NASA TECHNICAL MEMORANDUM

NASA TM X-53490

1965

NASA TM X-53490

FACILITY FORM 602

N66 37048
(ACCESSION NUMBER)

(THRU)

42
(PAGES)

1
(CODE)

TMX-53490
(NASA CR OR TMX OR AD NUMBER)

33
(CATEGORY)

RESEARCH ACHIEVEMENTS REVIEW SERIES NO. 2

RESEARCH AND DEVELOPMENT OPERATIONS
GEORGE C. MARSHALL SPACE FLIGHT CENTER
HUNTSVILLE, ALABAMA

GPO PRICE $ ________

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Hard copy (HC) 2.00

Microfiche (MF) .50

ff 653 July 65

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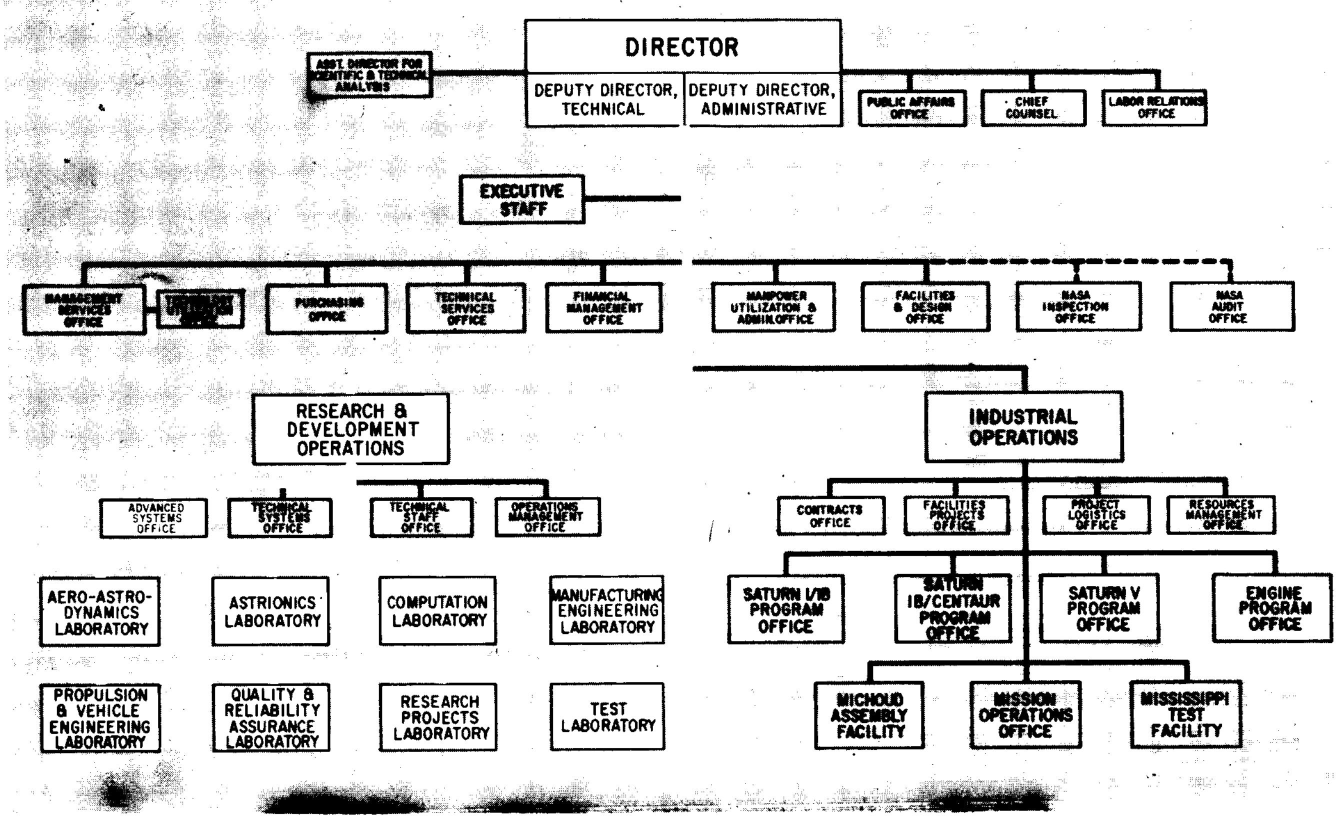

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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THERMOPHYSICS RESEARCH AT MSFC

RESEARCH ACHIEVEMENTS REVIEW SERIES NO. 2

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PREFACE

In 1955, the team which has become the Marshall Space Flight Center (MSFC) began to organize a research program within its various laboratories and offices. The purpose of the program was two-fold: first, to support existing development projects by research studies and second, to prepare future development projects by advancing the state of the art of rockets and space flight. Funding for this program came from the Army, Air Force, and Advanced Research Projects Agency. The effort during the first year was modest and involved relatively few tasks. The communication of results was, therefore, comparatively easy.

Today, more than ten years later, the two-fold purpose of MSFC's research program remains unchanged, although funding now comes from NASA Program Offices. The present yearly effort represents major amounts of money and hundreds of tasks. The greater portion of the money goes to industry and universities for research contracts. However, a substantial research effort is conducted in house at the Marshall Center by all of the laboratories. The communication of the results from this impressive research program has become a serious problem by virtue of its very voluminous technical and scientific content.

The Research Projects Laboratory, which is the group responsible for management of the consolidated research program for the Center, initiated a plan to give better visibility to the achievements of research at Marshall in a form that would be more readily usable by specialists, by systems engineers, and by NASA Program Offices for management purposes.

This plan has taken the form of frequent Research Achievements Reviews, with each review covering one or two fields of research. These verbal reviews are documented in the Research Achievements Review Series.

Ernst Stuhlinger
Director, Research Projects Laboratory

These papers presented February 25, 1965

TABLE OF CONTENTS

THERMOPHYSICS RESEARCH AT MARSHALL SPACE FLIGHT CENTER

LIST OF ILLUSTRATIONS

THERMOPHYSICS RESEARCH AT MARSHALL SPACE FLIGHT CENTER

By

Gerhard B. Heller

SUMMARY

The scope and status of thermophysics research at MSFC (in-house and contract) is given in this report. It includes work in the thermal space environment, the physics of radiation and radiative properties of solids, computer programs for thermal control, thermal similitude of time-dependent problems, effects of space environment on thermal control coatings, infrared physics, and thermal flight experiments. The report covers theoretical research, early experimental studies, and some early results of thermal experiments on Pegasus I.

author

I. INTRODUCTION

The main incentive for the considerable expansion in thermophysics research in recent years has been our national space effort. Active and passive control of space vehicles and spacecraft has become an essential activity of design, test, and evaluation in all space programs. Consequently, thermophysics has developed into a specialty in national space and guided missile work. The technical community in this field now comprises about 500 engineers and scientists, employed in industry, university laboratories, and government agencies such as NASA, Army, Air Force, Navy, and National Bureau of Standards.

A number of major activities at Marshall Space Flight Center (MSFC) are concerned with thermal problems, with the work being carried out by MSFC and by industry and research institutions under contract with MSFC. The in-house and contract investigations constitute a well rounded research program. Some of its achievements are described in this report, which deals particularly with thermophysics research as it applies to the exchange of thermal energy between a space vehicle or craft and its surroundings, especially space, and to the action of this energy on satellite instrumentation.

Through the early Explorer program, beginning with Explorer I, MSFC contributed to the establishment of many concepts which are generally accepted today, for example, those concerning passive thermal control, thermal vacuum testing, emissivity, and effects of space environment.

Later, the need for more in-house research arose, especially in connection with Pegasus problems. Laboratories were established as a result of this need at the Research Projects Laboratory of MSFC. They proved to be extremely valuable in the Pegasus project, and later in Saturn projects, as well. Research results, for example, have been applied to thermal control of the nine space vehicles illustrated in Figure 1.

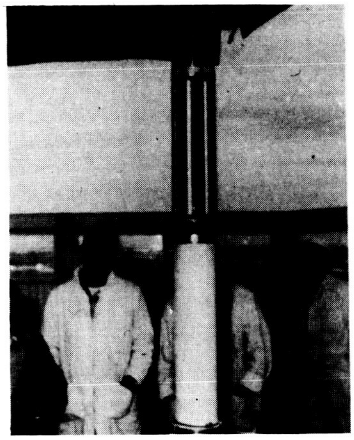
Experience gained in such in-house work is enabling MSFC to better supervise its contract work. The development of in-house research facilities, moreover, is enabling MSFC to handle projects which cannot practicably be delegated to contractors. Much work, of course, has been done, and is being done, under contract. As an incidental but beneficial consequence of all contract work, an effective relationship has been established between contractors and theMSFC thermophysics laboratories. Such past and present research connections are shown in Figure 2.

II. RESEARCH ACHIEVEMENTS

A. SPACE ENVIRONMENT

The thermal space environment is important in the thermal radiative exchange between a space vehicle and its surroundings. The major influx of thermal energy to the space vehicle is due to insolation, earth or planetary albedo, and earth or planetary infrared radiation. The general status of knowledge of thermal space environment is discussed here briefly.

The thermal space environment is not too well known. No direct measurement of the solar constant



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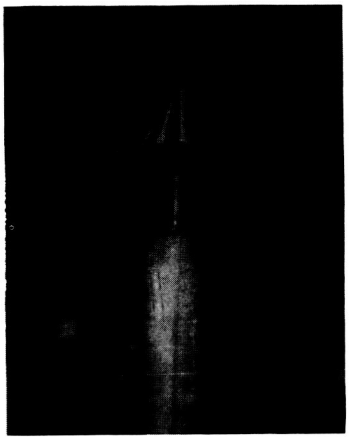

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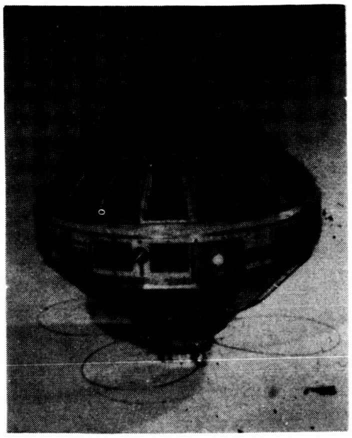

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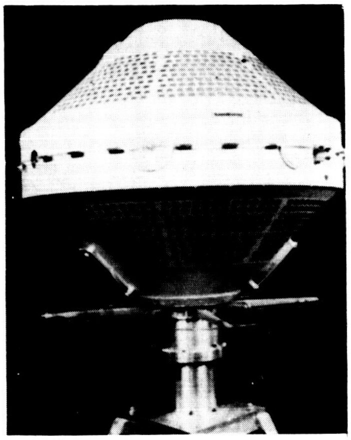

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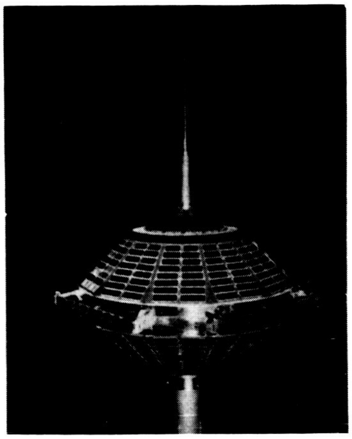
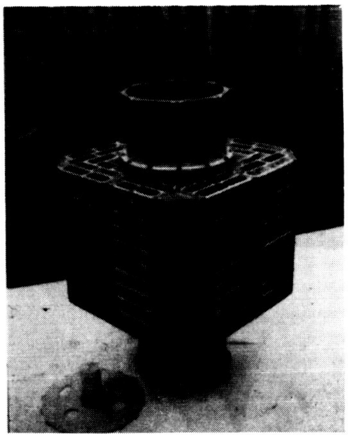
EXPLORER XI



S-45 IONOSPHERE SATELLITE



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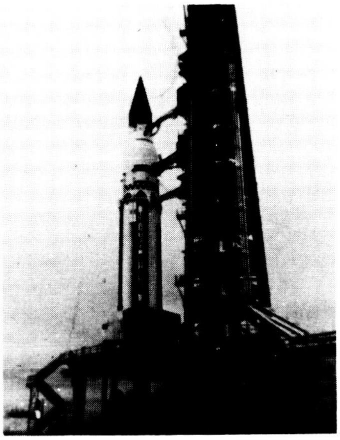

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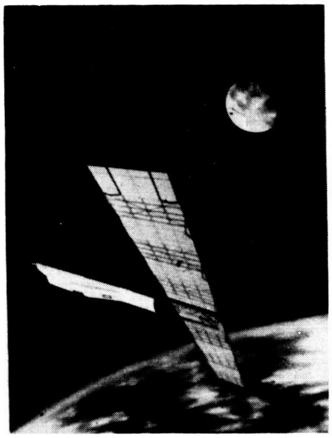


PEGASUS

FIGURE 1. SPACECRAFT THERMALLY DESIGNED BY RESEARCH PROJECTS LABORATORY

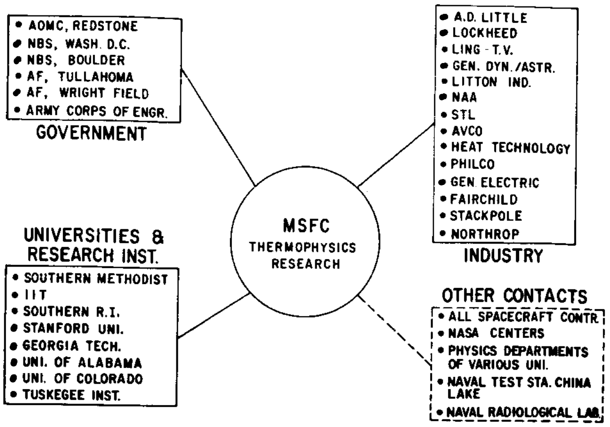


FIGURE 2. CONTRACTUAL AND PROJECT RELATIONSHIPS

in space has been made. Estimates from ground measurements are assumed to be accurate within 3 percent [1]. The spectral resolution is much less well known, and inaccuracies in the intensity of spectral lines can be expected to be 10 to 50 percent, or even higher [2]. More accurate information on solar ultraviolet is especially important because solar ultraviolet has a strong effect on the space stability of thermal control coatings.

The spectral distribution and intensity distribution of the earth albedo flux incident on the surface of a spacecraft constitutes another little-explored field of knowledge. The general equation for radiative transfer was written by Stokes [3] in 1852, and a solution was published nearly a hundred years later by Chandrasekhar [4], who solved the problem of an infinitely extended plane parallel atmosphere for the conservative case of scattering known as Rayleigh scattering. Chandrasekhar's equations were programed for computers by Coulson and others, and the results were published in table form [5]. This information was used by Snoddy [6] at MSFC in a study, discussed in this report, of the earth albedo due to Rayleigh scattering, and of the effect of the albedo on an area element of a satellite in space.

Figure 3 shows the Rayleigh diagram for scattering of nonpolarized electromagnetic radiation by molecules. The scattered radiation has two components of the distribution function, as shown by the equation:

$$I_{\theta, r} = \frac{f^4 \ p^2}{64\pi^2 \ \epsilon_0^{\ 2} \ c^4 \ r^2} \quad (1 + \cos^2 \theta)$$

in which

$I_{\theta, r}$ = intensity as a function of θ and r

θ = phase angle of radiation

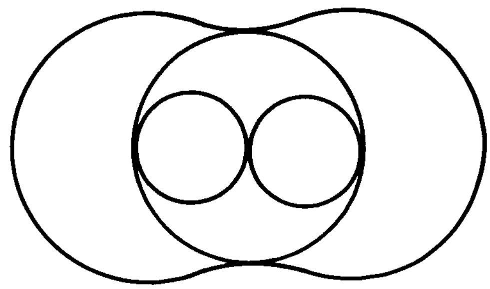
r = radius of scattering molecule

f = frequency

p = induced dipole moment

ϵ_0 = dielectric constant

c = velocity of light



$$I_{\theta, r} = \frac{f^4 p^2}{64 \pi^2 \epsilon_0^2 c^4 r^2} \quad (1 + \cos^2 \theta)$$

FIGURE 3. POLAR DIAGRAM OF RAYLEIGH SCATTERING OF UNPOLARIZED LIGHT

The outer envelope is the vector sum of these two functions. The radiative transfer equation has to account for multiple scattering. In this case, the scattering of fully elliptically polarized radiation must be considered. The Rayleigh scattering matrix, R, has to be used. For the "conservative case," only four elements of the matrix are required, as follows:

$$R = \frac{3}{2} \begin{pmatrix} \cos^2 \theta & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \cos \theta & 0 \\ 0 & 0 & 0 & \cos \theta \end{pmatrix} \qquad (1)$$

From the four S-functions which are obtained through the solution of the matrix for multiple scattering, the four required Stokes parameters can be derived. These are necessary and sufficient to describe the state of fully elliptically polarized radiation emanating at the bottom or top of the atmosphere.

Figure 4 shows the geometry for the albedo radiation falling on a satellite element in space. The sun's direction is given by the direction cosine μ_0 measured at a surface area unit (called a "section") in the direction of the sun. The spacecraft surface area unit (called "element") is seen from the "section" under the direction cosine μ. The azimuthal angle between the two dotted planes is ϕ. Other variables shown in Figure 4 are the altitude H, the angle at the center of the earth δ_n, the angle between element→section vector and the normal to the element β, and the angle α_m between the meridian plane of the element and the plane containing the element→section vector.

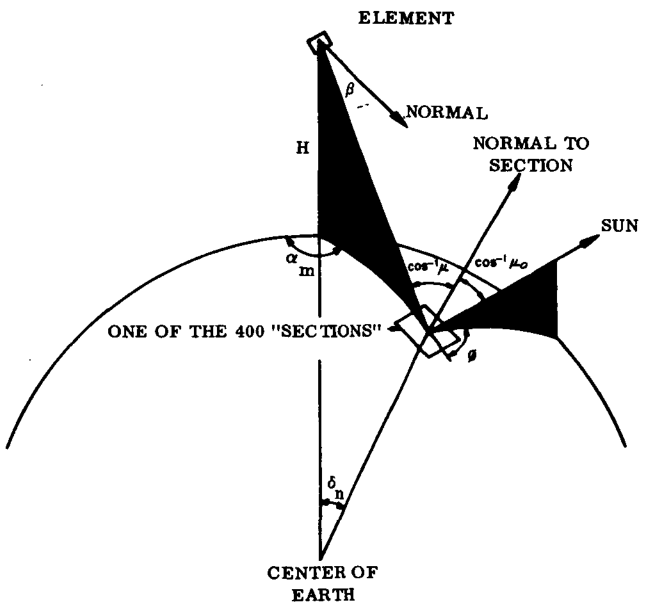


FIGURE 4. SECTION ON PLANET SURFACE

The four Stokes parameters, angular distribution, and spectral resolution of the radiation emanating at the top of the atmosphere depend upon five variables: (1) the direction cosine μ_0 of the solar radiation falling on the section, (2) the direction cosine μ of the section toward the satellite element, (3) the optical thickness of the atmosphere τ, (4) the earth surface albedo A, and (5) the azimuthal angle ϕ at the earth surface section between the vertical planes containing μ_0 and μ.

Snoddy determined the radiation intensity coming from each of the differential "sections." The total or effective albedo was obtained by numerically solving the following integral:

$$H_{R\lambda} = \int_{A_E} \frac{I_R(\mu, \mu_0, \phi, A, \tau) \cos\mu \cos\beta d A_E}{r^2} . \quad (2)$$

The results of the study are to be published separately; therefore, only a few examples are given here. Figure 5 is a map of isophotes for the area of the earth sensed by the spacecraft element as a function of given values of H, τ, A, and the solar incident angle at subelement point Θ_0. The illustration

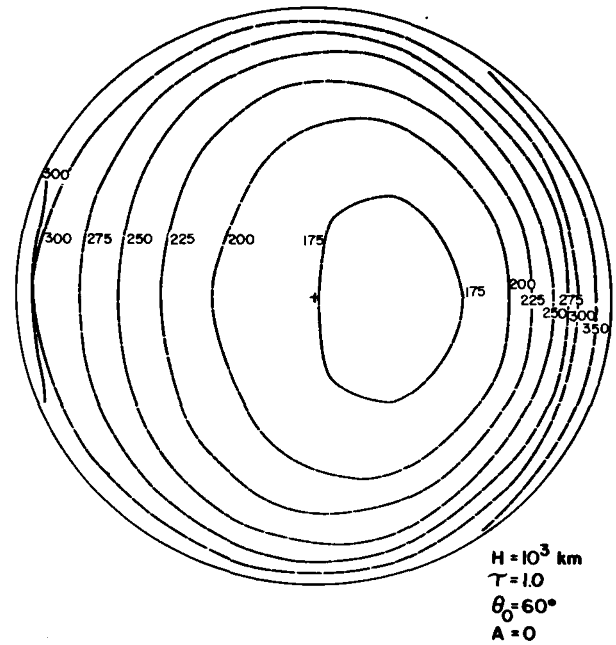


FIGURE 5. MAP OF ISOPHOTES FOR H = 10^3 km

shows the angular distribution as it affects the spacecraft thermal control computations. The sun vector is 30 degrees from the vertical to the right. The brightest area under the specific conditions of this case is not the subsolar point but the outside area. There is definitely a case of brightening toward the terminator. Figure 6 shows the isophotes for another set of parameters. Here, the conical intersection of the new field with the earth includes a shaded part of the earth.

Figure 7 shows the spectral resolution of the earth albedo incident on a spacecraft element. The surface albedo, A, of the earth is the variable parameter, and all other parameters are kept constant at the values indicated. These parameters are the altitude H, the elevation angle of the normal to the satellite element Θ_p, and the azimuth angle of the normal to the satellite element ϕ_p. It can be seen that the spectral distribution varies considerably for the three albedos shown.

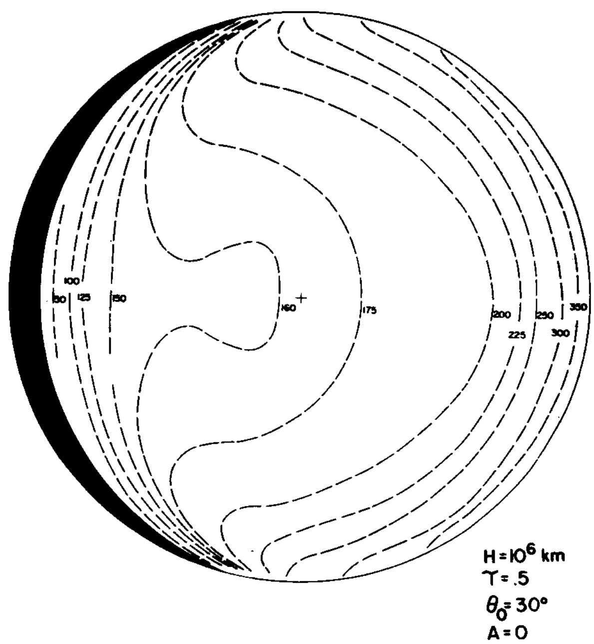


FIGURE 6. MAP OF ISOPHOTES FOR H = 10^6 km

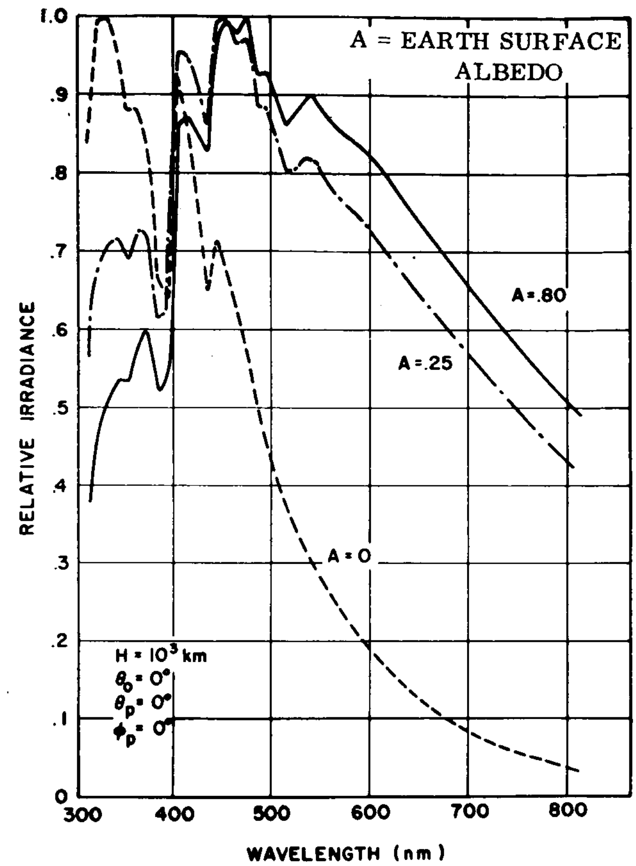


FIGURE 7. RELATIVE IRRADIANCE FOR THREE VALUES OF EARTH-SURFACE ALBEDO AS A FUNCTION OF THE WAVELENGTH

Because of its great importance for spacecraft in the neighborhood of planetary bodies, further research in this field is needed.

B. EMISSIVITY

Emissivity was the first research study in thermophysics at MSFC. It began ten years ago in the Army Ballistic Missile Agency, and was supplemented by a research contract for early satellite studies. The research results were helpful in solving the thermal problems of Explorer I and other Explorer satellites [7]. Emissivity research is continuing; current problems are concerned with wider temperature ranges and the fundamentals of the interaction of electromagnetic waves with matter.

Figure 8 shows a rotating-specimen furnace developed under contract [8] by Richmond and Moore of the National Bureau of Standards in support of MSFC high-temperature emittance research. The furnace heats samples to 1673° to 2073°K (1400° to 1800°C) while rotating them, so that they are evenly heated and an equally hot area of the sample is always exposed to the viewing port. The emitted flux is taken out in near-normal direction and analyzed by an infrared (IR) spectroradiometer. A shallow hole, drilled into the sample, serves as a "black body." Earlier work on the emittance of shallow holes by Guffé has been extended, and the applicability of this emittance research has been proven by further theoretical and experimental research.

Figure 9 shows some results of emittance research in the far IR at room temperature and at cryogenic temperatures [9]. It has generally been assumed that it is sufficient to measure the emittance of surfaces in the IR from 1 to 15 microns. However, for a typical surface like the S-IV stage with a white control coating, the peak of the Planck black-body radiation curve is at approximately 15 microns. This means that 75 percent of the total energy is emitted above this value. Figure 9 shows a reflectance curve measured by Blau and Aronson of A. D. Little Co. under MSFC contract [9]. The reflectance is plotted against the

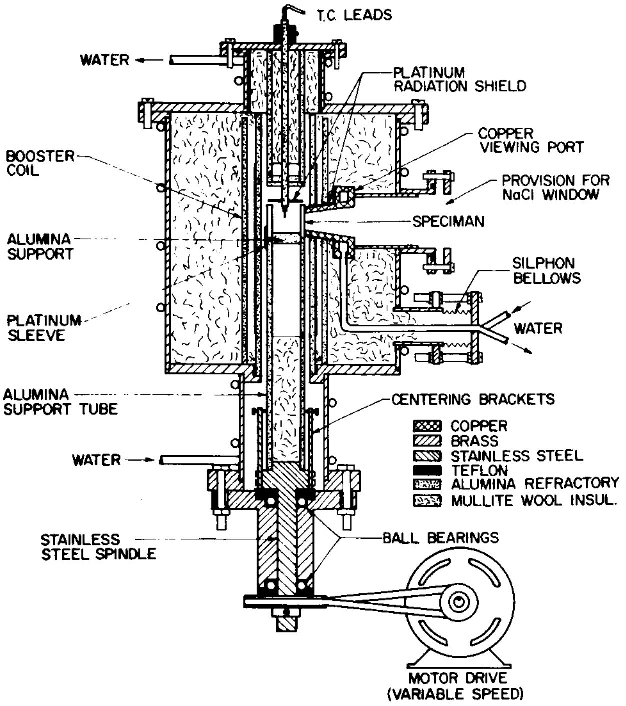


FIGURE 8. SCHEMATIC OF ROTATING-SPECIMEN FURNACE

wave number. The curve shows strong reflection bands. Any extrapolation of emittances beyond 15 microns, using the value measured at the wave-length, will mean a great error in the effective infrared absorptance. The far IR region of Figure 9 corresponds to wave numbers 667 cm^{-1} to 50 cm^{-1}. Very little study has been made of this region of the electromagnetic spectrum between IR and millimeter waves of the radio spectrum, partly because of the inherent experimental and theoretical difficulties. More research in this area is needed.

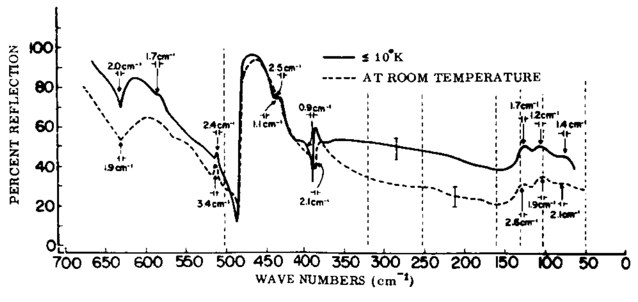


FIGURE 9. FAR INFRARED REFLECTION SPECTRUM OF Al_2O_3

Another outstanding research achievement in the field of emissivity is the quantum mechanical studies by Schocken (MSFC) and a group of physicists at Colorado State University (Burkhard and Ashby, with the assistance of Condon and Holstein) under a contract with P. E. C. Corp. at Boulder, Colorado [10, 11, 12]. The purpose of the studies was to derive emissivities ϵ and absorptivities α from basic principles. According to Kirchoff's law, the ratio of α/ϵ is always 1.0 for opaque substances, provided the same wavelength or the same spectrum distribution of the radiation is considered. Kirchoff's law can easily be derived for thermodynamic equilibrium from the laws of thermodynamics. The next step is to prove this on the basis of the electromagnetic wave fronts, using Huygen's principle. In the early part of this research, theoretical results previously obtained by other investigators were confirmed (i. e., Kirchoff's law is proven to be valid under the assumption of the wave theory). The final phase of this research was the analysis of the probability of photons leaving the lattice of a metal on the basis of principles of quantum mechanics. The main difficulty of this work was the generation of an attenuating function which provides an exponential decay of electric field strength. The total Hamiltonian takes into account interactions of photons with several different types of electrons and with lattice impurities. The overall result is a difference between emittance and absorptance. The main difference between these two nondimensional coefficients is due to the effect of the incoming electric vector field on the electronic states and on the probability of a quantum jump resulting in a photon leaving the lattice. Figure 10 shows the integrated gray-body radiation intensity as a function of the ratio of two temperatures: the temperature of the solid T_s and the temperature of the radiation environment T_r. The ratio of emissivity to absorptivity, ϵ/α, versus the temperature ratio, T_s/T_r, is shown. The deviations due to the quantum mechanical effects are especially great at low values of the nondimensional temperature ratio T_s/T_r. One interesting conclusion of this research is that the emissivity can no longer be defined and standardized as a materials property. It should also be pointed out that Figure 10 cannot be generalized for all applications, because in many cases the spectral distribution differs from the one used in the computation given. A corollary conclusion of this research is that geometry factors and radiative transfer coefficients can be in error if this effect is neglected.

Another research aspect of emissivity is the determination of effective emittance or IR absorptance values. Figure 11 shows the spectral distribution of the IR earth radiation [13]. It has two main components: (1) the radiation from the atmosphere,

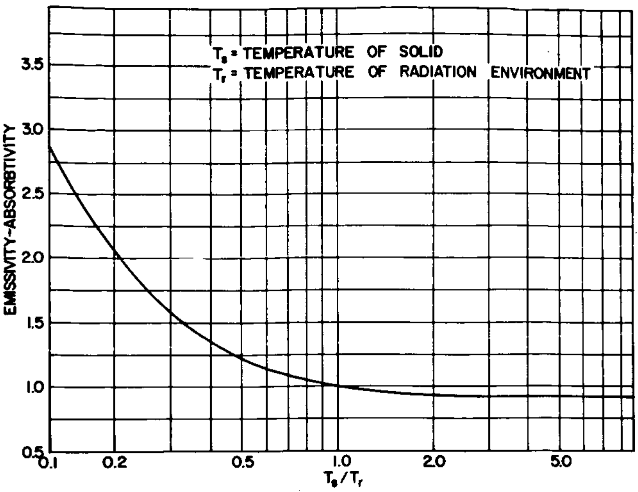


FIGURE 10. INTEGRATED GRAY-BODY RADIATION INTENSITY AS A FUNCTION OF THE RATIO T_s/T_r

which has nearly a black-body distribution corresponding to a temperature of 250°K and (2) radiation coming from the surface of the earth at about 288°K, with a peak about twice as high as the other component. However, only the bands for which the atmosphere is transparent (between 8 and 13 microns) contribute to the total radiative flux leaving the top of the atmosphere. The graph also shows a curve of the measured emittance of sandblasted aluminum. The effective absorptance of the surface for IR radiation is shown as a third curve (data from Snoddy and Miller [14]). The value for ϵ (earth) = α (earth) is obtained by integrating the last curve from 0 to ∞. This is one of the inputs to the general computer program for thermal control which will be discussed in more detail.

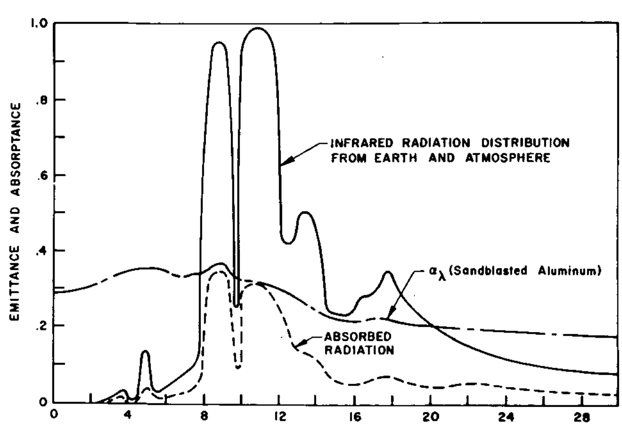


FIGURE 11. ABSORPTANCE OF SPACECRAFT SURFACE-TO-EARTH INFRARED RADIATION

C. COMPUTER PROGRAMS

The temperature of spacecraft depends mainly on: (1) the exchange of electromagnetic radiation with space and nearby celestial bodies, (2) spacecraft internal heat generation, and (3) energy fluxes between parts of the spacecraft. Computer programs have been developed at MSFC to properly analyze the complicated heat-exchange mechanisms. From the early phases of Explorer I thermal design, the computer program was developed to a high degree of sophistication. Papers on thermal design of Explorers and other space vehicles have been published by several investigators [15-26] at MSFC.

Research at MSFC has concentrated on computer-program use for satellite temperature prediction. Experimental research in the laboratory gives essential inputs and checks on specific points, but it does not replace the computed results. Our computer code is used as a powerful tool during the following phases of thermophysics activities:

1. Preliminary analysis during the study and early design of a satellite project. Requirements for thermal design are given during this phase.

2. Determination of thermal test requirements.

3. Verification of thermal design as expected throughout the lifetime of spacecraft. Design parameters, launch days and hours, results of thermal tests, and injection conditions are used in this thorough analysis.

4. Analysis of telemetered temperature measurements after successful launching of the satellite is accomplished. Special computer codes are used for analysis of data obtained from space environmental effects sensors which will be described in this report.

The establishment of thermal vacuum test requirements, a very important part of theoretical studies, is very often overlooked or ignored. It allows for the consideration of questions such as usefulness of solar simulation and accuracy requirements for simulation parameters. Often simulation knowledge is far behind spacecraft design, and therefore only comparatively low accuracies can be achieved in such testing. The use of a computer program shows whether the actual behavior of spacecraft in space can be determined better by a complete test, by improved determination of specific heat transfer coefficients, or by measurements of optical properties of thermal control surfaces immediately before launch. Thermal vacuum testing is a very active research field. In many cases, a test can give only a few check points such as the "cold case" (lowest temperature conditions) or the "hot case" (highest temperature conditions). Since more than 20 parameters affect thermal control, only a few can be tested. Our computer code verifies the soundness of the test results obtained and the computation of transient conditions and simultaneous variations of other parameters which can never be included in a test program because of limitations in cost and time. Following is a discussion of the heat flux equation in its basic form.

The computation of satellite temperature is based on the heat flux equation written for an isothermal element A_j of the satellite:

$$A_j \alpha_1 SD_1 + A_j \alpha_2 g\, h\, BS \cos\theta\, D_2 + A_j \alpha_3 g\, h\, E\, S$$

$$-A_j \epsilon_{T_j} \sigma T_j^4 + \sum_{\substack{j,\,k=1 \\ k \neq j}}^{n} \left[c_{kj}(T_k - T_j) + r_{kj}(T_k^4 - T_j^4)\right]$$

$$-A_j d_j c_p \rho \dot{T}_j + q_j = 0 \qquad (3)$$

$j = 1, 2, \ldots\ldots n.$

This equation has a number of flux terms which are explained here in more detail:

1. Flux terms for incoming energy are:

Insolation $= A_j \alpha_1 S\, D_1$

Albedo radiation $= A_j \alpha_2 g\, h\, B\, S \cos\theta\, D_2$

IR earth radiation $= A_j \alpha_3 g\, h\, E\, S$

wherein

A_j = isothermal surface element

α_1 = α_s absorptance for solar radiation

S = solar constant

D_1 = step function (D_1 = 1 in sunlight
= 0 in earth shadow)

α_2 = absorptance for albedo radiation

g = radiative transfer function (depends upon spacecraft attitude angles)

h = radiative transfer function (depends upon spacecraft altitude)

B = earth albedo

$\cos\theta$ = direction cosine of albedo

D_2 = step function (D_2 = 1 in hemisphere toward sun
= 0 in opposite hemisphere)

α_3 = α_E absorptance for earth IR spectrum

E = ratio of earth IR flux to solar constant

2. Flux term for radiative energy leaving the surface element A_j to space

$$A_j \epsilon_{T_j} \sigma T_j$$

wherein

ϵ_{T_j} = emittance of surface element A_j for its Planck temperature T_j. In many cases ϵ_{T_j} is set equal to α_E.

σ = Stephan-Boltzmann constant

T_j = temperature of element A_j

3. Internal flux terms

a. Heat exchange by conduction and radiation between isothermal surfaces

$$\sum_{j,k=1}^{n} \left[c_{kj}(T_k - T_j) + r_{kj}(T_k^4 - T_j^4)\right]$$

$k \neq j$

wherein

c_{kj} = conductive transfer coefficient from element k to element j

r_{kj} = radiative transfer coefficient from element k to element j

T_k, T_j = temperature of elements k, j

b. Heat flux absorbed due to heat capacity of the element A_j

$$-A_j d_j C_j \rho_j \dot{T}_j$$

wherein

d_j = thickness of area element A_j

C_j = specific heat of area element

ρ_j = density of area element

$\dot{T}_j$ = time derivative of T_j

c. Internal heat production of the element A_j

q_j

Equation (3) is a simplified version of the actual equation used for the computer program. It is a system of n (which may be up to 100) nonlinear fourth-order differential equations which are solved simultaneously on the 7094 computer. Many of the terms are functions of several variables, such as the step functions D_1 and D_2, which depend upon the six velocity and space coordinates of injection, the hour and day of injection, and the time after launch. Many parameters are also complicated functions of time. All surface properties are affected by the space environment, and the orbital parameters change by precession and rotation of the line of apsides.

Thermal control inputs to the computer program are shown in Figure 12. On the top line are the external parameters: insolation, albedo, earth IR, step functions, direction cosines, and station coordinates.

The terms are:

$S(D)$ = solar constant dependent on day D

$B(\vec{R}, \beta, \theta)$ = albedo, as function of radius $\vec{R}$ and angles β and θ

		S (D)	$B(\vec{R},\beta,\theta,)$	$E(\vec{R},\beta)$	STEP FUNCTION $D_1(t,D,H,l_0,\delta_0)$ $D_2(t,D,H,l_0,\delta_0)$	$\vec{R}\cdot\vec{\Gamma}$	$\vec{X},(t)\cdot\vec{\Gamma}(D,H,t)$ $\vec{Z},(t)\cdot\vec{\Gamma}(D,H,t)$	$\vec{X}\cdot\vec{R}$ $\vec{Z}\cdot\vec{R}$	STATION COORDINATES β_S, γ_S
PROPERTIES OF i OUTSIDE SURFACE ELEMENTS	$\alpha_{T,1}(t)$ $\alpha_{T,2}(t)$ ⋮ $\alpha_{T,n}(t)$ $\alpha_{S,1}(t)$ $\alpha_{S,2}(t)$ ⋮ $\alpha_{S,n}(t)$ C_1 C_2 ⋮ C_n	TEMPERATURE PREDICTION FOR TYPICAL CASES							
INTERNAL HEAT OF ELEMENT j	ΣQ_j								
GROSS LINKING TERMS BETWEEN ELEMENTS j,k	$\sum_{\substack{m=1 \\ j \neq k}}^{j,k} c_r(T_j^4 - T_k^4)$ $\sum_{\substack{m=1 \\ j \neq k}}^{j,k} c_c(T_j - T_k)$								
INJECTION h, β, γ PARAMETERS - V, ζ, τ					TIME IN SUNLIGHT PREDICTIONS FOR A YEAR				VISIBILITY FROM STATION

FIGURE 12. GENERAL COMPUTER PROGRAM INPUTS FOR THERMAL CONTROL

β = latitude of satellite position

θ = angle between sun vector and radius vector $\vec{R}$.

$E(\vec{R}, B)$ = earth IR radiation as function of radius $\vec{R}$ and latitude angle β.

D_1, D_2 = step functions dependent on day D and hour H of launching, the sun longitude l_0, and sun declination δ_0.

$\vec{R}$ = radius vector

$\vec{\Gamma}$ = sun vector

$\vec{X}$, $\vec{Z}$ = spacecraft fixed vectors

β_s, γ_s = latitude and longitude of observation station.

The input parameters in the vertical column are the properties of the surface elements, such as IR absorptance α_T at temperature T, solar absorptance α_s, and the heat capacities of these surface elements. There are the internal heat production and cross-linking terms for conductive and radiative exchange between all elements k and j. In addition there are the six injection parameters of the spacecraft. Figure 13 shows a table of the coefficients r_{kj} up to n isothermal areas A_j. These coefficients have to be determined by ground tests or by special analytical procedures based on view factors and emittances of inside or outside surfaces of the n area elements A_j. There are n (n-1) coefficients.

The computer program can be used to determine special aspects which have a bearing on the thermal control but which do not require step-by-step integration of the differential equations.

The time-in-sunlight of a spacecraft in earth orbit can be computed by combining the step function D_1 and the angular distance of the sun vector $\vec{\Gamma}$ from from the radius vector of the spacecraft $\vec{R}$ with the with the injection parameters of the satellite. The step function D_1 is, in turn, dependent on the day of

k \ j	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	•	•	n
1		$r_{2,1}$	$r_{3,1}$	$r_{4,1}$	$r_{5,1}$	$r_{6,1}$	$r_{7,1}$	$r_{8,1}$	$r_{9,1}$	$r_{10,1}$	$r_{11,1}$	$r_{12,1}$	$r_{13,1}$	$r_{14,1}$	$r_{15,1}$	$r_{16,1}$	$r_{17,1}$	•	•	$r_{n,1}$
2	$r_{1,2}$		$r_{3,2}$	$r_{4,2}$	$r_{5,2}$	$r_{6,2}$	•	•	•	•	•	•	•	•	•	•	$r_{17,2}$	•	•	•
3	$r_{1,3}$	$r_{2,3}$		$r_{4,3}$	$r_{5,3}$	$r_{6,3}$	•	•	•	•	•	•	•	•	•	•	•	•	•	•
4	$r_{1,4}$	$r_{2,4}$	$r_{3,4}$		$r_{5,4}$	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
5	$r_{1,5}$	$r_{2,5}$	$r_{3,5}$	$r_{4,5}$		•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
6	$r_{1,6}$	$r_{2,6}$	$r_{3,6}$	•	•		•	•	•	•	•	•	•	•	•	•	•	•	•	•
7	$r_{1,7}$	$r_{2,7}$	•	•	•	•		•	•	•	•	•	•	•	•	•	•	•	•	•
8	$r_{1,8}$	$r_{2,8}$	•	•	•	•	•		•	•	•	•	•	•	•	•	•	•	•	•
9	$r_{1,9}$	•	•	•	•	•	•	•		•	•	•	•	•	•	•	•	•	•	•
10	$r_{1,10}$	•	•	•	•	•	•	•	•		•	•	•	•	•	•	•	•	•	•
11	$r_{1,11}$	•	•	•	•	•	•	•	•	•		•	•	•	•	•	•	•	•	•
12	$r_{1,12}$	•	•	•	•	•	•	•	•	•	•		•	•	•	•	•	•	•	•
13	$r_{1,13}$	•	•	•	•	•	•	•	•	•	•	•		•	•	•	•	•	•	•
14	$r_{1,14}$	•	•	•	•	•	•	•	•	•	•	•	•		•	•	•	•	•	•
15	$r_{1,15}$	•	•	•	•	•	•	•	•	•	•	•	•	•		•	•	•	•	•
16	$r_{1,16}$	•	•	•	•	•	•	•	•	•	•	•	•	•	•		•	•	•	•
17	$r_{1,17}$	$r_{2,17}$	$r_{3,17}$	•	•	•	•	•	•	•	•	•	•	•	•	•		•	•	•
•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•		•	•
•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•		$r_{n,n-1}$
n	$r_{1,n}$	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	$r_{n-1,n}$	

FIGURE 13. COEFFICIENT OF RADIATIVE TRANSFER OF TERMS

launching after the vernal equinox and the hour of launching (Fig. 12). The geometry involved is shown in Figure 14. A typical result for the Pegasus I spacecraft is shown in Figure 15; this shows a plot of the percentage time in sunlight versus the days after launch. Three hours of the solar day, $T_0 = 0$, 2, and 4, are used as parameters.

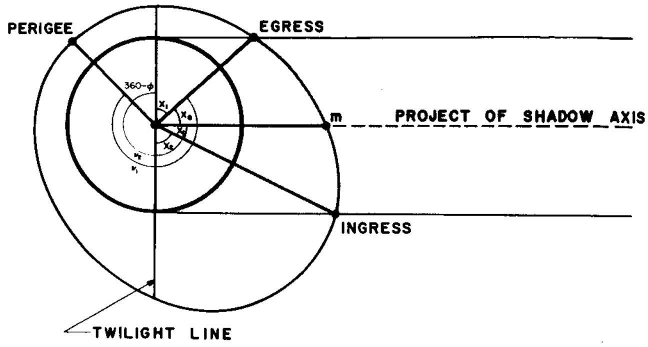


FIGURE 14. PARAMETERS IN CALCULATION OF SPACECRAFT TIME IN SUNLIGHT

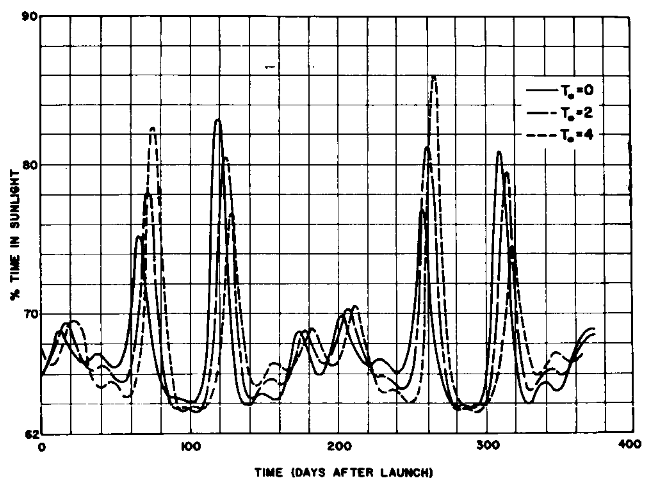


FIGURE 15. PERCENT TIME IN SUNLIGHT FOR PEGASUS I VS. DAYS AFTER LAUNCH

D. THEORETICAL THERMOPHYSICS

Although thermophysics research has been expanding rapidly under the stimulus of space programs, a great deal of fundamental knowledge has yet to be acquired. One field of thermophysics research which promises to yield basic information is that of thermal similitude. This deals with nondimensional numbers or π ratios; therefore, conclusions drawn from work on models may be usefully extrapolated. The theory of similitude has been well established in other areas of physics, such as mechanics (especially fluid mechanics). Wind-tunnel testing is a widely accepted tool of research and development for which π ratios like Mach and Reynolds numbers are common knowledge.

Such numbers are not well established in thermophysics, and even the problems or goals of the research activity are not well understood. Some investigators are trying to prove or disprove the usefulness of thermal modeling by running extensive series of tests in vacuum chambers. Claims have been made that these tests have proved that a space vehicle can be fully checked out by a thermal vacuum test of a model. This conclusion seems highly improbable, and may even be the wrong objective for this type of research. Model testing for aerodynamic shapes and problems has proved extremely valuable for airplane and space vehicle design. It is conceivable that its usefulness for solving thermal problems will develop ultimately in the same direction. It is not the checkout phase, however, but the research and development phase for which such techniques can become a powerful tool. Hence, the problems must be defined and solutions found by employing the proper set of experimental parameters. MSFC research is inclined in this direction. The greatest potential for thermal similitude research is in cost savings, because it may prove that expensive full-scale tests with solar simulation are not required. Thermal similitude investigations are more difficult in that six π ratios are required for the solution of the general case. These π's are the nondimensional numbers which must be considered in the similitude analyses. Such a set of π ratios can be obtained by trial and error methods, and a few of such sets have been proposed. The research done by Jones, in cooperation with the University of Alabama [27], started out with the theory of similitude rather than with a ready-made but limited solution. Some excellent research in thermal similitude is being done by Vickers of Jet Propulsion Laboratory [28]. Jet Propulsion Laboratory is interested in the equilibrium case for long periods of coasting in interplanetary space. Interest at MSFC is on the study of transient conditions as they occur in the eclipsing of satellites by the earth's shadow, and in thermal vacuum testing when heat is applied in terms of a step function. Research on thermal similitude at MSFC, therefore, includes the more general case in which the time derivatives of all functions have to be considered. A discussion of the early and very promising results of this research follows.

One example of many theoretically possible nondimensional groups is illustrated in Figure 16. The

π groups were derived on the basis of Brand's formulation of the π theorem in matrix form. This matrix has been programed for the 7094 computer

$$\pi_1 = \frac{C_j\ T_k}{R_{A_j}\ I_j\ t}$$

$$\pi_2 = \frac{C_{kj}\ t}{C_j}$$

$$\pi_3 = \frac{R_{A_j}^3\ I_j^3\ R_{kj}\ t^4}{C_j^4}$$

$$\pi_4 = \frac{I_{A_j}}{R_{A_j}}$$

$$\pi_5 = \frac{C_j\ T_j}{R_{A_j}\ I_j\ t}$$

$$\pi_6 = \epsilon_j$$

FIGURE 16. NONDIMENSIONAL π GROUPS

and solved. A total of 53 independent sets of six π ratios for thermal similitude have been obtained [29]. Theoretical and experimental work on the problem is being done at the University of Alabama. The experimental research by Matheny is directed toward time-scaling laws [30]. Figure 17 is a photograph of a prototype and model. The experimental setup provides for heating of the upper disk and for thermocouple measurements at various locations in the upper disk, stem, and lower disk. Some test results obtained by Matheny are shown in Figure 18. The temperature of upper disk T_1 and lower disk T_2 are plotted against time t. The time scale is not the same, but is compressed for the prototype by a factor of d^2, if d is the linear scaling factor. Theoretical evaluation of these results is made in connection with MSFC's in-house computer program [31].

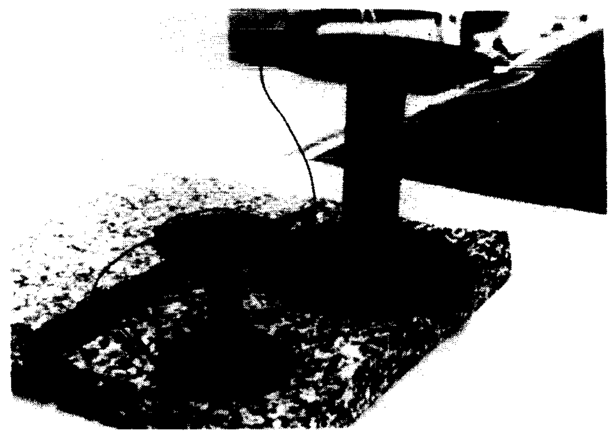


FIGURE 17. THERMAL SIMILITUDE PROTOTYPE AND MODEL

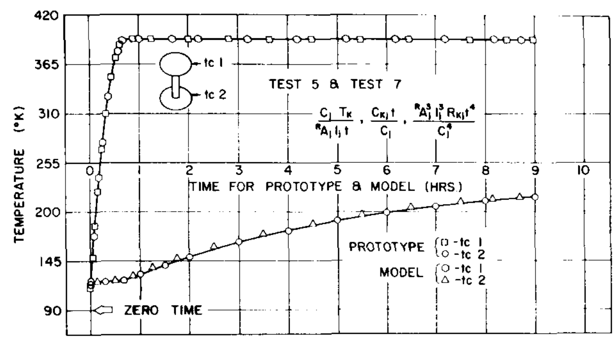


FIGURE 18. TRANSIENT TESTS ON PROTOTYPE AND MODEL

Other MSFC theoretical thermophysics research is concerned with the interface conductance of surfaces in the vacuum of space. The so-called "metallic contact" between two metal surfaces which are fastened together, such as in a flange, have very little thermal resistance under normal atmospheric conditions. It is known that the heat is mainly conducted across the interface by the absorbed or enclosed air in the gap. Research for space application is required to determine the parameters affecting the heat transfer in vacuum and the physical processes involved. Results of this research have been utilized by Astrionics Laboratory of MSFC in the design of the instrument unit (IU) of the Saturn vehicles S-IV, S-IVB, and S-V. The problem here is to maintain and assure a high heat conductance between the IU instruments and "cold plates" on which they are mounted. Research in this field has been carried out by Atkins through in-house studies supported by contracted research [32]. A complete bibliography is given in Reference 33. The experimental apparatus of Astrionics Laboratory, which was used in connection with the IU thermal work, will be discussed in the Measuring Techniques section of this report.

Further experiments were performed by Fried under an MSFC contract with General Electric Co. [34, 35]. Figure 19 presents results compared with earlier investigations by Clausing of the University of Wisconsin. The slope of the first portion of the curve is close to the theoretical slope of 2/3, which is the exponent for elastic deformation of the contact points.

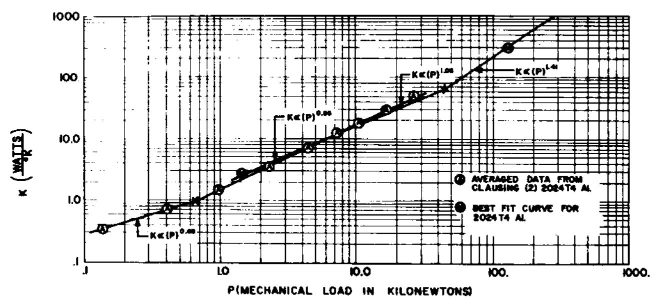


FIGURE 19. THERMAL INTERFACE CONDUCTANCE IN SPACE VS. LOAD APPLIED

Interface conductance between powder particles in "hard" vacuum (13×10^{-8} N/m^2 or 10^{-9} torr, and below) is of another type. Research Projects Laboratory at MSFC has measured thermal conductance of pumice powder with a special calorimeter, illustrated diagrammatically in Figure 20. This apparatus measures thermal conductivity of powders in the temperature range of 79°K (temperature of liquid nitrogen) to 450°K. Data on thermal conductivity of pumice powder as a function of vacuum and particle size are given in Figure 21. The vacuum causes a change of conductivity by two orders of magnitude. The effect of particle size is complex in that it varies with gas pressure. As shown in the illustration, at the lowest pressures tested, particles in the range of 44 to 104 microns had the lowest conductance. At intermediate pressure, however, particles less than 44 microns had the lowest conductance.

The research discussed was done mainly for information on insulating powders. Conclusions

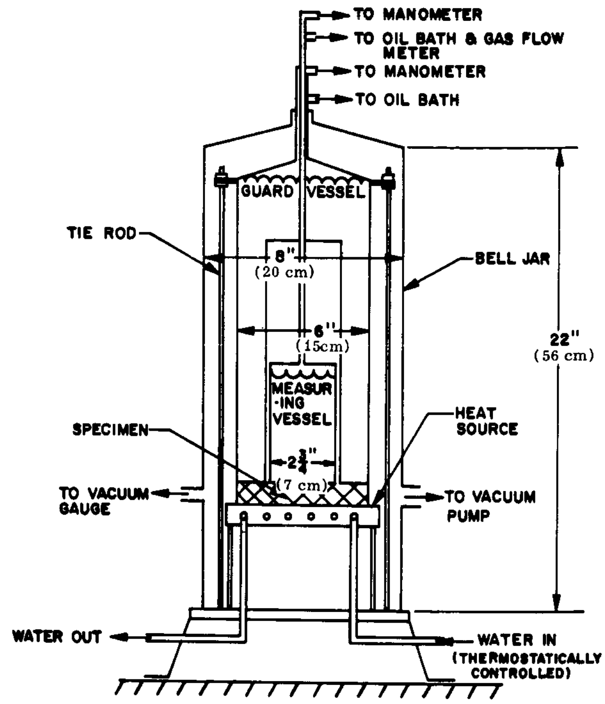


FIGURE 20. THERMAL CONDUCTIVITY CALORIMETER

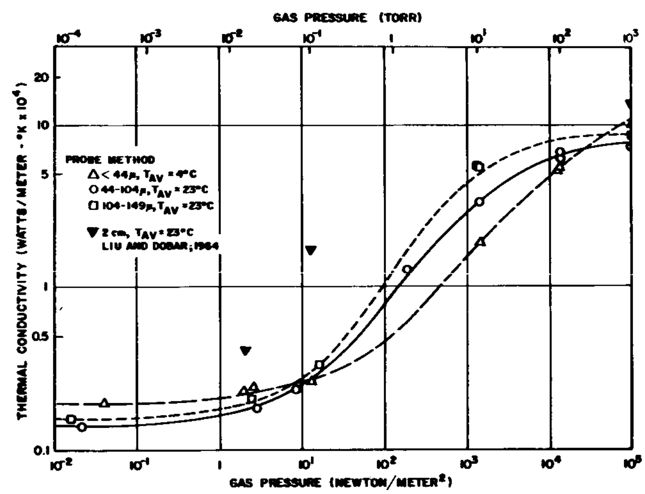


FIGURE 21. THERMAL CONDUCTIVITY OF PUMICE POWDER

can be drawn from this behavior and applied to the very underdense powders on the surface of the moon. Expansion of theoretical knowledge and the various techniques associated with the exploration of the lunar environment, and enlightenment on the composition of the "dust" layer of the moon, seem to be logical steps in the extension of this research [36-39]. Results of current studies indicate that the use of the concept of diffusivity, as in the Fourier differential equation for conduction in solids, is not necessarily applicable to thermal conductivity of powders. One reason is that the conduction through interfaces in "hard" vacuum is not well understood. Also, radiative conduction plays a major role since lunar "dust" is underdense by a factor of 10 to 30.

E. THERMAL CONTROL

Thermal control is one of the applied fields of thermophysics research. Most of the people mentioned as contributors in other sections of this report have contributed to space-vehicle thermal control at MSFC [40-48]. Research on the computer programs mentioned earlier contributes to this area. A study made by Snoddy and Miller on requirements for thermal control surfaces, which was given as a paper at the 1964 Thermophysics Specialist Conference [14], will be discussed here.

The outside surfaces of a space vehicle are among the essential parameters for effective thermal control. Figure 22 shows the result of a study of all available thermal control surfaces, such as metals with various surface characteristics, interference-type coatings, ceramic coatings, paints, etc. It reflects the status of knowledge early in 1964. The solar absorptance α_s is plotted against the IR absorptance at temperature α_T or ϵ_T, in which T is usually assumed to be 300°K. Solid lines have a constant ratio of α_s/ϵ_T. The white area indicates that they are unavailable.

In Figure 23 data are given for coatings with the requirement of those in Figure 22 and the special requirement of ultraviolet stability. The white area in this figure is considerably smaller, especially for surfaces below the line $\alpha_s/\epsilon_T = 1.0$, which includes most of the nonmetallic surfaces. An important requirement for MSFC is the applicability of thermal control coatings to large surfaces of space vehicles. The availability of these surfaces is shown in Figure 24. Here, the white area is narrowed down considerably, mainly because, for many cases where surfaces are known, processes for the coating of large vehicles are unavailable or are too costly for consideration at the present time. Electrically conductive surfaces are required for some scientifically instrumented spacecraft. This is important if the outer satellite skin has to be an equal-potential surface. This requirement was imposed for Explorer X. Figure 25 shows the thermal control surfaces available for this purpose. The selection is narrowed considerably compared to the previous illustrations. If several of these restrictive requirements are applied, as is necessary for most vehicle considerations, only a narrow band of availability remains. Research to fill some of these critical gaps has been successful at MSFC, notably the studies of Gates in collaboration with Zerlaut of IIT Research Institute.

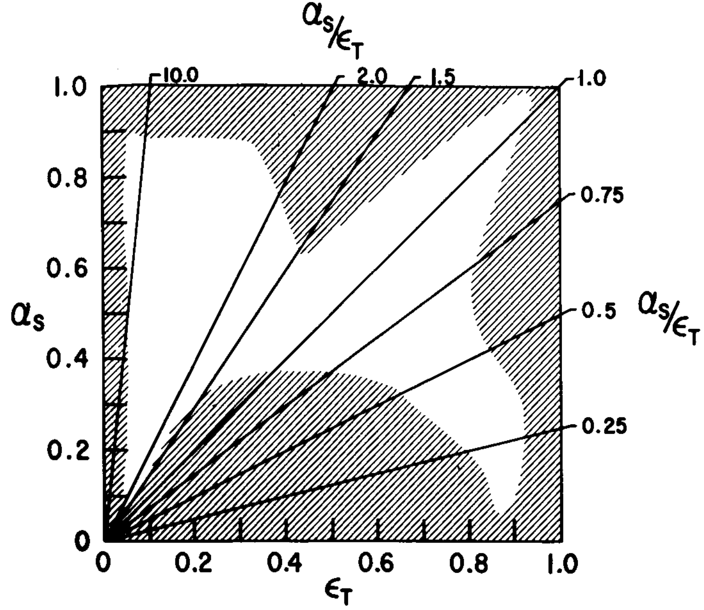


FIGURE 22. AVAILABLE THERMAL CONTROL SURFACES, OVERALL STATUS

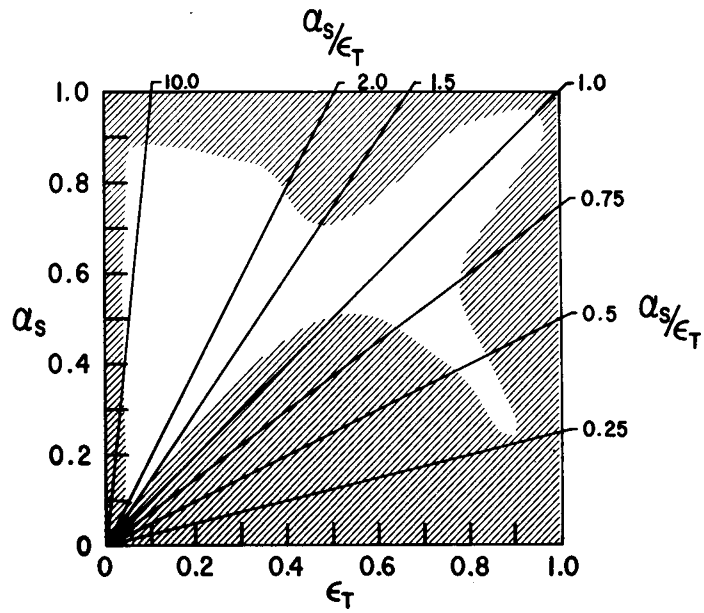


FIGURE 23. AVAILABLE THERMAL CONTROL SURFACES, ULTRAVIOLET-STABLE SURFACES

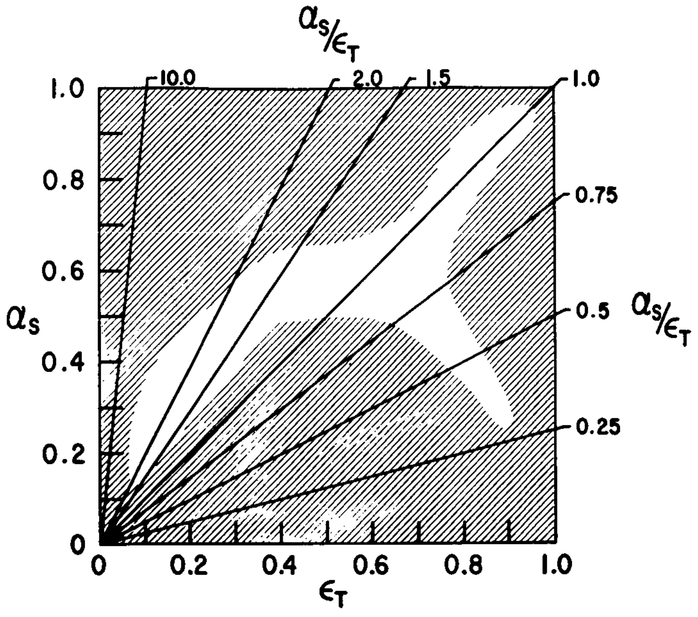


FIGURE 24. AVAILABLE THERMAL CONTROL SURFACES, LARGE-AREA SURFACES

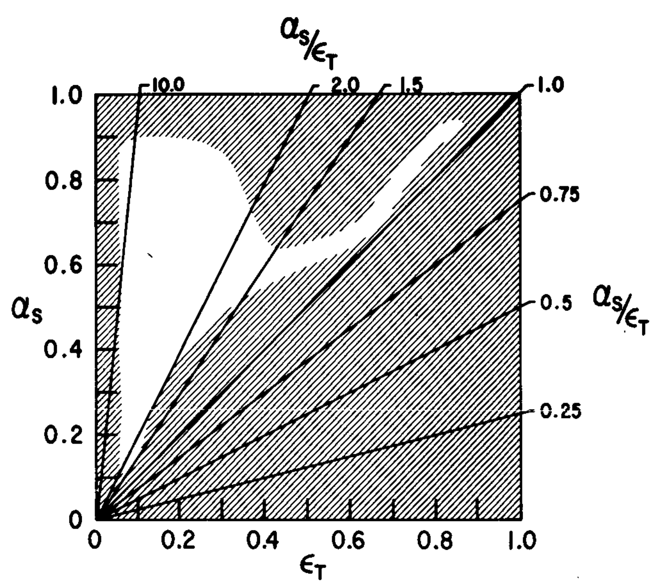


FIGURE 25. AVAILABLE THERMAL CONTROL SURFACES, ELECTRICALLY CONDUCTIVE SURFACES

The S-13 paint which found application as a coating for the S-IV stage and the Service Module Adapter of Saturn flights 8, 9, and 10, was a result of the research effort of Gates and Zerlaut over the past four years. A nation-wide survey, conducted two years ago by Fairchild-Hiller (the Pegasus prime contractor) and Miller of MSFC, revealed that no thermal control coating which would meet the Pegasus requirements was available. At that time, the decision was made to use the S-13 paint (90 gallons were required for a Saturn vehicle). Although the production of thermal control coating is not considered a research effort, it is mentioned here because the earlier research started in 1960 by Gates has found direct application to the Saturn coating problem. Several laboratories of MSFC have been involved in the procurement contract of the S-13 paint and its application to the Saturn vehicle. Materials research for improved thermal control paints is being done by Lucas and his coworkers in the Propulsion and Vehicle Engineering Laboratory of MSFC. This work in materials research is especially important for filling the large gaps which exist in the availability of thermal coatings shown in Figures 22 to 25.

F. EFFECTS OF SPACE ENVIRONMENT ON THERMAL CONTROL COATINGS

The effects of three environmental factors (ultraviolet, solar wind, and micrometeoroids) on thermal control coatings are discussed here.

1. Ultraviolet Effects. It was assumed in early Explorer experiments that inorganic white oxides such as TiO_2 or Al_2O_3 were stable in the space environment. Since then it has been learned that this is not necessarily correct, and a great number of substances now have been checked empirically in the laboratory for ultraviolet effects. It has been found that the semiconductor ZnO is less affected than many other oxides. The mechanisms of the interactions are not fully understood; consequently, a considerable amount of research is being conducted in this area. Research personnel who have made notable contributions are: Snoddy, Miller, and Arnett of MSFC [14], and Zerlaut of IIT Research Institute [49], under contract to MSFC. The S-13 coating already mentioned in connection with the S-IV application uses ZnO as a pigment, with a semiorganic silicone resin as binder. It is used to keep a component cool, especially under solar irradiation. Research is continuing toward a better understanding of the degradation mechanisms and to obtain better thermal control surfaces [50].

Research on UV effects is presently the most active research area of thermophysics. Each government and industrial thermophysics laboratory is engaged in research on UV effects because of the immediate need for space vehicle thermal control coatings. Unfortunately, most of this activity emphasizes testing rather than research. The status of laboratory UV degradation studies was the subject of a nation-wide "round-robin" at Ames Research

Center. Identical paint samples previously had been prepared from one batch and shipped at the same time to the sixteen participating laboratories. For the degradation experiments, all laboratories used the same high-pressure mercury UV lamps (A-H6 made by General Electric). Results of the experiments and information about special test conditions were sent to the Ames Research Center for evaluation. Figure 26 shows some of the results of this evaluation [51]. The increase of the absorptance for solar radiation $\Delta\alpha_s$ is plotted against the equivalent sun hours. The temperatures of the samples under the simulated illumination are indicated on the graph. The length of the dashes of each curve indicates the intensity used (in some cases, an intensity of 10 to 15 suns). This was also connected with the highest sample temperatures. The darkening of the surfaces could increase the temperature of the spacecraft by 30° to 50° C. It was impossible to arrive at a conclusive analysis of the effects. However, it became clear that the simulation techniques were completely inadequate at the times the measurements were made (end of 1963). Each of the round-robin participants knew that his measurements would be evaluated and correlated with others. Therefore, each experiment was carefully done. However, results differed by a factor of 5.

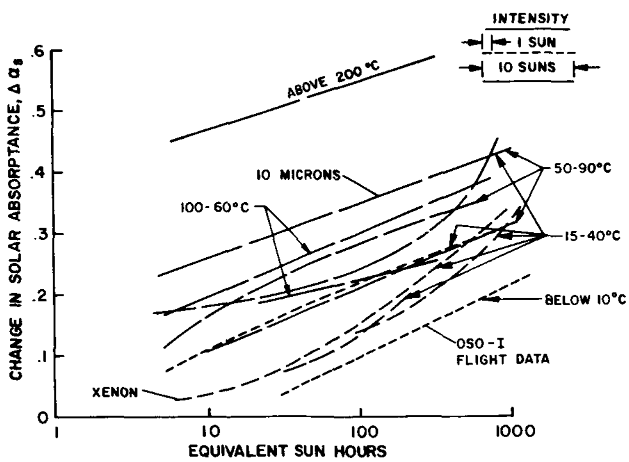


FIGURE 26. RESULTS OF ULTRAVIOLET DEGRADATION, "ROUND-ROBIN" TEST

Most determinations of UV stability of thermal control coatings of space hardware were made by the same laboratories. It is understandable that the thermal control of some spacecraft did not turn out as expected. The participants learned that more careful research is necessary. The experimental equipment recently acquired by MSFC under OART sponsorship has taken into account the lessons learned and additional experience gained since the time of the UV degradation experiments. Most of the UV experimental work still is done by contractors of MSFC. However, in-house scientific research and in application to the Pegasus project.

A few illustrations will highlight some of the contract research results. Figure 27, taken from Reference 50, shows the spectral absorptance as a function of wavelength for the composite coating TiO_2 and epoxy resin. The solid line curve shows the unexposed sample with the sharp UV absorption edge which is typical for the TiO_2. After exposure to the UV rays of an A-H6 lamp, the absorption edge is shifted to lower energy and becomes less steep (dashed curve). Another fact shown is the increase of the absorptance at wavelengths in the visible and IR. The third curve between the other two gives the results of measurements after exposure of the yellowed sample to the light of a fluorescent lamp. A bleaching takes place. Apparently, some of the color centers can be activated by the less energetic light, and displaced electrons can fall back to their original positions. Similar bleaching also takes place by exposure of a UV-darkened sample to atmospheric oxygen or to a combination of oxygen and daylight. Some of the differences in past measurements could at least qualitatively be traced to such bleaching mechanisms. For all cases investigated, bleaching neither eliminated all color centers nor brought back the spectral absorptance to its original value. The mechanisms of degradation and the means to prevent or control it are not yet fully understood.

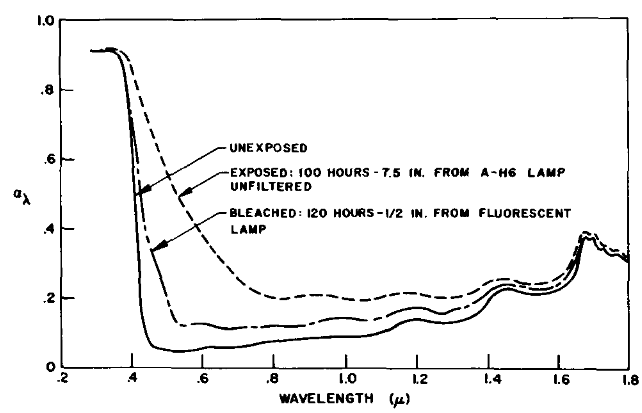


FIGURE 27. SPECTRAL ABSORPTANCE, TiO_2/EPOXY

Figure 28 shows an approach to the analysis taken by IIT Research Institute under a NASA Headquarters contract (OART), for which Gates of MSFC is technical monitor [52, 53]. The upper portion of Figure 28 shows the scattering of light by a matrix of a UV-transparent substance, and embedded UV-absorbing particles are shown as black balls. Many paints follow this principle. If the matrix is completely nonabsorbent, and the particles absorb UV and are not affected, the combination is stable. Since about 5 percent of the solar spectrum energy is in the UV and is absorbed by such a combination, the solar absorptance α_s is limited to a minimum value of 0.12 to 0.18. A lower value may be obtained if the UV is scattered. The lower half of Figure 28 shows a combination of a matrix with a UV-transparent pigment which could be particles or voids (microbubbles). A smaller α_s could be

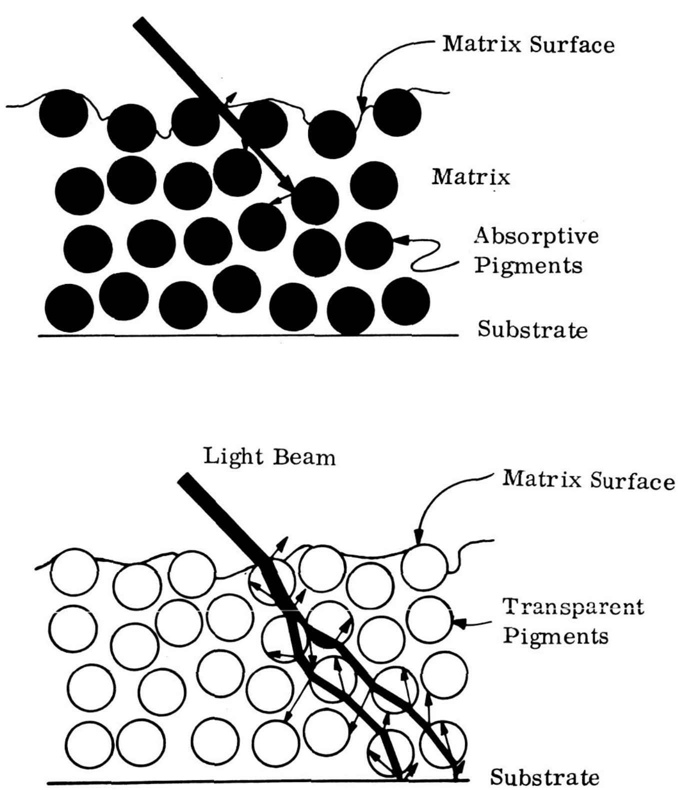


FIGURE 28. SCHEMATIC OF LIGHT WITH TWO TYPES OF PAINT MATRICES

achieved by such a combination, and this is the goal of present IIT research. The difficult problems are: (1) requirements for UV transparency of the matrix better than present by an order of magnitude and (2) a perfect reflectance at the matrix-substrate interface. Theoretical studies have been made by Miller and other scientists of MSFC and of Ling-Temco-Vought, in which Rayleigh-Gans and Mie scattering [54] is applied. Figure 29 shows a schematic of the system investigated. The purposes of the research are to obtain an understanding of the theory of the theory of the scattering process and to apply it to the development of

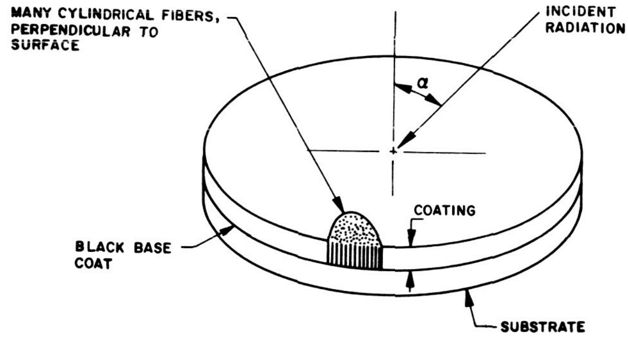


FIGURE 29. SCHEMATIC OF DIELECTRIC CYLINDER SCATTERING MODEL

thermal control surfaces with directional characteristics. Figure 30 shows results of the study. The backscattering coefficient is shown versus the angle of incidence for different length-to-diameter ratios of the cylinders. Strong directionality is obtained with high length-to-diameter ratios.

2. Solar Wind. For the low-eccentricity orbit of Pegasus, the problem of solar wind is negligible because of the shielding by the earth's magnetic field. For deep-space probes and vehicles traveling to the moon, however, solar-wind effects are important. A research program on solar-wind effects is being conducted through in-house studies by Miller and Arnett, and contract support by Wehner, of Litton Industries. Figure 31 is a schematic of Wehner's sputtering apparatus for simulating solar-wind effects [55]. The gas (hydrogen or helium) contained in the bell jar is ionized by a 40.68-MHz rf excitation coil. The ensuing plasma is accelerated by a second rf field of lower frequency (about 2.5 MHz) applied to the sample. Accelerating voltages of 100 to 3000 V can be achieved, and the sample is kept electrically neutral. Figure 32 shows some of Wehner's early results with samples furnished by Miller and Arnett. The ratio of solar reflectance to the initial solar reflectance is plotted against time of solar-wind bombardment simulated for one Astronomical Unit. The interesting result is that some inorganic composite samples (e. g., ZnO with potassium silicate) are strongly affected by the solar-wind bombardment. In general, the heavy (α particle) component of the solar wind seems to

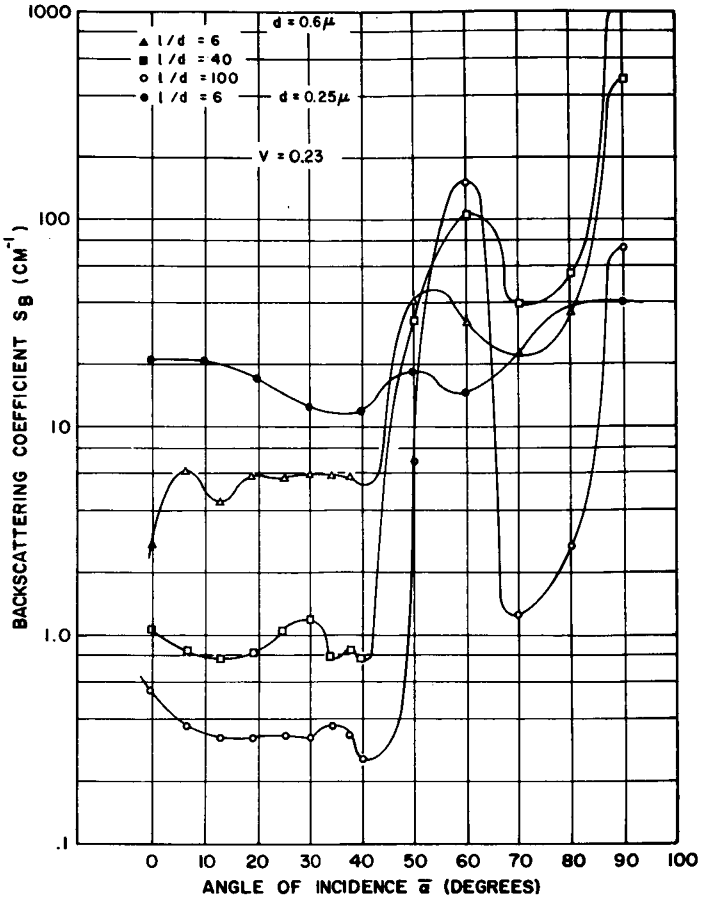


FIGURE 30. BACKSCATTERING COEFFICIENT VS. ANGLE OF INCIDENCE AS A FUNCTION OF LENGTH-TO-DIAMETER RATIOS OF THE CYLINDERS

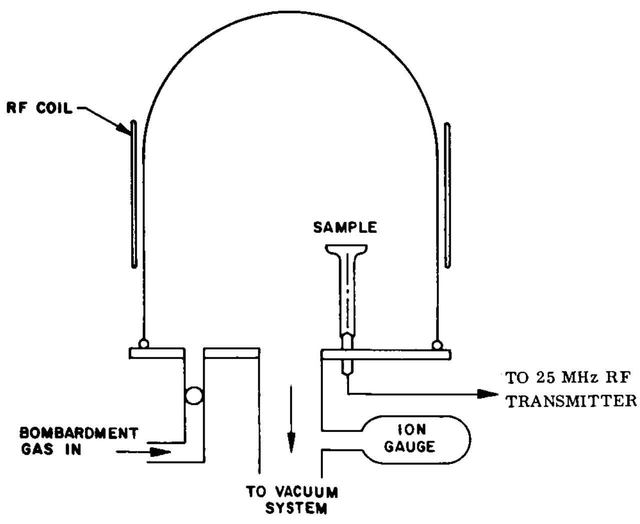


FIGURE 31. APPARATUS FOR SIMULATING SOLAR-WIND BOMBARDMENT

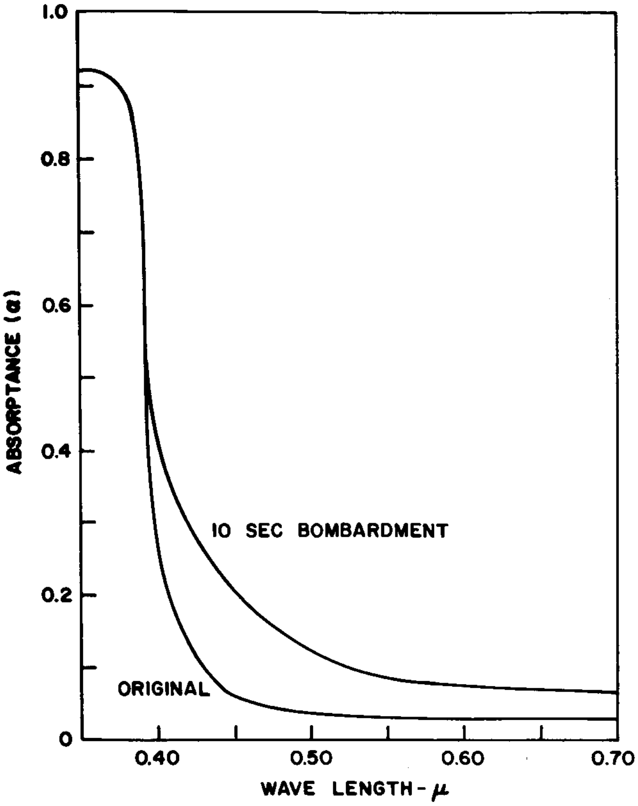


FIGURE 32. ABSORPTANCE VS. WAVELENGTH AS A FUNCTION OF PROTON BOMBARDMENT

have stronger effects than protons, although there is a greater abundance of protons. However, these results are tentative and require further analysis. In several cases, the reducing property of hydrogen on some metal oxides contributes to the generation of color centers. Research on the solar-wind effects and an understanding of the basic physical phenomena involved are particularly important to cislunar and deep-space operation.

3. Micrometeoroids. Deleterious effects of micrometeoroids on the optical properties were minimized in Explorer I and later spacecraft by using sandblasted metallic surfaces, which were assumed to be little affected by the erosion of micrometeoroids. The effect has never been successfully determined by a space experiment. Theoretical studies at MSFC (by Schocken, Merrill, and Fountain) are being supplemented by experimental investigations under contract. Figure 33 shows the Van deGraaf accelerator [56] used by Friichtenicht (Space Technology Laboratories) for the simulation of micrometeoroid bombardment of thermal control surfaces [57]. The particle injector and charging electrode generates a distinct spectrum of particles. The charge is the maximum possible, based on the

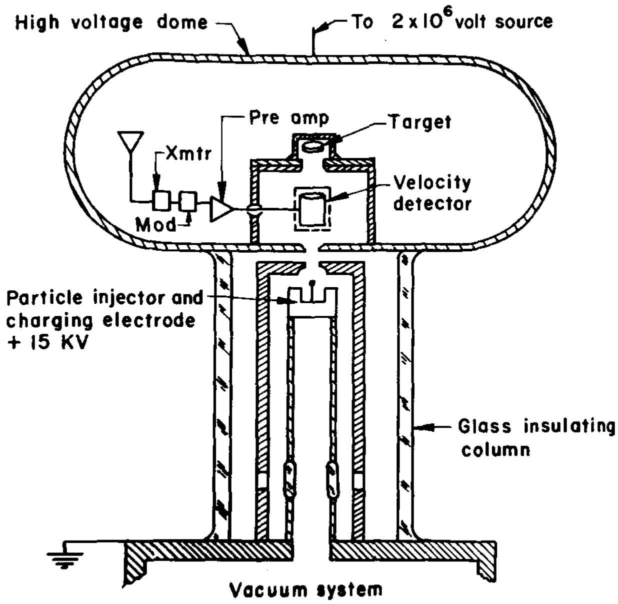


FIGURE 33. ELECTROSTATIC ACCELERATOR FOR MICROMETEOROID SIMULATION

radius of the spherical capacitors and the given charging voltage of 15 kV. Figure 34 (taken from Reference 57) shows some of the results obtained by bombarding a gold sample. The spectral reflectance is plotted against the wavelength. The solid-line curve is for the unbombarded sample and the two dashed-line curves are for the sample after bombardment by 200 000 and 400 000 particles. The sample dimensions were 3 by 12 millimeters. The sandblasting effect changes the reflectance at all wavelengths. It is strongest in the yellow and red of the visible spectrum and up to 5 microns in the near IR, while the effect becomes definitely smaller about 5 microns. It should be pointed out that plotting in this fashion gives only one number, namely the total energy of the reflected radiation. It is possible that after some micrometeoroid bombardment, the total reflectance changes very little, but that the percentages of diffuse light increases considerably. Further research is required for an understanding of these effects and of the correlation of laboratory results with flight experiments.

Research in environmental effects is of immediate importance for NASA's projects. Additional work at MSFC is being done on the effects of nuclear radiation or simulated Van Allen or cosmic radiation on materials, especially by Lucas and his co-workers in the Propulsion and Vehicle Engineering Laboratory. This work will be discussed in more detail in the nuclear physics and engineering materials reports of this research achievements review series.

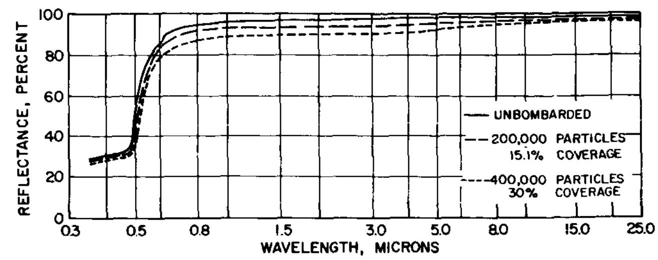


FIGURE 34. SPECTRAL REFLECTANCE OF A GOLD SAMPLE

G. THERMAL ENVIRONMENT FLIGHT EXPERIMENTS

Many spacecraft have been launched into space, and temperature measurements obtained from critical components onboard have confirmed or disproved the contention that the thermal radiation equilibrium in space has been correctly predicted. In many cases, it was sufficient to find out that the component stayed in the allowed temperature range (e. g., 0° to 50° C).

The most powerful tool for a detailed analysis of telemetered temperature data is the computer program which was used during the design phase. However, because of the more than 20 parameters (often there are more than 10 different thermal control surfaces on the outside), it is not possible to resolve the effects to better than ±10° to ±20° C. This means that the next spacecraft must be designed with the same amount of uncertainty.

This problem arose in the analysis of telemetry data of Explorer satellites. At that time, some people at MSFC began thinking of methods for obtaining meaningful results which would allow analysis of the space environment and effects of the space environment on thermal control surfaces. Work was initiated by Snoddy of Research Projects Laboratory, who started a thermal environment measuring device [58, 59]. The instrument was fabricated by Burke of Astrionics Laboratory, and the design will be described in another report of this series. For a scientific instrument, the measuring device is comparatively simple in principle; however, it took five years to develop it to its present state.

Figure 35 shows the type of instrument flown on the Explorers. It is a disk, mounted flush with the vehicle surface and connected by an insulating stem to the housing which is bolted to the spacecraft. This flight instrument can serve as a tool for engineering tests to qualify thermal control surfaces, but it also allows for the determination of space environmental effects. Because of its small time constant, effects of insolation, albedo, and infrared can be resolved. The analysis of the results is not as simple as might be expected. A knowledge of the space-fixed attitude is required. From the dot products of the vehicle-fixed vector with the sun vector and radius vector, the direction cosines of the sun and earth can be derived. Two independent measurements are needed to determine these vectors. The attitude information is needed to explain fluctuations of temperatures due to variable insolation, variable albedo, and infrared effects. Further variation of the orbital characteristics have to be taken into account. The proper tool for evaluation is the general thermal computer program.

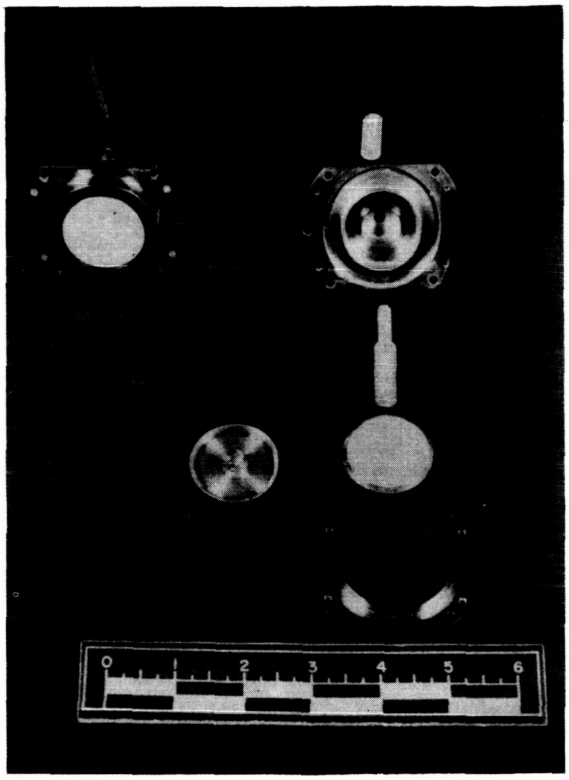


FIGURE 35. EARLY ENVIRONMENTAL EFFECT SENSOR

Figure 36 shows telemetered results of the sensor flown on Explorer XI [14, 58] . The coating of the sensor, applied by Haas of the Army Corps of Engineers, was a multiple layer, optically thin, with the following composition: one-half wavelength thickness of SiO over 20 nanometers of germanium over one and one-half wavelengths of SiO on an aluminum substrate.

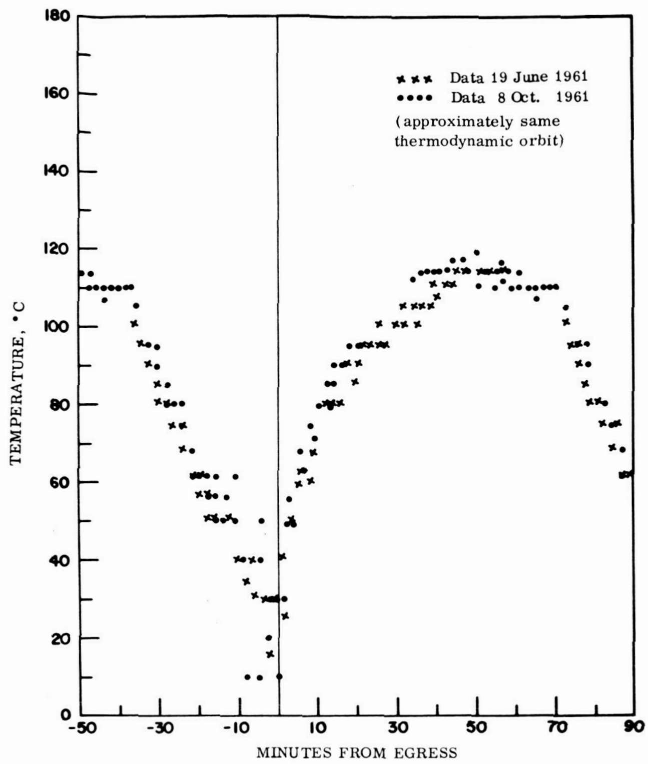


FIGURE 36. COMPARISON OF TEMPERATURES FOR TWO DAYS, EXPLORER XI SENSOR

The data points were assembled from several orbits of similar characteristics on June 19, 1961, and October 8, 1961. The spread of points is not due to lack of measuring accuracy, but to some of the effects described above. It shows clearly the difficulties involved. Through the use of the sensor, the number of variables has been reduced. However, a considerable variation of parameters has to be taken into account. A detailed analysis of the data presented in Figure 36 showed that the coating had not undergone a major change of its total absorption or emission characteristics in the three and one-half month period considered.

The environmental effects sensors flown on the Saturn I SA-4 suborbital flight are very similar to the one shown in Figure 35 [59]. Four of these sensors were arranged linearly in a common housing and mounted flush with the Saturn skin. The sensor coatings were: anodized aluminum, sandblasted aluminum, black paint, and vapor-deposited gold. The coatings were applied by Manufacturing Engineering Laboratory and Propulsion and Vehicle Engineering Laboratory, MSFC.

Figure 37 shows the telemetered temperatures of the four sensors and the internal housing temperature plotted against flight time of the Saturn space vehicle. The sharp increase at 125 seconds is due to the retrorocket firing of the solid-propellant rockets attached to the first stage.

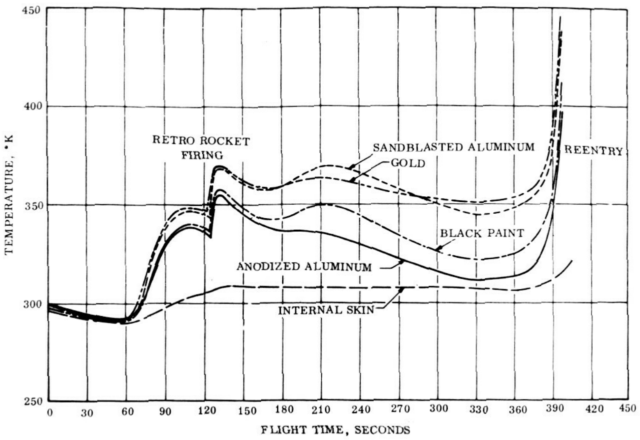


FIGURE 37. SA-4 FLIGHT OF ISOLATED TEMPERATURE SENSOR

Figure 38 is a photograph of the thermal environment sensors used on the SA-9, the first Pegasus satellite. The thermal control coatings [60] used were:

1. an Alodine inversion coating (same as used on meteoroid penetration detectors)

2. S-13 UV-stable white paint (same as used on Service Module Adapter and on Zener diodes)

3. black paint (same as used on frame of Pegasus; also used as a standard)

4. TiO_2-silicone paint (same as used on S-16 flight and by 16 laboratories participating in the round-robin tests).

The bottom portion of Figure 39 shows a theoretical curve of the temperature of the black standard. On the upper half of this figure are shown the measured results from the core memory for the Alodine coating. In both graphs, the temperature is plotted against the time of an orbit. The telemetered curve shows some interesting results due to variation of the thermal environment. A more thorough analysis will have to be made before conclusions can be drawn.

The thermal environment sensors have proved to be a very valuable experimental tool. They have

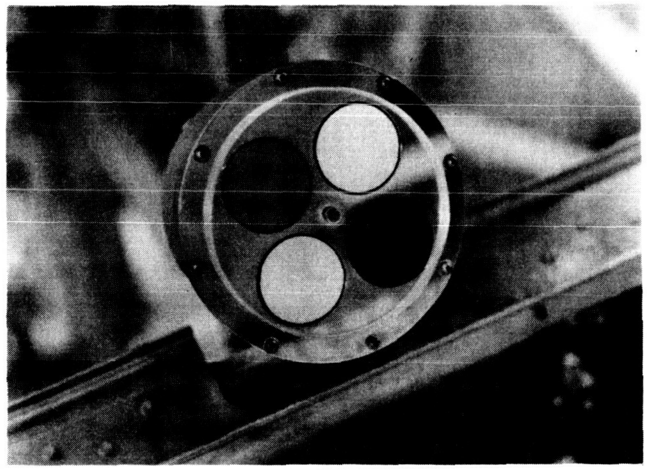


FIGURE 38. PEGASUS ENVIRONMENTAL EFFECT SENSOR

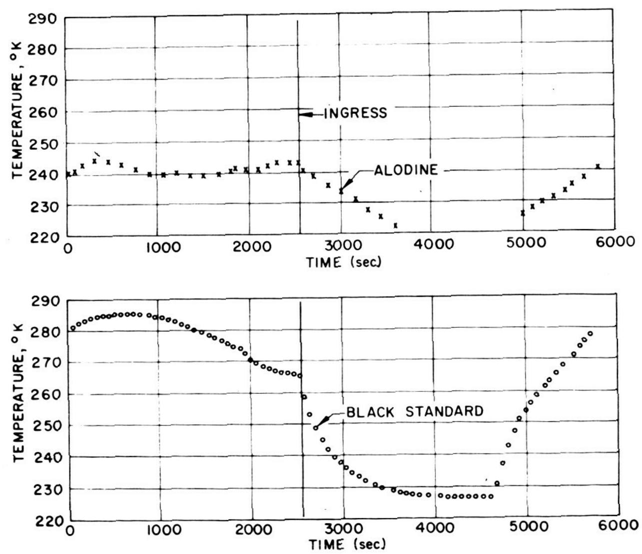


FIGURE 39. TELEMETERED TEMPERATURE OF ALODINE-COATED SENSOR, AND COMPUTED TEMPERATURE OF BLACK STANDARD

provided useful information on the space environment and its effects on thermal control surfaces. Conclusions drawn from the data acquired will be the basis for better thermal control in the future.

H. MEASURING TECHNIQUES

The greater part of the experimental research in thermophysics at MSFC is conducted under contracts to research institutes and research groups in industry, government, and universities. However, because of the urgent need for direct experimental support of MSFC projects, especially scientific payloads, in-house work has been started at the Research Projects Laboratory of MSFC.

Additional experimental facilities directly connected with Saturn vehicles have been built in other MSFC laboratories. Figures 40 and 41 illustrate research apparatus built in Astrionics Laboratory with the cooperation of Atkins of Research Projects Laboratory and its support contractor, General Electric. The apparatus was made for measuring interface conductance under the "hard" vacuum conditions of space. This research is of importance in connection with the problems of heat conduction between electronic packages of the IU and the mounting plates. Figure 19 shown previously in this report is an interface conductance curve measured by Fried of General Electric. Coating facilities have been built by Manufacturing Engineering Laboratory, and engineering materials investigations are being conducted in the Propulsion and Vehicle Engineering Laboratory. As mentioned earlier, some of the coatings were prepared by these laboratories.

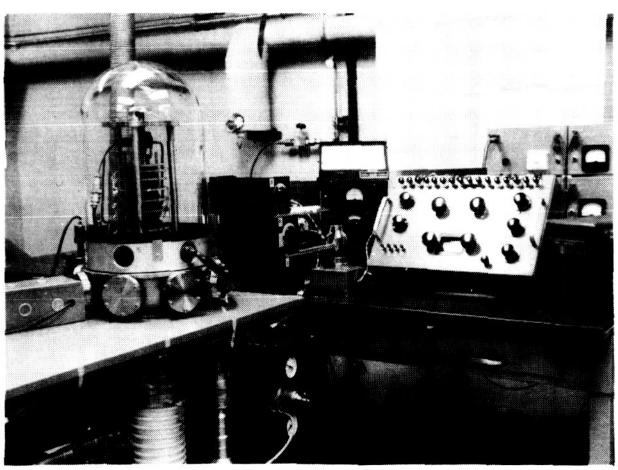


FIGURE 40. APPARATUS FOR MEASURING THERMAL INTERFACE CONDUCTANCE IN SIMULATED SPACE VACUUM

A small in-house research capability in experimental thermophysics is being established in

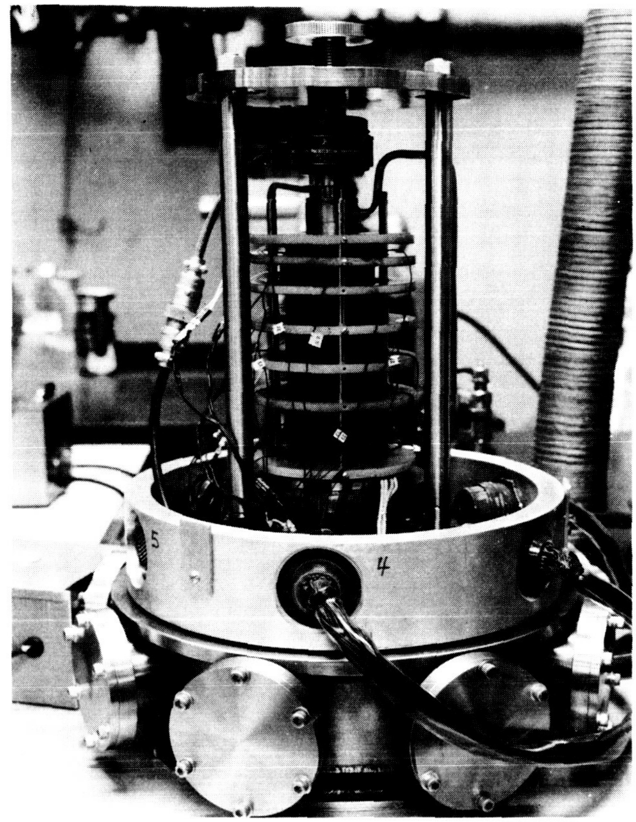


FIGURE 41. DETAILED VIEW OF THERMAL CONDUCTANCE MEASURING EQUIPMENT

Research Projects Laboratory. Research will deal mainly with problems in space thermal environment, ultraviolet, electromagnetic radiation, and emissivity. Approval and funding of the experimental research tasks was obtained by OART and OMSF.

A space thermal-environment chamber, shown in Figure 42 is an example of the research equipment in use. It has a chamber bakable at 450°C and an LN_2-cooled shroud with a special radiation absorptive coating. The chamber working space is 0.9 m in diameter and 1.5 m high. A carbon-arc lamp provides solar simulation through a quartz window. There is a viewing port and an infrared window for radiometric measurement, and provision for feed-through of thermocouples, high voltage, and high current. The maximum vacuum capability is 13×10^{-8} N/m^2 (10^{-9} torr).

I. PEGASUS THERMAL RESULTS

Pegasus A was launched on February 16, 1965. The primary purpose of the satellite experiment is the determination of the frequency of meteoroid

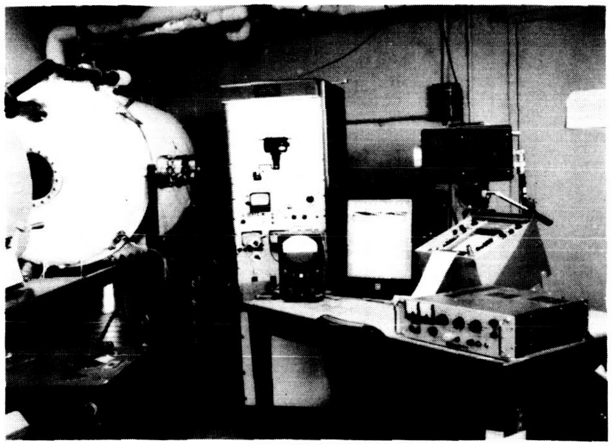


FIGURE 42. SPACE THERMAL-ENVIRONMENT-CHAMBER FACILITY

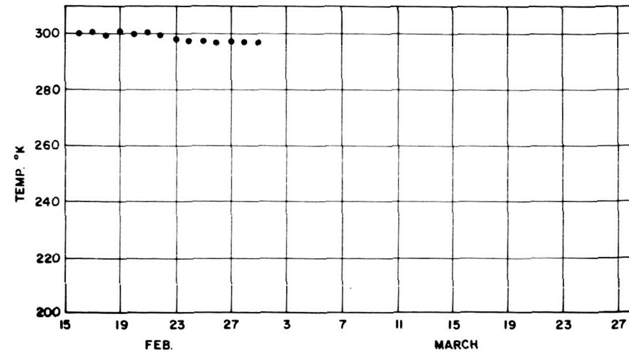


FIGURE 43. PEGASUS I ELECTRONIC CANISTER TEMPERATURES

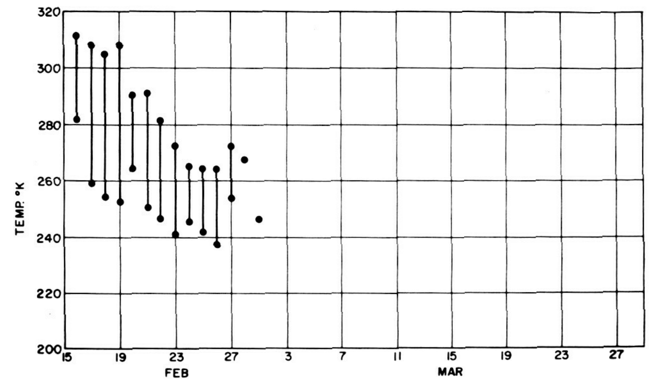


FIGURE 44. PEGASUS I FORWARD SOLAR PANEL TEMPERATURES

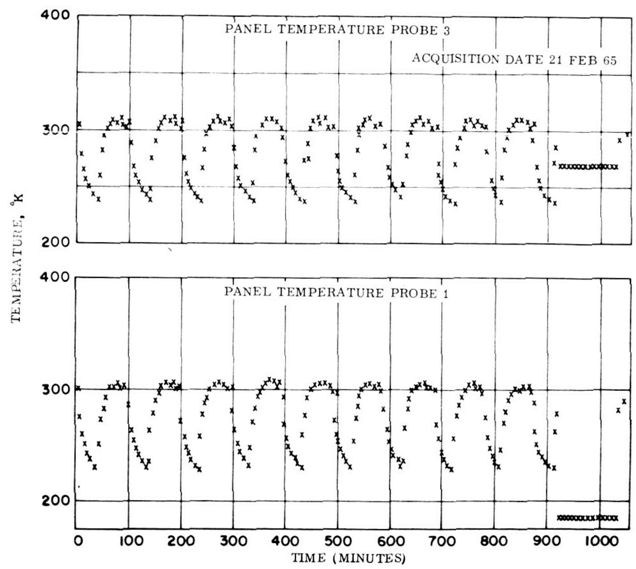


FIGURE 45. PEGASUS I MICROMETEOROID DETECTOR PANEL TEMPERATURES

penetration of three thicknesses of aluminum. Two additional experiments being conducted with the satellite are considered vital for the scientific data evaluation and correlation of results. These deal with a radiation experiment and the four thermal environmental effects sensors described previously.

Besides other data, nineteen temperature measurements are telemetered over the Pulse Amplitude Modulation (PAM) channel. These measurements serve to check on the functioning of onboard equipment and to determine the correctness of the thermal control. The evaluation of the thermal effects sensors and temperature measurement is part of the scientific evaluation task of the Research Projects Laboratory. Thermal aspects of the Pegasus experiments were studied by Heller, Snoddy, Miller, Bannister, and Arnett. Other members of Research Projects Laboratory contributed in their specific areas of research to the Pegasus thermal measurements and thermal control of the electronic canister.

Some early results are reported to indicate the excellent type of information received over the various channels. Figure 43 shows a 14-day record of typical electronic canister temperatures. Only day-to-day changes are recorded because of the large time constant (15 hours) of the canister. The critical battery temperatures are in the middle of the band required by the design specifications. The forward solar panel temperatures are shown in Figure 44. Orbital variations occur; therefore, the maximum and minimum temperatures received during any day are shown. Figure 45 and 46 are examples of the stored Pulse Code Modulation (PCM) temperature data. Figure 45 shows the micrometeoroid detector panel temperature probes. Note the calibrations at 920 minutes. Figure 46 shows data obtained from the Alodine reference temperature sensor. Major fluctuations are caused by passages

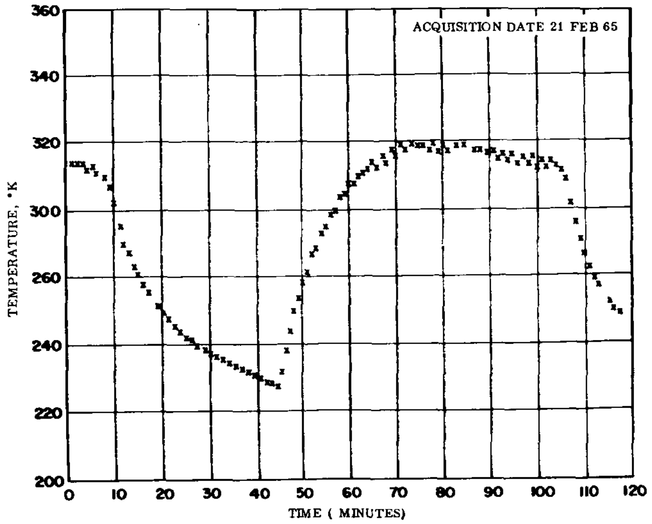


FIGURE 46. TYPICAL TEMPERATURES FROM ALODINE REFERENCE TEMPERATURE SENSOR

into and out of the earth's shadow, while the "ripple" is caused by vehicle roll. Detailed analysis of the data promises to be very interesting. Details of the Pegasus satellite experiments and data transmission channels may be found in Pegasus Bulletins No. 1 and No. 2 [61, 62].

In Figure 47 results of the Pegasus thermal control surface S-13 are shown in terms of its spectral absorptance. Measurements were made using a spectroreflectometer with an integrating sphere.

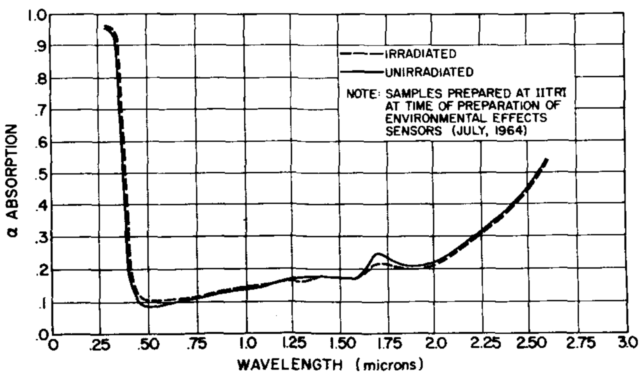


FIGURE 47. PEGASUS THERMAL CONTROL STUDIES OF S-13

III. PROJECT SUPPORT

In addition to the assignment of thermophysics research, the Space Thermodynamics Branch (RP-T) of Research Projects Laboratory is actively engaged in project support of MSFC. Contributions made to various SATURN I vehicles, as previously mentioned are:

SATURN flight IV	thermal environment sensor
SATURN flight V	thermal control sensor of orbiting upper stage
SATURN flight VIII SATURN flight IX	thermal control of canister of satellite and thermal environment sensors
SATURN flight X	coupons with 352 thermal control surfaces

Portable infrared equipment and reflectometers of RP-T have been used at Cape Kennedy to determine the IR and optical properties of thermal control surfaces prior to launch. These are compared to laboratory measurements and in-flight telemetered values.

IV. RESEARCH CONTRACTS OF THE SPACE THERMODYNAMICS BRANCH

A. TITLE: SOLAR WIND DAMAGE TO SPACECRAFT THERMAL CONTROL SURFACES

Technical Supervisor: Edgar R. Miller
Contract No: NAS8-11269
Contractor: Litton Systems, Inc.

Description of Research: To establish experimentally the effect of simulated solar wind bombardment on surfaces for thermal control, to perform theoretical and experimental investigation of the damage mechanisms involved, and to distinguish the separate factors that operate synergistically.

B. TITLE: RESEARCH ON THERMAL CONTROL SURFACES FOR THE EXTRATERRESTRIAL ENVIRONMENT

Technical Supervisor: Edgar R. Miller
Contract No.: GO #H71465

Interagency Purchase Order: Wright Air Development Center

Description of Research: To perform research and development on thrust control surfaces for the extraterrestrial environment, especially areas of large vehicles.

a. High solar absorptance to thermal emittance ratio surfaces (ratios of 1 - 3)

b. Universal reflector surfaces ($\alpha_s \simeq \alpha_{IR} < 0.1$)

C. TITLE: THERMAL CONTROL UTILIZING FUSIBLE MATERIALS

Technical Supervisor: Tommy C. Bannister
Contract No.: NAS8-11163
Contractor: Northrop Space Laboratories

Description of Research: Development of analytical and engineering techniques for utilizing (in a sealed passive system) the heat associated with changes in state, phase, and temperature of specially selected materials for the thermal control of temperature sensitive vehicle and satellite components. Studies include operation in zero-g environment.

To advance the use of phase-change materials for thermal control to the point where space thermal design engineers will not have reservations about using the technique.

D. TITLE: RADIOMETRIC MODELS OF LUNAR SURFACE

Technical Supervisor: William C. Snoddy
Contract No.: NAS8-20512
Contractor: General/Dynamics Convair

Description of Research: The measurement and evaluation of the thermal (mainly radiometric) properties of simulated lunar material. This information will be related to known lunar characteristics with the end result being a thermal model of the moon.

E. TITLE: SOLAR-RADIATION-INDUCED DAMAGE TO OPTICAL PROPERTIES OF ZnO-TYPE PIGMENTS

Technical Supervisor: William C. Snoddy
Contract No.: NAS8-11266
Contractor: Lockheed Missiles and Space Co.

Description of Research: This study is directed toward identification of the primary mechanisms involved in solar-radiation-induced damage to the optical properties of ZnO-type semiconductor pigments, as exemplified by ZnO itself.

F. TITLE: INVESTIGATION OF SPACE STABLE COATINGS WITH LOW α_s/ϵ_{IR} RATIOS

Technical Supervisor: Daniel W. Gates
Contract No.: NAS8-5379
Contractor: IIT Research Institute

Description of Research: The purpose of this research is the study of thermal control surfaces suitable for space vehicle surfaces to be maintained at low temperatures. Emphasis is on the long-time space stability.

G. TITLE: STUDY OF MICROMETEOROID DAMAGE TO THERMAL CONTROL MATERIALS

Technical Supervisor: James A. Fountain and Klaus Schocken
Contract No.: NAS8-20120
Contractor: TRW Systems

Description of Research: The main purpose of this research is to simulate the micrometeoroid impacts (especially particles of micrometer size) in the laboratory, using a Van deGraaf accelerator. The effect of these impacts on the optical properties of thermal control surfaces are investigated with spectroradiometers.

H. TITLE: STUDY OF DIRECTIONALLY REFLECTIVE SURFACES

Technical Supervisor: Edgar R. Miller
Contract No.: NAS8-11273
Contractor: Ling-Temco-Vought

Description of Research: The purpose of this research is to conduct analytical and experimental studies on surfaces whose reflectance by scattering is directional with the angle of incidence. Fiber optics plates are being investigated whose back-scattering characteristics are in the Rayleigh-Gans domain.

I. TITLE: EMITTANCE OF MATERIALS AT LOW TEMPERATURES

Technical Supervisor: Klaus Schocken
Contract No.: GO #H2153A
Interagency Purchase Order: National Bureau of Standards

Description of Research: Emissivity of surfaces at cryogenic temperatures is an important research area. It has been found that strong variations in reflectance occur at wave numbers below 500 cm^{-1}. The purpose of this research is to apply new equipment and new techniques to the determination of reflection bands in the far IR to wave numbers of 20 cm^{-1} and below.

J. TITLE: MATHEMATICAL ASPECTS OF DIMENSIONAL ANALYSIS AND THERMAL SIMILITUDE

Technical Supervisors: Jimmy R. Watkins and Billy P. Jones
Contract No.: NAS8-20065
Contractor: University of Michigan

Description of Research: To extend through a generalized approach the mathematical theory of dimensional analysis and the application of such mathematical models to physical systems of thermal problems. This is an extension of the work on π theorems by L. Brand and A. G. Hansen.

K. TITLE: THERMAL SIMILITUDE STUDIES APPLICABLE TO SPACECRAFT

Technical Supervisor: Jimmy R. Watkins
Contract No.: NAS8-11152
Contractor: Lockheed Missiles and Space Co.

Description of Research: The purpose of this research is an experimental determination of modeling laws for correlation with mathematical analyses based on the theory of thermal similitude. Emphasis is on the time-dependent problems.

L. TITLE: THERMAL DESIGN STUDIES TO DETERMINE LAWS OF THERMAL SIMILITUDE

Technical Supervisors: Jimmy R. Watkins and Billy P. Jones
Contract No.: NAS8-5270
Contractor: University of Alabama

Description of Research: The purpose of this research is to determine new mathematical approaches and the physical processes involved in the thermal similitude. Emphasis is on time-dependent relationships such as occur in transient conditions. The program is primarily experimental.

M. TITLE: EFFECTS OF REDUCED GRAVITY ON THERMAL PROPERTIES OF INSULATION MATERIALS

Technical Supervisor: Klaus Schocken
Contract No.: NAS8-5413
Contractor: Arthur D. Little, Inc.

Description of Research: It is the purpose of this research to study the effects of reduced gravity on heat transfer in particulate systems. Consideration of the mechanisms of heat transfer in particulate materials indicates that reduced gravity may affect solid thermal conduction across contact points and thereby influence heat transfer.

N. TITLE: RADIATIVE EMISSIVITY OF MATERIALS

Technical Supervisor: Klaus Schocken
Contract No.: NAS8-5210
Contractor: P. E. C. Research Associates

Description of Research: It is the purpose of this contract to develop a new theory of emissivity, to apply the new theory to a large number of specific substances, and to design and carry out experimental tests to verify deviations from Kirchhoff's Law under other than equilibrium conditions.

O. TITLE: INTERFACE THERMAL CONTACT CONDUCTANCE

Technical Supervisor: Harry L. Atkins
Contract No.: NAS8-5207
Contractor: General Electric

Description of Research: Two metals in contact touch only at small irregular points. The principal parameter which affects metallic interface conduction is the applied mechanical pressure. It is the purpose of the contract to measure thermal interface conductance of certain metals which are representative of those used in spacecraft components and structures

P. TITLE: THERMAL CONDUCTIVITY OF NON-METALLIC MATERIALS

Technical Supervisors: Klaus Schocken and Charles D. Cochran
Contract No.: NAS8-1567
Contractor: Arthur D. Little, Inc.

Description of Research: The purpose of the contract is an analytical and experimental investigation of the thermal and dielectric properties of nonmetallic materials. Special emphasis is on the contributions of solid conduction and thermal radiation to the effective thermal conductance of heterogeneous materials. The results of experimental measurements and theoretical analyses will be applied to the thermal behavior of lunar surface materials.

Q. TITLE: USE OF THERMAL MODELS FOR ENVIRONMENTAL TESTING

Technical Supervisor: James K. Harrison and Billy P. Jones
Contract No.: GO #H-71483
Interagency Purchase Order: Arnold Engineering Development Center

Description of Research: The purpose is to confirm by experiment the theoretical validity of dimensional analysis and similitude. Three shapes have been selected for study (flat plate, sphere, and cylinder). Scaling of gross dimensions from prototype to model is 2 to 1.

REFERENCES

1. Anon.: Solar Electromagnetic Radiation. NASA Space Vehicle Design Criteria, vol. I, part B, ch. I, sec. I (NASA Accession No. X65-18719; distribution limited to government agencies and contractors), June 1965.

2. Thekoekara, M. P.: Survey of the Literature on the Solar Constant and the Spectral Distribution of Solar Radiant Flux. NASA SP-74, 1965.

3. Stokes, G. G.: Trans. Camb. Philos. Soc. vol. 9, 1852, p. 399.

4. Chandrasekhar, S.: Radiative Transfer. Dover Publications, Inc., New York, 1960.

5. Coulson, K. L.; Dove, J. V.; and Sekera, Z.: Tables Related to Radiation Emerging from a Planetary Atmosphere with Rayleigh Scattering. University Press, Berkeley and Los Angles, Calif., 1960.

6. Snoddy, W. C.: Irradiation Above the Atmosphere Due to Rayleigh Scattering and Diffuse Terrestrial Reflections. AIAA Paper No. 65-666, presented at the AIAA Thermophysics Specialist Conference (Monterey, Calif.), Sept. 13-15, 1965 (see also Thesis for Masters Degree, Univ. of Ala., 1964).

7. Merrill, R. B.; Snoddy, W. C.; and Schocken, K.: The Results of Emittance Measurements Made in Relation to the Thermal Design of Explorer Spacecraft. NASA TN D-1116, May 1962.

8. Anon.: Equipment for Thermal Emittance Measurements Above 1400° K. National Bureau of Standards, Annual Summary Report, Contract No. H-41986, Jan. 1964.

9. Aronson, J. R.; and McLinden, H. G.: An Investigation of the Optical Properties of Materials at Room and Liquid Helium Temperatures. A. D. Little, Inc., Final Report, Contract No. NAS8-2537, Nov. 1963.

10. Schocken, K.; and Ashby, N.: The Theory of Emissivity of Metals. Paper presented at Symposium on Thermal Radiation of Solids (San Francisco, Calif.), Mar. 4-6, 1964.

11. Ashby, N.: Theoretical Study of the Radiative Emissivity of Materials. P. E. C. Corp., Interim Summary Report (period of Apr. 1, 1963 - Apr. 30, 1964), Contract No. NAS8-5210.

12. Ashby, N.: Theoretical Study of the Radiative Emissivity of Materials. P. E. C. Corp., Technical Summary Report (period Apr. 1, 1964 - Apr. 30, 1965), Contract No. NAS8-5210.

13. Johnson, F. S., ed.: Satellite Environment Handbook. Stanford Univ. Press, Stanford, Calif., 1961.

14. Snoddy, W. C.; and Miller, E. R.: Areas of Research on Surfaces for Thermal Control. Paper presented at Symposium on Thermal Radiation of Solids (San Francisco, Calif.), Mar. 4-6, 1964 (also NASA SP-55, 1965).

15. Snoddy, W. C.: Calculations Concerning the Passage of a Satellite Through the Earth's Shadow. MSFC, MTP-RP-61-1, Feb. 1961.

16. Zwiener, J. M.: General Space Thermal Program. MSFC, M-RP-T-WP-1-63, May 1963.

17. Meiners, H. F., Jr.: A Study of Efficient Computational Methods Related to Space Thermal Equations. Research Projects Laboratory (MSFC), R-RP-T-WP-63-5, Aug. 1963.

18. Preston, R. A.: Heat of Fusion Program for 'Freeze and Fry' Testing. Research Projects Laboratory (MSFC), R-RP-T-WP-14-65, Sept. 1965.

19. Bannister, T. C.: A Computer Program Describing the MMC Electronic Canister Thermal Design. Research Projects Laboratory (MSFC), R-RP-WP-63-6, Nov. 1963.

20. Snoddy, W. C.: MSFC Computer Programs Utilized in the Thermal Design and Analysis of Satellites. Proceedings of Conference on Heat Transfer Computer Programs, NASA Headquarters, May 7, 1964.

21. Bannister, T. C.: Radiation Geometry Factor Between the Earth and a Satellite. NASA TN D-2750, July 1965.

22. Watkins, J. R.; and Hilliard, J. W.: A Computer Program for Derivation of Similarity Ratios for Use in Thermal Similitude Analyses and Experiments. Research Projects Laboratory (MSFC), R-RP-INT-64-14, Apr. 15, 1964.

23. Jones, B. P. : A Computer Program for Solving by Several Numerical Methods a System of First Order, Non-linear Differential Equations that Represent Transient Temperatures in Objects Used in the Study of Thermal Similitude. NASA TM X-53121, Aug. 5, 1964.

24. Harrison, J. K.: Computer Program—Cryogenic Storage on the Moon (Subroutines A and C). NASA TM X-53270, June 1965.

25. Harrison, J. K.: Modification of a Pegasus Spacecraft to Perform a Cislunar Mission. NASA TM X-53279, June 1965.

26. Harrison, J. K.: A Means of Determining the Infrared Emission of the Moon from Temperature Measurements of a Lunar Orbiting Object. Master's Thesis, Univ. of Ala., Aug. 1964.

27. Jones, B. P.: Thermal Similitude Studies. J. Spacecraft & Rockets, vol. 1, no. 4, Aug. 1964, pp. 364-369.

28. Vickers, J. M. F.: Space Programs Summary 37-30. Jet Propulsion Laboratory, vol. 4, Dec. 1964, pp. 75-77, and Feb. 1965, pp. 111-112.

29. Watkins, J. R.: A Computer Program for Derivation of Similarity Ratios. Research Projects Laboratory (MSFC), R-RP-INT-64-14, Apr. 15, 1964.

30. Matheny, J. D.: Thermal Design Studies. Bureau of Engineering Research, Univ. of Ala., Final Report, Contract NAS8-5270, Sept. 1965.

REFERENCES (Continued)

31. Jones, B. P.; and Harrison, J. K.: A Set of Experiments in Thermal Similitude. NASA-MSFC TM X-53346, Oct. 1965.

32. Atkins, H. L.; and Fried, E.: Thermal Interface Conductance in a Vacuum. Paper presented at 1st AIAA Annual Meeting and Technical Display (Washington, D. C.), June 29-July 2, 1964 (also published in AIAA J.).

33. Atkins, H. L.: Bibliography on Thermal Metallic Contact Conductance. NASA TM X-53227, Apr. 15, 1965.

34. Anon.: Study of Interface Thermal Contact Conductance. General Electric, Summary Report (period of 27 Mar. 1964-27 Mar. 1965), Contract No. NAS8-11247, Doc. No. 65SD4395.

35. Anon.: Study of Interface Thermal Contact Conductance. General Electric, Summary Report, Contract No. NAS8-5207, May 1, 1964.

36. Schocken, K.: Heat Transfer by Infrared Radiation in Powders. MSFC, R-RP-INT-64-7, Feb. 1964.

37. Schocken, K.: The Lunar Surface. MSFC, R-RP-INT-63-17, Nov. 1963.

38. Schocken, K.: Electromagnetic and Thermal Parameters of Powders. MSFC, R-RP-INT-62-6, May 1962.

39. Schocken, K.: The Thermal Properties of Powders. MSFC, R-RP-INT-65-4, Mar. 18, 1965.

40. Heller, G. B.: Temperatures of Explorer I. ABMA, TN-61-58, 1958.

41. Heller, G. B.; and Jones, B. P.: A Comparison of Experimental and Theoretical Temperatures of Explorer III. ABMA, TN-76-58, Sept. 26, 1958.

42. Heller, G. B.: Thermal Control of the Explorer Satellites. ABMA, TN-17-59, June 1, 1959.

43. Heller, G. B.: Problems Concerning the Thermal Design of the Explorer Satellites. ABMA, DV-TM-11-60, May 17, 1960.

44. Jones, B. P.: Solar Aspect of Explorer VII Compared with Certain Measured Temperatures (Satellite 1959 Iota). Research Projects Laboratory (MSFC), MTP-M-RP-60-2, Oct. 1960.

45. Lumpkin, W. L.: Heat Transfer Measurements on the Explorer XI Temperature Sensor. Research Projects Laboratory (MSFC), M-RP-INT-61-21, Sept. 1961.

46. Snoddy, W. C.: Theoretical and Measured Temperatures of Explorer IV. ABMA, TN-6-59, Mar. 14, 1959.

47. Lumpkin, W. L.: Temperature Data of Explorer XI (S-15 Payload). Research Projects Laboratory (MSFC), MTP-RP-62-6, Aug. 1962.

48. Lal, R. B.; and Arnett, G. M.: Electron Paramagnetic Resonance Spectroscopy. MSFC, R-RP-INT-11, 1965.

49. Zerlaut, G. A.: Utilization of Pigmented Coatings for the Control of Equilibrium Skin Temperatures of Space Vehicles. Proceedings, Aerospace Finishing Symposium, Ft. Worth, Tex., Dec. 1959.

50. McKellar, L. A. (Project Leader): Solar-Radiation-Induced Damage to Optical Properties of ZnO-Type Pigments. Lockheed Missiles & Space Co., Tech. Summary Report (period June 27, 1964 to June 27, 1965), Contract No. NAS8-11266; this work is also found in Olson, R. L.; McKellar, L. A.; and Stewart, J. V.: The Effects of Ultraviolet Radiation on Low α_s/ϵ Surfaces. NASA SP-55, 1965, pp. 421-428.

51. Arvesen, J. C.; Neel, C. B.; and Shaw, C. C.: Preliminary Results from a Round-Robin Study of Ultraviolet Degradation of Spacecraft Thermal Control Coatings. NASA SP-55; Air Force ML-TDR-64-159, 1965, pp. 443-452.

52. Zerlaut, G. A.; Katz, S.; and Stockham, J.: Investigations of Light Scattering in Highly Reflecting Pigmented Coatings. IITRI-C6018-6, Contract No. NASr-65(07), Jan. 1964, STAR Access, N64-16757.

53. Raziunas, V.; Zerlaut, G. A.; and Stockham, J.: Experimental Studies of Light Scattering by Monodisperse and Bimodal Dispersions of AgBr. Results of IITRI Project C6018-14, Contract No. NASr-65(07), May 13, 1965.

54. Cox, R. L.: Directionally Reflective Coatings Study. Ling-Temco-Vought Astronautics, Tech. Summary Rpt. No. 00.603, Contract No. NAS8-11273, Mar. 12, 1965.

55. Wehner, G. K.: Solar Wind Damage to Spacecraft Thermal Control Coatings. Applied Sciences Division, Litton Systems, Inc., Summary Rpt. No. 2842 (period June 20, 1964 to June 20, 1965), Project No. 57006, Contract No. NAS8-11269, July 20, 1965.

56. Shelton, H.; Hendricks, C. D., Jr.; and Wuerker, R. F.: Electrostatic Acceleration of Microparticles to Hypervelocities. J. Appl. Phys., vol. 31, no. 7, July 1960, pp. 1243-1246.

57. Friichtenicht, J. F.: Study of Micrometeoroid Damage to Thermal Control Materials. Thompson-Ramo-Wooldridge (Space Technology Laboratories), Final Report, Contract No. NAS8-11149, Feb. 1965.

58. Snoddy, W. C.: Thermal Design of S-46. Juno II Summary Project Report, vol. II, ch. 6, NASA TND-608, 1962.

59. Merrill, R. B.: The Thermally Isolated Temperature Sensors for Saturn. Research Projects Laboratory (MSFC), M-RP-INT-63-1, Jan. 1963.

60. Bannister, T. C.: Special Temperature Sensors for MMC. Research Projects Laboratory (MSFC), R-RP-T-WP-6-64, June 1964.

61. Pegasus A Satellite Bulletin No. 1. Pegasus Data Evaluation Group, Research Projects Laboratory, MSFC, Feb. 23, 1965.

62. Pegasus A Satellite Bulletin No. 2. Pegasus Data Evaluation Group, Research Projects Laboratory, MSFC, Mar. 1, 1965.

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RESEARCH ACHIEVEMENTS REVIEW NO. 2

by

Gerhard B. Heller

This information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

Ernst Stuhlinger

ERNST STUHLINGER
Director, Research Projects Laboratory

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Mr. Robert Hinckley NASA, Electronics Research Center Room 323 B 575 Main Street Cambridge, Massachusetts 02139	1
Dr. William G. Melbourne Mail Stop 180-300 Jet Propulsion Laboratory 4800 Oak Grove Drive Pasadena, California 91103	1
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CONTRACTORS

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"In January of this year NASA directed that the international system of units should be considered the preferred system of units, and should be employed by the research centers as the primary system in all reports and publications of a technical nature, except where such use would reduce the usefulness of the report to the primary recipients. During the conversion period the use of customary units in parentheses following the SI units is permissible, but the parenthetical usage of conventional units will be discontinued as soon as it is judged that the normal users of the reports would not be particularly inconvenienced by the exclusive use of SI units."

The International System of Units (SI Units) has been adopted by the U. S. National Bureau of Standards (see NBS Technical News Bulletin, Vol. 48, No. 4, April 1964).

The International System of Units is defined in NASA SP-7012, "The International System of Units, Physical Constants, and Conversion Factors," which is available from the U. S. Government Printing Office, Washington, D. C. 20402.

SI Units are used preferentially in this series of research reports in accordance with NASA policy and following the practice of the National Bureau of Standards.