

DEPARTMENT OF PHYSICS
GEORGETOWN UNIVERSITY
WASHINGTON 7, D. C.

RESEARCH PROPOSAL
to the
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LANGLEY RESEARCH CENTER

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RESEARCH PROPOSAL

to the

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

1. Title of Project: Thermal Equilibrium of Spacecraft
2. Total Amount Requested: \$312,524.00
3. Period of Proposal: 24 Months
4. Principal Investigator: Professor William J. Thaler
5. Statement of Objectives:

An integrated theoretical-experimental research program will be conducted to investigate the processes determining thermal equilibrium of surfaces in a space environment. Studies will be made of:

- (1) The ratio of absorptivity to emissivity, (α/ϵ), of surfaces in terms of the spectral energy distribution of reflected and emitted electromagnetic radiation in the wavelength range from 0.2 microns to 15 microns (solar source).
- (2) The variability of the α/ϵ ratio of selected surfaces by command variation of the physical, chemical, or geometrical properties of the surface.

6. Approved for the University by: _____

7. Date: August 1, 1962

Rev. Brian A. McGrath, S. J.
Acting President

DEPARTMENT OF PHYSICS

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1. Title of Project: Thermal Equilibrium of Spacecraft
2. Work to be done in the Department of Physics, Georgetown University, Washington 7, D. C.
3. Scientific Background:

A. Statement of the Problem

In the next ten years, NASA missions will require spacecraft of many types, each type especially designed and configured to accomplish its particular objective. These objectives will include manned and unmanned Earth orbiters, Lunar orbiters, Planetary orbiters, and deep space probes. In general, these missions will require sending complex scientific instruments into unfamiliar environments with little or no chance to effect maintenance and repair enroute. It is mandatory to provide the ultimate in reliability and dependability of spacecraft components. This proposal concerns those characteristics of the space-flight environment which determine the thermal equilibrium of a spacecraft. A research program is proposed which will investigate the basic physics involved in maintaining the spacecraft at thermal equilibrium by controlling the ratio of the absorptivity (α) of the surface to the emissivity (ϵ) of the surface.

B. Technical Background

A spacecraft in flight may absorb energy from any one or all of these sources:

- (1) Solar Radiation
- (2) Albedo
- (3) Planetary (or Lunar) Blackbody radiation
- (4) Multiple absorption-reflection due to spacecraft geometry

Solar radiation is essentially equivalent to blackbody radiation at a temperature of 5800°K . The spectral distribution of the electro magnetic energy radiated from the sun can, therefore, be calculated from the Planck equation. This calculation has been confirmed by measurements on the earth's surface and by sounding rocket and satellite measurement. The sun emits 99.95 per cent of its energy in the wavelength region above 0.2μ ($1\mu = 10^{-4}\text{ cm}$). About 45 per cent is radiated in the infrared region above 0.76μ ; about 46 per cent in the visible region from 0.40μ to 0.76μ and about 8 per cent in the ultraviolet region below 0.40μ . As regards the problem of thermal equilibrium of spacecraft, it is safe to consider the region from 0.2μ to 15μ as the region of interest since only about 0.1 per cent of the total solar energy lies outside of this region. It is also of interest to recall that the radiation intensity varies with distance from the sun in accordance with the inverse square law and that the rays are effectively parallel at large distances.

Albedo is that portion of the incident solar radiation which is scattered and reflected back into space from a planet and its atmosphere. Since its magnitude depends on the nature of the surface and the atmosphere and the wavelength of the incident radiation, it is highly variable. For example, the astrophysical textbooks give

albedo values of 0.7 for Venus, 0.15 for Mars, 0.10 for the Moon, and 0.35 for Earth.

Planetary Blackbody Radiation is that energy radiated from the surface of a planet which is considered in equilibrium with solar and galactic radiation and its own emissivity due to internal temperature. The equivalent blackbody temperature for Mars, for example, is about 250°K , which means that its radiation peaks at about $10\ \mu$. Due to the absence of an atmosphere, no convection or conduction takes place in space. The only way the spacecraft gains or loses energy is by radiation. The effective temperature of empty space has been estimated at about 4°K . This is essentially a perfect heat sink for radiation leaving the spacecraft.

Thermal equilibrium is achieved as a balance between the solar energy, albedo, and planetary radiation incident and absorbed by the spacecraft, and the energy radiated from the spacecraft to the heat sink of empty space.

The proposed research program will investigate the interaction of solar radiation in the 0.2 micron to 15 micron region of the spectrum with typical satellite surfaces. The major effort will be the investigation of surfaces whose geometrical and physical composition offer the possibility of controlling the ratio of the absorptivity to the emissivity (α/ϵ) in such a way as to permit control of the equilibrium temperature of the surface. Both theoretical and experimental investigations will be conducted.

To attack the problem of "Thermal Equilibrium of Spacecraft" we need first to attempt to define and delimit the nature of the problem - and its several major aspects.

For the sake of orientation and setting of extreme (ideal) limits on the problem, we may first suppose that we deal only with a temperature radiation (Kirchoffian) exchange between an idealized blackbody (b.b.) source, the Sun, and a second idealized blackbody receiver in a heat sink, the idealized one-sided (heat insulated) unit surface. Taking rough figures for estimation, we may take the solar constant S_e at approximately Earth distance ($\sim 100 \cdot 10^6$ miles) as 1.35×10^6 erg cm^2 sec and the hemispherical Stefan-Boltzmann constant σ as 5.75×10^{-5} erg cm^2 sec deg^4 K; we readily find the following:

Distance from Sun: (in 10^6 miles)	Temp. K:	Effective (α/ϵ) required to maintain <u>actual</u> real sur- face at $\sim 300^\circ\text{K}$.
10^4	$\sim 10^2$	~ 10 (?)
10^2	$\sim 10^3$	$\sim 10^{-3}$
1	$\sim 10^4$	$\sim 10^{-7}$

Thus, subject to intentionally simplified assumptions, we have a fairly accurate estimate of extreme limits on the effective (α/ϵ) required and its range of variation between the assumed limiting distances. (Of course, actual spacecraft geometry would complicate matters even in the idealized b.b. case but hardly by order of magnitude.)

It may be noted that in the dominant spectral region ($.2-15 \mu$) materials appear to exist for which (α/ϵ) falls in the range $10^{-4} < (\alpha/\epsilon) < 1$; beyond these, and the corresponding distances, the character of the problem appears to change radically with respect to maintaining thermal equilibrium without major (internal) cooling or heating of the vehicle. This, as with all the preceding elementary considerations, hinges on viewing the problem as entirely one of temperature radiation balance which it certainly is not. (cf. Infra).

Other Processes

If we were dealing solely with temperature radiation balance then, at any given equilibrium temperature, we would be severely restricted in possible adjustment of the absorptivity/emissivity by the Kirchoff relation for the emissive power/absorptive power ratio, for any body, given by $E_{\nu}/A_{\nu} = E_{\nu}(bb) = \frac{h^3}{c^2} e^{-\frac{h\nu}{kT}}$ so that choice of material, thickness, and geometry would be our limiting variables.

However, the solar spectral distribution combines the overall envelope of a blackbody type (sufficient for some limited considerations) together with a superposition of a multiplicity of spectral contributions which are not, apriori, subject to Kirchoff restrictions. This circumstance allows for the further possibility of choice of materials involving other types of radiative processes without apriori limitation upon the (α/ϵ) ratio.

Thus, it appears essential to separate out thermal and non-thermal parts of the source spectrum (solar or artificial simulator), particularly in the .2-15 μ range, and investigate the (α/ϵ) - absorption/emission characteristics - with respect to frequency and temperature dependence of the major classes of materials. (There is no reason at all for assuming a T^4 law for the non-thermal contributions.)

Only then can we expect to establish a realistic and accurate analysis of the thermal equilibrium problem, prior to examining issues of spacecraft geometry.

Theory:

All objects are continuously emitting and absorbing radiation. The emitted radiation results from the acceleration of electrical charges within the material. In solids, the interaction of these charges is very complex and the electromagnetic theory has not been applied to electrons in a solid to explain such things as the variation in spectral emissivity. The usual approach is to apply Thermodynamics to predict and explain radiative transfer. From this approach, the concept of a "blackbody" arises. If a solid object, S , at temperature T is placed in an evacuated cavity maintained at a uniform temperature, T_0 , then radiative transfer will take place between S and the walls of the cavity. If $T > T_0$, the net flow of radiant energy is toward the walls. If $T < T_0$, there will be a net flow toward S . Eventually, the system will come to thermal equilibrium, at which time:

$$R = \alpha H$$

where R = radiant emittance, or power per unit area emitted by S

$$\alpha = \text{absorptivity of } S$$

$$H = \text{power per unit area striking } S$$

Since $\alpha \leq 1$, a perfect absorber would emit maximum power. Such a perfect absorber is called a "blackbody". For less efficient absorbers, the emissivity is correspondingly lower, so $\epsilon = \alpha$.

This is conceptually true for each spectral component of the radiation; that is $\epsilon_\lambda = \alpha_\lambda$. If we express the conservation of energy as:

$$P_i = P_a + P_s + P_r$$

where P refers to radiant power and the subscripts are

α = absorptivity

ρ = reflectivity

τ = transmissivity

we have $\alpha + \rho + \tau = 1$ on dividing through by P_i .

If the body is opaque, the $\tau = 0$ and $\alpha = 1 - \rho$ which indicates that highly reflecting surfaces are poor emitters.

The way in which the absorptivity and emissivity affect the exchange of radiant power may be considered as follows: The radiant emittance of a blackbody, R_{bb} is given by:

$$R_{bb} = \sigma T^4 = \int_0^{\infty} R_{bb\lambda}(T) d\lambda = \int_0^{\infty} \left\{ \int_0^{2\pi} R_{bb\omega\lambda} d\omega \right\} d\lambda$$

where σ = Boltzmann's constant

T = absolute temperature in °K.

For real surfaces we write:

$$R = \epsilon_{eff} \sigma T^4 = \int_0^{\infty} \epsilon_{\lambda hem} R_{bb\lambda}(T) d\lambda = \int_0^{\infty} \left\{ \int_0^{2\pi} R_{\omega\lambda} d\omega \right\} d\lambda$$

$$\text{or } R = \int_0^{\infty} \left\{ \int_0^{2\pi} R_{bb\lambda}(T) \epsilon_{\omega\lambda}(T, \theta, \phi) d\omega \right\} d\lambda$$

where $\epsilon_{eff}(T) \equiv R(T)/R_{bb}(T)$, the effective hemispherical emissivity

$\epsilon_{\lambda hem}(T) \equiv R_{\lambda}(T)/R_{bb\lambda}(T)$, the spectral hemispherical emissivity

$\epsilon_{\omega\lambda}(T, \theta, \phi) \equiv \frac{R_{\omega\lambda}(T)}{R_{bb\omega\lambda}(T)}$, the spectral, goniometric emissivity.

These equations essentially say that the effective emissivity is the ratio of the total power emitted into a hemisphere by a surface to the total power emitted into a hemisphere by a black-

body at the same temperature. This ratio is always less than or equal to unity. The same general form of the equation holds for any spectral region (ϵ_λ) and any goniometric (directional) geometry ($\epsilon_{\omega\lambda}$). All these quantities, in the general case, vary with the temperature, T . Also, in general, the radiation emitted by a body is a volume effect. If the surface is opaque throughout the wavelength band under consideration, the surface effects predominate. For other cases, the spectral transmissivity and its temperature dependence must be considered.

We can set down the conditions under which the emissivity is equal to the absorptivity in the following way. It has already been shown that

$$\epsilon_{eff}(T_s) = \frac{\int_0^\infty \epsilon_{\lambda hem}(T_s) R_{bb\lambda}(T_s) d\lambda}{\int_0^\infty R_{bb\lambda}(T_s) d\lambda}$$

where T_s = temperature of the emitting body.

The effective absorptivity of the surface, α_{eff} , is the ratio of the absorbed radiation, $\alpha_{eff} H_i$, to the incident irradiance, H_i . The spectral absorptivity, $\alpha_{\lambda hem}(T_i)$ of the body temperature T_i , is defined as the ratio of the spectral absorbed radiation to the incident spectral irradiance, so the effective absorptivity is

$$\alpha_{eff}[T_s, T_i] = \frac{\int_0^\infty \alpha_{\lambda hem}(T_i) H_i(T_s) d\lambda}{\int_0^\infty H_i(T_s) d\lambda}$$

Examining these equations for α_{eff} and ϵ_{eff} , we see that α_{eff} is not in general equal to ϵ_{eff} . The equality only exists when the incident radiation is black and when $T_i = T_s$.

The effective emissivity and absorptivity depend on the chemical and physical condition of a surface and these conditions are difficult to describe precisely. In general, one divides materials into three classes: dielectrics (insulators), semi-conductors, and conductors. The basic problem to be investigated both theoretically and experimentally, is the ability to modify the ratio $\alpha_{\text{eff}}/\epsilon_{\text{eff}}$ of a given surface by some external influence to maintain the temperature of the surface constant. The identification of the physical parameters of the material which affect the absorptivity and emissivity as a function of wavelength and the range and magnitude of adjustment of these parameters due to a particular external influence must be determined. When one considers that the significant wavelength range of solar radiation extends from the ultraviolet through the visible and into the near infrared, the problems are somewhat imposing.

The usual theoretical approach is the application of Maxwell's equations to the problem of reflection, transmission, and absorption. One proceeds by deriving the differential equations which describe the transmission of an electromagnetic disturbance through any medium. These are:

$$\nabla^2 \vec{E} - \text{grad div } \vec{E} = \mu \nabla \frac{\partial \vec{E}}{\partial t} + \epsilon \mu \frac{\partial^2 \vec{E}}{\partial t^2}$$

and

$$\nabla^2 \vec{H} = \mu \nabla \frac{\partial \vec{H}}{\partial t} + \epsilon \mu \frac{\partial^2 \vec{H}}{\partial t^2}$$

where \vec{E} is the electric field vector

\vec{H} is the magnetic field vector

ϵ is the permittivity

μ is the permeability

∇ is the electrical conductivity

t is time

If, for simplicity, we consider plane waves (sun far removed from the satellite) we can examine the propagation parameter in free space, in dielectric media, and in conductors.

In free space there is no net electric charge, so $\text{div } \vec{E} = 0$ and $\nabla = 0$. The wave equations then become

$$\nabla^2 \vec{E} = \epsilon_0 \mu_0 \frac{\partial^2 \vec{E}}{\partial t^2}$$

and

$$\nabla^2 \vec{H} = \epsilon_0 \mu_0 \frac{\partial^2 \vec{H}}{\partial t^2}$$

For plane waves with the electric vector in the xy, plane and propagation in the +x direction, $E_x = E_z = 0$ so

$$\frac{\partial^2 E_y}{\partial x^2} = \epsilon_0 \mu_0 \frac{\partial^2 E_y}{\partial t^2}$$

which is the familiar plane wave equation whose solution is of form

$$E_y = f\left(t \pm \frac{x}{c_0}\right), \text{ say } E_y = E_{y0} \cos\left\{\omega\left[t - \frac{x}{c_0}\right]\right\}$$

where $c_0 = (\epsilon_0 \mu_0)^{-\frac{1}{2}}$ (propagation velocity).

In dielectric media, $\nabla = 0$ and $q_v = 0$ so the same form of wave equation and solution are applicable but the propagation velocity is $c = (\mu \epsilon)^{-\frac{1}{2}}$ where μ and ϵ are the permeability and capacitivity of the dielectric medium. We define the index of refraction as the ratio c_0/c

$$\text{or } n = \frac{c_0}{c} = \left(\frac{\mu \epsilon}{\mu_0 \epsilon_0}\right)^{\frac{1}{2}} = (K_m K_e)^{\frac{1}{2}}$$

where $K_m \equiv \frac{\mu}{\mu_0}$ and $K_e \equiv \frac{\epsilon}{\epsilon_0}$

Except for ferromagnetic materials, $K_m \approx 1$ so $n = (K_e)^{\frac{1}{2}}$.

Actually this only holds for long wavelength radiation since

K_e is a function of frequency for short wavelengths due to the inability of the charges in the medium to follow the fields.

In conductors, $\text{div } \vec{E} = 0$ but $\sigma \neq 0$. The wave equation for \vec{E} becomes

$$\nabla^2 \vec{E} = \mu \nabla \frac{\partial \vec{E}}{\partial t} + \epsilon \mu \frac{\partial^2 \vec{E}}{\partial t^2}$$

In plane wave approximation, the solution is of the form

$$E_y = E_{y_0} e^{(2\pi j \nu t - \Gamma x)}$$

where Γ is the propagation coefficient

j is $(-1)^{\frac{1}{2}}$

ν is frequency

$$\Gamma = [2\pi \nu j \mu \sigma - 4 \epsilon \mu \pi^2 \nu^2]^{\frac{1}{2}}$$

$$= 2\pi \nu (\epsilon \mu)^{\frac{1}{2}} \left[1 + \left(\frac{\sigma}{2\pi \nu \epsilon} \right)^2 \right]^{\frac{1}{4}} - \frac{j}{2} \arctan \left(\frac{\sigma}{2\pi \nu \epsilon} \right)$$

Expressed in terms of complex numbers,

$$\Gamma = \frac{2\pi \nu j}{c_0} [n - jK]$$

where

$$n = \left[\frac{\epsilon \mu}{\epsilon_0 \mu_0} \right]^{\frac{1}{2}} \left[1 + \left(\frac{\sigma}{2\pi \nu \epsilon} \right)^2 \right]^{\frac{1}{4}} \sin \left\{ \frac{1}{2} \left[\arctan \left(\frac{\sigma}{2\pi \nu \epsilon} \right) \right] \right\}$$

and

$$K = \left[\frac{\epsilon \mu}{\epsilon_0 \mu_0} \right]^{\frac{1}{2}} \left[1 + \left(\frac{\sigma}{2\pi \nu \epsilon} \right)^2 \right]^{\frac{1}{4}} \cos \left\{ \frac{1}{2} \left[\arctan \left(\frac{\sigma}{2\pi \nu \epsilon} \right) \right] \right\}$$

Then the solution can be written

$$E_y = E_{y_0} e^{-2\pi \nu K x / c_0} \cdot e^{j 2\pi \nu (t - \frac{n x}{c_0})}$$

where $e^{-2\pi \nu K x / c_0}$ is the damping term and K is called the absorption coefficient.

This very brief summary of the application of Maxwell's equation to the propagation of an electromagnetic wave shows that the two quantities m and k essentially characterize the propagation. If we consider the limiting case $\nabla \ll 2\pi\epsilon\nu$ we have the dielectric case or the case of radiation of extremely short wavelength or high spectral frequency. $k \approx 0$ and

$$m = \left[\frac{\epsilon\mu}{\epsilon_0\mu_0} \right]^{\frac{1}{2}} \approx (K_e)^{\frac{1}{2}}$$

The wave propagates with no absorption and with the wavelength reduced by m . As the wavelength decreases, the index of refraction increases and the medium starts to absorb. For the case where $\nabla \gg 2\pi\epsilon\nu$, which is the situation for metals or when the incident radiation has an extremely long wavelength,

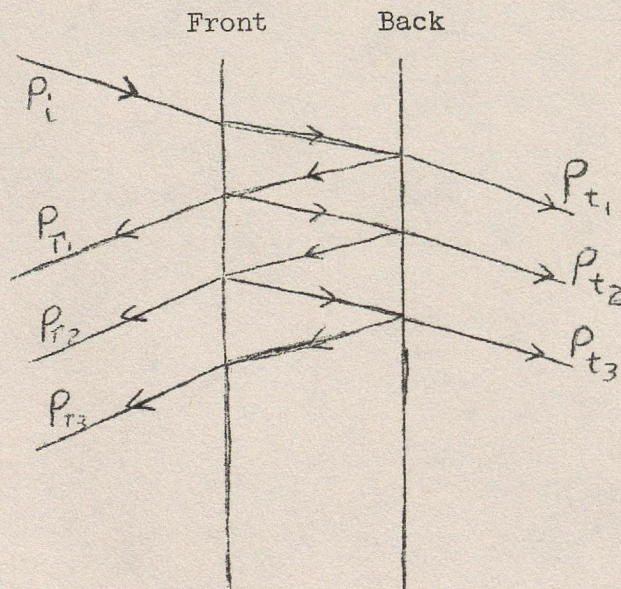
$$k = m = c_0 \left(\frac{\mu\nabla}{4\pi\nu} \right)^{\frac{1}{2}} = \left(\frac{\mu\nabla\lambda c_0}{4\pi} \right)^{\frac{1}{2}}$$

so for long wavelengths, ∇ controls the absorption characteristics of metals. At short wavelengths this simple relation does not hold.

The foregoing discussion is appropriate to electromagnetic wave propagation in an infinite, homogeneous medium. Our problem involves the interaction of the radiation at the boundary between free space (vacuum) and a material medium (dielectric, conductor, or semiconductor). The properties of the medium determine what fraction of the total energy is associated with the electric field and what fraction is associated with the magnetic field. At a boundary between two media of different index (and thus different electric and magnetic properties),

energy adjustments occur between the two fields. These energy adjustments manifest themselves in the form of reflected and transmitted energy and are calculable from Maxwell's equations if we know the appropriate boundary conditions. The resulting relationships describing the reflectivity and transmissivity at an interface between two media are called Fresnel's equations. In the general case of absorbing media, the mathematical treatment is rather complicated and will be the subject of our theoretical effort in the research program.

When considering the reflection, absorption, and transmission properties of materials, one must differentiate between reflectivity and reflectance, absorptivity and absorptance, and transmissivity and transmittance. Consider an optically flat piece of material (Fig. 1):



If P_i = incident radiant power, then the power, P_r , reflected from the front surface is

$$\begin{aligned}
 P_r &= P_{r_1} + P_{r_2} + P_{r_3} + \dots + P_{r_m} \\
 &= \left\{ \rho + \rho(1-\rho)^2 e^{-2ad} + \rho^3(1-\rho)^2 e^{-4ad} + \dots \right\} P_i \\
 &= P_i \left\{ \rho + \frac{(1-\rho)^2 \rho e^{-2ad}}{1-\rho^2 e^{-2ad}} \right\}
 \end{aligned}$$

where

ρ = reflectivity

a = absorption coefficient

d = thickness

The reflectance, ρ_t , is:

$$\rho_t \equiv \frac{P_r}{P_i} = \rho + \frac{(1-\rho)^2 \rho e^{-2ad}}{1-\rho^2 e^{-2ad}}$$

The power transmitted is:

$$\begin{aligned}
 P_t &= P_{t_1} + P_{t_2} + P_{t_3} + \dots + P_{t_m} \\
 &= \left\{ (1-\rho)^2 e^{-ad} + (1-\rho)^2 \rho^2 e^{-3ad} + \dots \right\} P_i \\
 &= P_i \left\{ \frac{(1-\rho)^2 e^{-ad}}{1-\rho^2 e^{-2ad}} \right\}
 \end{aligned}$$

and the transmittance, τ_t , is

$$\tau_t \equiv \frac{P_t}{P_i} = \frac{(1-\rho)^2 e^{-ad}}{1-\rho^2 e^{-2ad}}$$

Since $1 - \rho_t - \tau_t = \alpha_t$, the absorptance is

$$\alpha_t \equiv \frac{P_a}{P_i} = \frac{(1-\rho)(1-e^{-ad})}{1-\rho e^{ad}}$$

If the material is opaque, that is, if $e^{-ad} = 0$

then: $\rho = \rho_t$ and $\alpha_t = 1 - \rho_t$

When experimental measurements of reflection, transmission, and

absorption are made, the measured values are the reflectance, ρ_t ,

absorptance, α_t , and transmittance, τ_t .

In summary, the general properties which determine the interaction of matter with incident radiation in the wavelength range 0.2 microns to 15 microns are dependent on the state of the electrons in the material and their behavior as a function of the wavelength and intensity of the incident radiation. In principle, if one can change the state of the electrons within the material by external means (electric or magnetic fields, temperature, etc.), then the interaction will change and measurable quantities such as the reflectance, absorptance, and transmittance will change. A coordinated theoretical and experimental research effort is required to examine these fundamental interactions.

Theoretical Research Program

Classical electromagnetic theory should be applicable in the long wavelength region down to about ten microns. At shorter wavelengths of interest (visible through ultraviolet), the theoretical approach will involve the wave mechanics of crystalline solids. This is basically the treatment of the theory of motion of electrons in crystalline solids. The basic phenomena attendant on the interaction of light and near infrared radiation with semiconductors and metals will be treated. These are the two most interesting materials presently envisioned as of use in controlling the ratio of a surface. It is intended to closely coordinate this work with the experimental program so that the theory and experiment can reinforce each other as the program progresses.

Experimental Research Program

4. Test Chamber and Test Equipment

An experimental laboratory facility will be set up to allow systematic, quantitative measurement of the $\frac{\alpha}{\epsilon}$ ratio of various surfaces under conditions approaching those encountered by a satellite in outer space.

Sample studies will be made under simulated space conditions - high vacuum, cold black walls, and solar radiation - while the sample temperature is controlled to duplicate the satellite mounting conditions. A stainless steel vacuum chamber with a liquid nitrogen cooled liner provides the surrounding environment for the sample holder, while an external carbon arc lamp closely reproduces the solar radiation. Three quartz windows in the chamber permit use of any optical equipment desired to measure sample characteristics. Electrical feedthroughs and coolant tubes leading to the sample holder permit temperature measurement and control of the holder.

The basic chamber is a short cylinder with vertical axis (approximately 18" diameter by 12" tall) with a removable lid. The sample holder is supported from the bottom with electrical leads and coolant tubes reaching the holder from hermetic feedthroughs located in the bottom of the chamber. The pumping port is located in the rear of the chamber while the three quartz windows are located on both sides and the front.

The liquid nitrogen cooled liner is made of stainless steel in two sections, one in the chamber proper and one mounted in the lid. Holes in the lower section line up with the windows and the sample holder support. Covers are supplied for the window holes when they are not used. The interior of the liner is

blackened to provide a high emissivity and the two sections form an optically dense surrounding for the sample except for the windows.

All the windows are made of optical grade quartz and provide a clear four inch diameter opening. Located at accurate 90° spacings reflected or transmitted light can be used as desired. Sapphire windows 2" in diameter can be substituted when desired for far ultraviolet work.

The vacuum pumping system is composed of a 6" high vacuum valve, liquid nitrogen cooled baffle, diffusion pump, mechanical pump and associated valves, gages and sensors to provide a fail-safe system with simple operation. The design of the overall system is typical of good ultra high vacuum practice with Viton A used to seal all high vacuum joints. A cold cap on the diffusion pump together with the baffle reduces oil back streaming to a negligible value. Interlocks on water temperature, foreline pressure and procedure of operation protect the system. A Bayard-Alpert ionization gage covers the pressure region of interest. All of the vacuum pumping system is located to the rear of the chamber giving free access to the windows for the associated optical instruments.

The sample holder is designed to place the sample at the center of the chamber with adjustments to provide exact positioning before the chamber is closed. Electrical heating elements and coolant tubes provide temperature control over the range -195°C to +200°C. Thermocouple sensors drive a strip chart recorder controller to regulate the holder temperature. This controller is a Minneapolis Honeywell Electronic 15 or equal with proportioning control.

A carbon arc light equipped with quartz optics provides simulated solar radiation with collimation, spectra, and intensity closely matching solar characteristics at the earth's orbit. Automatic intensity control and electrode changing provide constant intensity over long times.

Provision can be made for emission spectroscopic studies of small areas of the sample by rapid heating with a pulsed high intensity laser. Such measurement could serve to prove the composition of the sample. This would be an extension to the work by Nelson using flash discharge tubes (Intense Rapid Heating with Flash Discharge Lamps, L. S. Nelson, Science Vol 136, No. 3513 pp 296-303.)

Source

The radiation source should produce both a radiant intensity and a spectral energy distribution closely simulating that of the sun above the earth's atmosphere. Sources under consideration are:

- (1) Xenon arc lamp
- (2) Mercury arc lamp
- (3) Xenon-mercury arc lamp
- (4) 13.6 mm High Intensity Carbon arc
- (5) 10 mm Ultrex Carbon arc

An optical system will be required to produce a collimated beam of uniform intensity for injection into the chamber. At the moment, the 13.6 mm H. I. Carbon arc appears to be the most promising. Since the total area of the specimen will be relatively small, there appears to be no basic problem in assembling such a source.

It is also suggested that a high intensity LASER be used to conduct material degradation studies. Since the LASER can focus on a very small surface area, this could probably be done simultaneously with the regular measurements. We are also investigating the applicability of LASER irradiation as a micrometeorite collision simulator.

Instrumentation

Measurements will be made of the intensity and spectral energy distribution from the specimen in the wavelength range from 0.2 to 15 microns. It will be necessary to use a variety of sensors for these measurements. In the UV-Visible region, the department has available a Littrow Spectrograph and a Jarrell-Ash Spectrophotometer with the following capabilities:

The Jarrell-Ash Spectrophotometer is a high resolution instrument with an eight speed scanning drive. It is most useful for the wavelength range 0.3μ to 1.4μ . The dispersive element is a grating in Ebert mounting. We already have the spectrophotometer with slit and phototube assembly and are in the process of acquiring the high sensitivity recording electronics with a stabilized high voltage supply for the phototube, a high gain stable amplifier and a Bristol one-second recorder. The main advantage of the Jarrell-Ash Spectrophotometer in connection with the present proposal is that its dispersive power, resolution, high degree of precision and versatility of control are the best that can be wished for and that the instrument covers a wavelength range which covers nearly 82 per cent of the solar radiation outside the earth's atmosphere.

The Littrow mounting quartz prism Spectrograph is a photographic instrument of 10 ft. focal length. Its maximum usefulness is in the ultraviolet range below 0.3μ . Though the percentage of solar energy below 0.3μ is very small, this spectral range is of importance in solar simulation since degradation effects on materials is most pronounced in the extreme ultraviolet. The Littrow Spectrograph may also be used in the visible and infrared regions up to 1.1μ . For spectroscopic analysis of a specimen under rapidly changing conditions the photographic technique is preferable to the photoelectric. A densitometer and other accessories for conversion of the photographic densities to intensity of light flux are also available.

The infrared region from 1μ to 15μ can be covered by a Beckman IR2T instrument available in the department. However, extensive modification would be required since this instrument is primarily intended for routine analysis using a Nernst Glower source. The source chamber would have to be removed and an optical adaptor designed to focus radiation from the surface under study onto the entrance slit of the monochromator. The Beckman IR-7 Infrared Spectrophotometer has much improved optics with higher resolution and faster scanning speed. Furthermore, it is designed for optional use of an external source of radiation which in this project would be the surface under study. A reflectance attachment is also available as an accessory which would permit rapid survey of the infrared reflectance properties of surfaces using the Nernst Glower source. It is, therefore, recommended that a Beckman IR-7 Prism-Grating

Infrared Spectrophotometer and reflectance attachment be purchased for project use.

Surfaces

A survey of the literature has indicated a lack of fundamental data on emissivity and absorptivity of surfaces. Most of the measurements have been made at selected wavelengths or in small wavelength bands. Practically no measurements of the spectral energy density distribution in the reflected or emitted radiation has been made using the latest spectrophotometric techniques. It is presently planned to prepare a surface of highly polished silver deposited on aluminum and use this to check out the instrumentation procedures. It is expected that NASA will supply or specify types of surface now employed on satellites for thermal equilibrium. These specimens will be examined. Once the experimental equipment and techniques have been checked out, we will begin to study surfaces whose physical or chemical state can be varied by external influence and determine the change of $\frac{\alpha}{\epsilon}$ ratio, if any, as well as the magnitude of the change as a function of the spectral energy distribution from 0.2 μ to 15 μ . In particular, certain phenomena exhibited by various materials and enumerated in a NASA-LANGLEY MEMORANDUM by Dr. William J. O'Sullivan appear to be promising candidates for variable $\frac{\alpha}{\epsilon}$ ratio materials. So little fundamental data is available in this problem area that it is difficult to predict where our investigations will lead us.

Conclusion

We feel that this is a very interesting and neglected area of basic research that holds the key to many important applications in space technology. The magnitude of the effort requires careful planning and execution of a well coordinated, carefully integrated theoretical-experimental team effort. It is estimated that a two year research program will be required to complete the investigations with satisfactory results.

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Scientific Personnel:

Senior Investigator: Dr. William J. Thaler

Professor of Physics, Georgetown University, 1960 -

Ph.D. The Catholic University of America, 1952

Publications:

"Distortion of Progressive Ultrasonic Waves"
Phys. Rev. 74, 107-108, (1958).

"Study of Turbulence by Light Defraction"
Phys. Rev. 74, 708-798, (1948).

"Intensity as a Factor in Precision Measurements in Ultrasonics"
Bull. Am. Phys. Soc., April 29, 1948.

"A New Method of Measuring Sound Velocity"
Am. J. Phys., 6, (1950).

"A High Intensity Short Duration Spark Light Source"
Am. J. Phys. 21, 1269-1271, (1950).

"Absorption and Dispersion of Sound in Oxygen as a Function of
the Frequency-Pressure Ratio"
Am. Acoust. Soc. Am. 24, 15, (1951).

"Ultrasonics - A Tool for Biological Research"
Research Reviews, Jan., 1952.

"Effects of Ultrasonic Waves on the Refractive Media of the Eye"
AMA Archives of Ophthalmology 47:2; 204-19, Feb., 1952.

Numerous additional publications from 1952 to 1960, in connection
with nuclear weapons research and ballistic missile research are
classified and no reprints or references are available.

Co-Investigator: Dr. Edward M. Corson

Professor of Physics, Georgetown University, 1961 -

Ph.D. Johns Hopkins University 1942

Publications

"Theory of X-ray Absorption Fine Structure in Polyatomic Molecules"
Phys. Rev. 70, 654 (1946).

"Quantization and Representation Theory"
Phys. Rev. 70, 728 (1946).

"Invariant Form of Quantum Equations and the Schrödinger-
Heisenberg Parallelism"
Phys. Rev. 71, 200 (1947)

"The Oscillator Concept in the Theory of Solids"
Phys. Rev. 71, 130 (1947)

"The Dirac Character Operators"
Phys. Rev. 73, 53 (1948)

"A New Equation of State"
Phys. Rev. 75, 1264 (1949)

"On Problems Involving Permutation Degeneracy"
Phys. Rev. 75, 1266 (1949)

"The Exclusion Principle: Evolution and Present Status"

"Functional Integrals: A Critique"

Books

"Perturbation Methods in the Quantum Mechanics of n-Electron Systems"
Blackie & Son, publishers. England, 1951, pp. 308.

"Tensors, Spinors, and Relativistic Wave-Equations"
Blackie & Son, publishers, England, 1955, pp. 221.

.

"Comparative Study of U.S.--USSR Standards and Methods in College and Graduate School Training in Physics and Mathematics"
U. S. Department of Education Report, 1959.

"Philosophy of Science"

Co-Investigator: Dr. Matthew P. Thekaekara, S. J.

Associate Professor of Physics, Georgetown University, 1957 -

Ph.D. Johns Hopkins University 1956

Publications

"Automatic Techniques in Spectroscopy using a Small Computer"
J. Opt. Soc. Am. 48, 871 (1958).

"Emission Lines from Pre-ionized Levels in Krypton & Xenon"
Phys. Rev. 109, 20 (1958).

"Semiautomatic Methods in Spectroscopy at Georgetown Observatory"
Jesuit Science Bulletin, 35, 82 (1958).

"The Ultraviolet Spectrum of Ti I"
J. Opt. Soc. Am., March 1961.

Books

"Practical Physics, Vols. 1 & 2 for Freshman, Sophomore & Junior"
St. Joseph's Trichy, 1944.

"Spectrum of Xenon I (with Dr. G. H. Deike)"
Johns Hopkins University, 1956.

"Revision of the Term Values of Ti I"
Georgetown Obs. Monograph 13, 1959.

"Recent Advances in Astrogeophysics"
Georgetown Obs. Monograph 14, 1960.

Co-Investigator: Dr. Edward J. Finn

Assistant Professor, Georgetown University, 1956 -

Ph.D. Georgetown University 1962

Publications

"Preliminary Measurements of the Frequency Dependence of Sound Velocity in Aerated Water"
Master's Thesis, 1955.

"Power Series Expansions of Vibrational Potentials. II. Two Classical Potentials for Ionic Molecules"
Journal of Chemical Phys, Vol. 33, No. 6, December 1960. (with Charles L. Beckel).

"Power Series Expansions About Equilibrium of the Heitler-London and Rittner Vibrational Potentials"
Paper delivered June 1960 at Symposium on Molecular Structure and Spectroscopy, Columbus, Ohio. (with Prof. Beckel of G. U. Physics Dept.) Supported in part by grants from G. U. Research Fund and U.S. Air Force Office of Scientific Research.

"Vibrational Energy Levels of Ionic Molecules Bound by Classical Forces"
Paper delivered June 1961 at Symposium on Molecular Structure and Spectroscopy, Columbus, Ohio.

"A Study of Vibrational Properties of Ionic Molecules Bound by Classical Forces"
Doctoral Thesis, 1961.

Co-Investigator: Mr. Franklin Fletcher

Research Assistant in Physics, Georgetown University 1960 -

Graduate Study at the Johns Hopkins University and private
research in the physics of nerve impulse propagation
1958 - 1960

Consultant and Research Associate in Applied Mathematics
and Mathematical Physics, ACF Electronics 1958 - 1958

Mathematical Physicist, Ordnance Development Division,
National Bureau of Standards (Chief of Analysis Section
during approximately latter half of period) 1944 - 1954

Assistant Professor of Physics, Howard University 1942 - 1944

Assistant Professor of Physics, Howard University
(part-time) 1944 - 1954

Graduate Study in Physics, Harvard University 1936 - 1938
1940 - 1942

Numerous classified reports from 1944 to 1958 dealing with the
application of optics, electromagnetic theory, circuit
theory, probability and statistics, and systems analysis to
development of military devices.

5. Other Personnel

In addition to the above staff, the services of four
graduate students will be required; they will be working for
the doctorate. One electronics technician and a machinist
(instrument maker) half-time will also be required.

6. Other Financial Assistance

There is no other sponsorship for this program.

7. Materials, Equipment, and Facilities

The primary facility will be provided by the Physics Depart-
ment. Space will be assigned in the new Basic Science and Re-
search Building which the department will occupy in August 1962.
The following equipment is available for this research in the
Physics Department:

- A. Littrow Spectrograph
- B. Jarrell-Ash Spectrophotometer
- C. Burroughs El01 Computer
- D. Usual support equipment such as power supplies, oscilloscopes, etc.

Due to the specialized requirements for simulating the space environment and the solar radiation source, the following equipment will be purchased under the contract:

- A. Thermal Vacuum Chamber
- B. Beckman IR-7 Infrared Grating Spectrophotometer with Accessories. The basic instrument is prism-grating double monochromater.
- C. Radiant Sources simulating Solar spectral intensity and distribution.
- D. High Power LASER system.

8. Travel and Other Items

The only travel requirements are attendance at scientific meetings where research in this area is presented and visits to NASA-Langley for consultation with project monitors.

9. Proposed Budget

A. First Year

Direct Costs - Salaries

Dr. W. J. Thaler (3 full summer months)	\$4500
(1/4 released teaching time during academic year)	3000
Dr. M. P. Thekaekara (3 full summer months)	3200
(1/4 released teaching time during academic year)	2400

Dr. E. M. Corson (3 full summer months)	\$4500
(1/4 released teaching time during academic year)	3000
Dr. E. J. Finn (3 full summer months)	2400
(1/4 released teaching time during academic year)	1800
Mr. F. Fletcher (12 months full time)	7500
Four graduate Research Fellows (Doctoral candidates) (3 full summer months)	8000
(1/2 time for academic year)	12000
Electronics Technician	5000
Machinist (1/2 time)	3000
Secretarial Services	1000
Total Salaries	<u>\$65300</u>

Equipment and Materials

1. #28300 Beckman IR-7 Spectrophotometer with N CL Optics	\$18000
Accessories: #45170 Dual Air Dryer	950
#45900 Scale Expansion Accessory	275
#24425 Specular Reflectance Attachment	150
25 rolls Chart Paper	<u>142</u>
	\$19517
2. Special Environmental Equipment	
a. Vacuum System - Stainless steel top opening chamber, approx. 18" diameter by 12" tall, 6" valved diffusion pumping system, internal blackened liquid nitro- gen liner, three quartz windows located 90° apart with 2" sapphire windows for far ultraviolet work, clear access to all windows for other equipment, built in leak detector.	\$40000

b. Sample holder - Adjustable position near center of chamber, temperature controlled between -195°C (liquid nitrogen) and $+200^{\circ}\text{C}$. Strip chart recorder controller with proportional control (Minneapolis-Honeywell or equal).	\$ 7000
c. Carbon Arc Solar Simulator - Complete unit with quartz optics, automatic intensity control and electrode changing, including a calibrated phroheliometer for accurate intensity measurements.	15000
d. Pulsed High Intensity LASER - System to be used for spot heating for sample surface for emission spectroscopic studies in the vacuum system.	8000
e. Surface Materials and Coating	5000
f. Machine Shop Materials	4000
g. Miscellaneous Supplies and Expenses	<u>2000</u>
	\$81000
<u>Total Equipment and Materials</u>	\$100517
<u>Travel</u>	1000
<u>Total Salaries</u>	<u>65300</u>
<u>Total Direct Costs</u>	\$166817
* <u>Indirect Costs</u> - 29.08% of Total Direct Costs	<u>48510</u>
<u>Total amount requested</u>	<u><u>\$215327</u></u>
B. <u>Second Year</u>	
<u>Direct Costs - Salaries</u>	
Same as first year	\$65300
<u>Travel</u>	1000
<u>Equipment and Materials</u>	
Machine Shop Materials	4000
Miscellaneous Supplies and Expenses	<u>5000</u>
Total Direct Costs	\$75300

<u>Total Direct Costs</u>	\$75300
* <u>Indirect Costs</u> - 29.08% of Total Direct Cost	<u>21897</u>
Total amount requested	<u><u>\$97197</u></u>

*The latest determination of indirect expense rate submitted by Georgetown University to the Army Audit Agency, cognizant audit agent, is 29.08 per cent of total direct expenditures.

Submitted by:

William J. Thaler
Principal Investigator

Approved:

William J. Thaler
Chairman, Physics Department