Geometric Factor, \( F = \frac{q}{P \bar{E}_t} \)
### Table 5

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Figure 5. Geometry for Planetary Reflected Solar Radiation to a Sphere

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Figure 6. Geometry for Planetary Reflected Solar Radiation to a Cylinder

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Table 8. Geometric Factor for Reflected Solar Radiation to a Cylinder

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- 331 -
Table 9. Geometric Factor for Reflected Solar Radiation to a Cylinder

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Table 10. Geometric Factor for Reflected Solar Radiation to a Cylinder

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Table 11. Geometric Factor for Reflected Solar Radiation to a Cylinder

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\( \gamma = 30^\circ \), \( \phi_2 = 120^\circ \)
Table 13. Geometric Factor for Reflected Solar Radiation to a Cylinder

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- 336 -
Table 14. Geometric Factor for Reflected Solar Radiation to a Cylinder

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\hat{\alpha} = 30^\circ, \quad \phi_c = 180^\circ
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Table 15. Geometric Factor for Reflected Solar Radiation to a Cylinder

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Table 16. Geometric Factor for Reflected Solar Radiation to a Cylinder

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Table 22. Geometric Factor for Reflected Solar Radiation to a Cylinder

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Table 24 Geometric Factor for Reflected Solar Radiation to a Cylinder

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- 347 -
Table 25. Geometric Factor for Reflected Solar Radiation to a Cylinder

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Table 26. Geometric Factor for Reflected Solar Radiation to a Cylinder

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Table 27. Geometric Factor for Reflected Solar Radiation to a Cylinder

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Table 28. Geometric Factor for Reflected Solar Radiation to a Cylinder

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Figure 7. Geometry for Planetary Reflected Solar Radiation to a Hemisphere

Geometric Factor, \( F = \frac{g}{\int r^2 \, ds} \)
Table 29. Geometric Factor for Reflected Solar Radiation to a Hemisphere

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Table 30. Geometric Factor for Reflected Solar Radiation to a Hemisphere

\[ \gamma = 30^\circ; \quad \phi = 0^\circ \]

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Table 34. Geometric Factor for Reflected Solar Radiation to a Hemisphere

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Table 36. Geometric Factor for Reflected Solar Radiation to a Hemisphere

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Table 38. Geometric Factor for Reflected Solar Radiation to a Hemisphere

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Table 39. Geometric Factor for Reflected Solar Radiation to a Hemisphere

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-363-
Table 40. Geometric Factor for Reflected Solar Radiation to a Hemisphere

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$\theta = 60^\circ$, $\phi = 120^\circ$
Table 42. Geometric Factor for Reflected Solar Radiation to a Hemisphere

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### Table 48. Geometric Factor for Reflected Solar Radiation to a Hemisphere,

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Table 49. Geometric Factor for Reflected Solar Radiation to a Hemisphere

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Table 51. Geometric Factor for Reflected Solar Radiation to a Hemisphere

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Table 52. Geometric Factor for Reflected Solar Radiation to a Hemisphere

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Table 53. Geometric Factor for Reflected Solar Radiation to a Hemisphere

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\[ \gamma = 120^\circ, \quad \phi = 120^\circ \]
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Table 63. Geometric Factor for Reflected Solar Radiation to a Hemisphere
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Table 65. Geometric Factor for Reflected Solar Radiation to a Hemisphere

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Figure 8. Geometry for Planetary Reflected Solar Radiation to a Flat Plate

Geometric Factor, \( F = \frac{q}{P \cdot S_b} \)
### Table 66. Geometric Factor for Reflected Solar Radiation to a Flat Plate

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Table 68. Geometric Factor for Reflected Solar Radiation to a Flat Plate

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Table 70. Geometric Factor for Reflected Solar Radiation to a Flat Plate

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Table 73. Geometric Factor for Reflected Solar Radiation to a Flat Plate

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Table 75. Geometric Factor for Reflected Solar Radiation to a Flat Plate

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Table 76. Geometric Factor for Reflected Solar Radiation to a Flat Plate

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Table 79. Geometric Factor for Reflected Solar Radiation to a Flat Plate

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Table 82. Geometric Factor for Reflected Solar Radiation to a Flat Plate

\[ \gamma = 90^\circ \]

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Table 83. Geometric Factor for Reflected Solar Radiation to a Flat Plate

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Table 84. Geometric Factor for Reflected Solar Radiation to a Flat Plate

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Table 85. Geometric Factor for Reflected Solar Radiation to a Flat Plate

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Table 86. Geometric Factor for Reflected Solar Radiation to a Flat Plate

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**Note:** The table provides geometric factor values for different altitudes and for two different sun elevations ($\phi_c = 90^\circ$ and $\phi_c = 160^\circ$).
Table 87. Geometric Factor for Reflected Solar Radiation to a Flat Plate

$\phi = 90^\circ$

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$\phi = 180^\circ$

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Table 91. Geometric Factor for Reflected Solar Radiation to a Flat Plate

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Table 93. Geometric Factor for Reflected Solar Radiation to a Flat Plate

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Table 94. Geometric Factor for Reflected Solar Radiation to a Flat Plate

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Table 95. Geometric Factor for Reflected Solar Radiation to a Flat Plate

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Table 97. Geometric Factor for Reflected Solar Radiation to a Flat Plate

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Table 98. Geometric Factor for Reflected Solar Radiation to a Flat Plate

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Table 101. Geometric Factor for Reflected Solar Radiation to a Flat Plate

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\[ \phi_c = 180^\circ \]