COATINGS FOR TEMPERATURE CONTROL IN SPACE VEHICLES

J. H. Weaver

Lt. Cecil Jacobs

Directorate of Materials and Processes, ASD

Introduction

In the past, coatings have been used primarily for oxidation, corrosion and erosion resistance, decoration, and in some instances to camouflage aircraft and ground support vehicles. Since the emphasis is now on space and space vehicles, these uses become secondary considerations. Coatings take on new roles as overall temperature control, to enhance the efficiency of heat sinks or radiators, for thermal insulation and for selective solar energy collection. Each of these uses are individual problems and require different coatings. This paper is primarily concerned with coatings for temperature control in space vehicles.

Figure 1 shows the thermal forces that contribute to space vehicle temperature. The space vehicle generally receives heat from several sources, but the sun is invariably the most important one. Of the minor sources of heat, internal energy always contributes to the space vehicle temperature balance. It consists of the wast energy generated in the space vehicle due to electrical resistance and mechanical friction; it exerts a minor effect on present day space vehicles but the effect will be proportionately larger in future space vehicles when more complex equipment is launched. The space vehicle receives some energy from the earth, consisting of the earth's own radiation and the solar energy reflected from the earth. The latter quantity, called albedo, is slightly richer in shorter wavelengths than is direct solar radiation. The prime source of heat, is however, absorption of solar energy by the space vehicle.

To control the amount of energy absorbed from the sun, and more important, the amount transferred to the interior of the vehicle, the design engineer must choose between conventional insulating materials and the optical properties of specifically prepared surface coatings. In all aerospace applications, weight and space factors are a prime consideration. Low thermal conductive insulating materials which reduce heat transfer to any appreciable extent are either bulky, heavy, or both as is illustrated in figure 2. Conventional insulating materials have limited utility in the problem of preventing heat transfer in space vehicle travel. However, selective coatings can reduce heat transfer while at the same time govern energy absorption adding only a small amount of weight and volume to the overall system. This may be accomplished by a brief analysis of the basic optical properties of materials. These properties may be used to prepare general types of temperature controlling systems.

Basic Optical Properties

Materials having selective optical properties can be used to control radiant heat transfer by control of the three basic optical properties: 1 reflectance, 2 absorptance and 3 emittance. In most practical systems, a balance between these three conditions will be used to obtain the desired temperatures as illustrated in figure 3.

Energy incident upon an opaque space vehicle surface will be reflected or absorbed. If it is reflected, the energy is diverted and will not cause a rise in temperature. However, if the energy is absorbed, it must be reradiated. The reradiation of the absorbed heat is independent of its source, but at equilibrium, it must be numerically equal to the absorbed energy. The temperature required to radiate the absorbed heat is dependent upon the emittance of the exterior surface and the exposed area of the space vehicle. Since the geometry factors are fixed on a given space vehicle, the temperature is now a function of the ratio of the absorption coefficient and the emittance.

This can be better understood by referring to figure 4. The solar energy is at short wavelengths and a coating which is dark in the visible and near infrared will absorb much of the sun's energy. At equilibrium, all the absorbed energy is reradiated at wavelengths represented by the right curve. Since the reradiation is at longer wavelengths, the power of a coating to radiate heat often differs from its power to absorb heat. This is shown in figure 5. The white coating absorbs very weakly, but is a very efficient radiator of heat, that is, it has high emittance which provides a very cold surface.

The complexity of controlling the heat balance is made more difficult by orbital and space environmental factors, but it has been shown that all of these problems can be overcome through the application of scientific principles. The varying degree of success attained with space probes and orbiting vehicles, has revealed both the existence of the temperature control problem as well as a logical approach to its solution.

A payload, heated by solar radiation on the one hand and cooled by reradiation on the other, must be protected from widely varying temperature differentials. Constant temperatures are presently maintained by techniques such as painting, polishing and shuttering. Ultimately, a material is sought which has the proper conditions to obtain the required optical properties.

Metallic Coatings

A number of different types of inorganic and organic coatings have been used successfully in designing specific heat balances within the various spacecrafts which have been launched to date. A spherical body which absorbs and reradiates heat with the same efficiency ($\alpha = \epsilon = .5$) will operate at approximately 40°F, neglecting the earth's heat contribution. This condition is approximated by a flat black organic coating. Metallic coatings generally absorb little solar energy, but absorb infrared energy even to a lesser extent. This is shown in figure 6. Aluminum, for instance, absorbs 12 percent of the sun's energy but has an emittance of 3 percent. The result is a very high temperature of about 250° - 300°F, again neglecting the earth's heat contribution. Similar effects are observed with other metals such as stainless steel. For this reason, almost all metal coatings have high solar α/ϵ ratios. Therefore, an uncoated metal sphere would give us a hot space vehicle. The temperature of the metallic coating can be reduced in a number of ways. If the metal surface is sandblasted, the infrared reflectance is reduced more rapidly than the short wavelength reflectance, thus decreasing the solar α/ϵ ratio. It can be coated with a material which is transparent to solar energy but black or emissive in the infrared. This is true of many lacquers and inorganic coatings such as silica. Inorganic or organic coatings, for example, alumina or a white enamel respectively, can be applied in stripes or over the entire metal surface to increase the emittance with or without affecting the solar absorption. Metals can be combined with organic coatings to get a compromise in properties. Thus an aluminized silicone, has an absorption of 40 percent and an emittance equal to about 0.3 or an α/ϵ ratio of 1.3. By changing the solar α/ϵ ratio of the metal coatings, one can control the temperature.

One method of temperature control of an electronic blackbox in a heat radiation field is to place it in a container whose surface has known optical properties. The fabrication of a container entirely of a material of known and desired optical properties, such as gold or silver, is impractical because of weight, economy, mechanical strength, and cost of mechanically polishing the surface. Therefore, the outside of the blackbox could be coated with a material containing the desired optical properties, again saving some of the overall weight and space problem. Gold, silver, copper and aluminum are being used on metallic and nonmetallic substrates to produce highly reflective surfaces to heat radiation as shown in figure 7.

Organic Coatings

Organic coatings are virtually all very absorptive in the infrared and hence have high emittance. Such a surface is the most stable and efficient to use for long heating periods. The short wavelength absorption can be readily varied by pigmentation with organic and inorganic materials. The organic coatings will have α/ϵ ratios of 1 or less and can be used to give cool or cold surfaces in space (figure 8). It is obvious that the reflectance and the absorptance of the pigmented coating varies with the pigment. A leafing aluminum pigment is the most efficient reflector of ultraviolet energy. Several white pigments are superior to leafing aluminum in the visible and near infrared spectral regions, but are inferior to it as a reflector of ultraviolet energy. Of the nonleafing pigments, basic white lead carbonate is superior to all others in reflecting ultraviolet energy. The white lead pigmented coatings lose much of their efficiency as ultraviolet reflectors when exposed to the simulated space environment. In other regions of the spectrum, zinc sulfide is an excellent reflector of visible and near infrared energy. Other paint formulations using rutile, carbon black, red iron oxide and chrome oxide green in various amounts are used as the pigments, depending on the ratio desired.

Inorganic Coatings

Inorganic (anodic and ceramic) coatings are generally quite absorptive in the infrared although their absorption is less than most organic coatings. Many of the inorganic materials used as pigments in an organic binder give a high reflectance to difference in refractive index between the pigment and binder. However, emittance of 0.4 to 0.85 for the bulk material is common. Ceramic coatings may be used to give cool surfaces, but at present these coatings are most effective in increasing the reflectance when used as a pigment in organic coatings.

Ceramic coatings are somewhat inferior to organic coatings when α/ϵ ratios, application ease, and mechanical properties are considered. The one main advantage ceramic materials have over organic materials is their thermal stability. For example, flame sprayed aluminum oxide, having an emittance up to 0.85, has utility at temperatures many times that of the pigmented organic. The coating, however, is brittle and unable to stand rigorous thermal shock.

One important role ceramics plays in temperature control is that of diffusion barriers for highly reflective (low emittance) coatings. The temperature stability of ceramics combined with their chemical structure can be controlled to suitably deter diffusion, and consequently contamination of the reflective metal. Materials such as SiO, NiO, CeO, and NBS ceramic A-418 have prevented diffusion between gold and Inconel-X at 1500°F for periods up to 300 hours.

Some evaluation has been made on methods to improve the emittance of anodized coatings. By taking advantage of the porous coating, a high temperature dye or other pigments may be sealed within the coating to increase its emittance. Some work is being done with anodized coatings to provide a surface with a ratio of solar absorptance to long wavelength emittance of less than 0.2. Pure aluminum oxide is considered transparent to radiation in the visible region. Therefore, polished aluminum with a transparent coating of aluminum oxide would be expected to possess a low α/ϵ ratio. This is a double surface effect since the polished aluminum reflects the solar radiation which is permitted to penetrate the aluminum oxide coating.

Problem Areas

Because of their unique functions, coatings used for temperature control introduce many problem areas. The old problems of oxidation, diffusion, cleaning and application techniques will be supplemented by the influence of the space environment. (These problem areas are shown in figure 9.)

The coating materials presented must withstand the space environment and in particular,ultraviolet radiation, vacuum, and temperature extremes. These particular problems will be discussed in length in the accompanying paper on environmental considerations.

One of the problem areas in the use of reflective metal surfaces is oxidation. When a metal oxidizes it will change the reflectance properties of the metal. For example, clean polished copper has a reflectance of 0.97 to 0.98 in the temperature range 600° to 1800°F, whereas oxidized copper has a reflectance of 0.75 to 0.85 in the same temperature range. This means that any metal to be useful as a highly reflective coating against heat transfer must be oxidation resistant or must be protected from oxidation. At present, few materials are known which can both protect a metal from oxidation at elevated temperatures and are sufficiently transparent to radiant energy. The requirement of oxidation resistance without an overcoat eliminated as high temperature reflective coatings the use of all metals except gold, rhodium and platinum. Much effort is being directed toward the development of oxidation resistant coatings which will not reduce the reflectivity of metal surfaces. When it appears, oxidation resistance cannot be built into the basic metal, effort will have to be extended toward finding a suitable transparent overcoat.

The major problem associated with the use of a reflective metal such as gold as a high temperature-high reflectance coating is that it readily diffuses with practically all substrate materials at temperatures above 600°F. This diffusion is a very serious problem and a major effort in research is needed to obtain methods of retarding the diffusion with substrate materials.

Another serious problem area associated with selective coatings for temperature control is the application techniques necessary to produce high quality coatings. Trace amounts of extraneous materials may significantly influence the optical properties of the coatings. Materials, such as sensitizers and activators, may influence the resistance of the coating to the deterioration of the optical properties because of radiation or vacuum effects. From all indications, problems of contamination control are going to become more critical in the future. Advances in the state-of-the-art in cleaning and application techniques are necessary to make significant advances in temperature control coatings.

Summary

It has been shown that radiant heat transfer in space can be effectively controlled with coatings having selective optical properties. Since these coatings must be designed for a special system and cannot be altered after the launch of that system, research and development must continually be in advance of present needs. It must produce methods whereby special optical properties can be built into organic, inorganic and metallic materials. These methods of building are not presently available. Only token effort has been expended to understand the mechanisms controlling selective optical properties. Only through vigorous and imaginative research and development programs can we obtain these answers. Research and development must present methods for the control of other problems such as ultraviolet light breakdown, higher thermal stability, better application techniques and better evaluation procedures.

In conclusion, the Air Force fully intends to continue the pursuit of vigorous programs of materials research and development in temperature control of space vehicles. As the speeds and complexity of aerospace vehicles become greater, the need for temperature control will increase. The conquest of space is a huge undertaking and requires the utmost in a cooperative effort encompassing not only the military services and other Government agencies, but all of industry and academic centers as well. A unified, coordinated, cooperative effort with all elements contributing creative thinking, time, and resources to best advantage cannot be overstressed if we are to attain our goals.

BIBLIOGRAPHY

1. Belser, R. B., et. al., "Reflective Inorganic Coatings," ASD TR 61-151, 1961

2. Harrison, W. N., et. al., "Standardization of Thermal Emittance Measurements," WADC TR 59-510, 1960

3. Schmit, R. C., et. al., "Studies on the Protective Ultraviolet Absorbers in a High Vacuum Environment," WADC TR 59-354, 1960

4. Withers, J. C., et. al., "Development of Heat Barrier Coatings," ASD TR 61-5, 1961

5. Van Vliet, R. M., "Spectrally Selective Coatings for Temperature Control of Space Probes," WADD TR 60-386, 1960

6. Van Vliet, R. M., "Organic Coatings for Control of Spacecraft Temperatures," ASD TN 61-72, 1961

7. Proceedings - "Coatings for the Aerospace Environment," WADD TR 60-773

SPACE VEHICLE ENERGY BALANCE

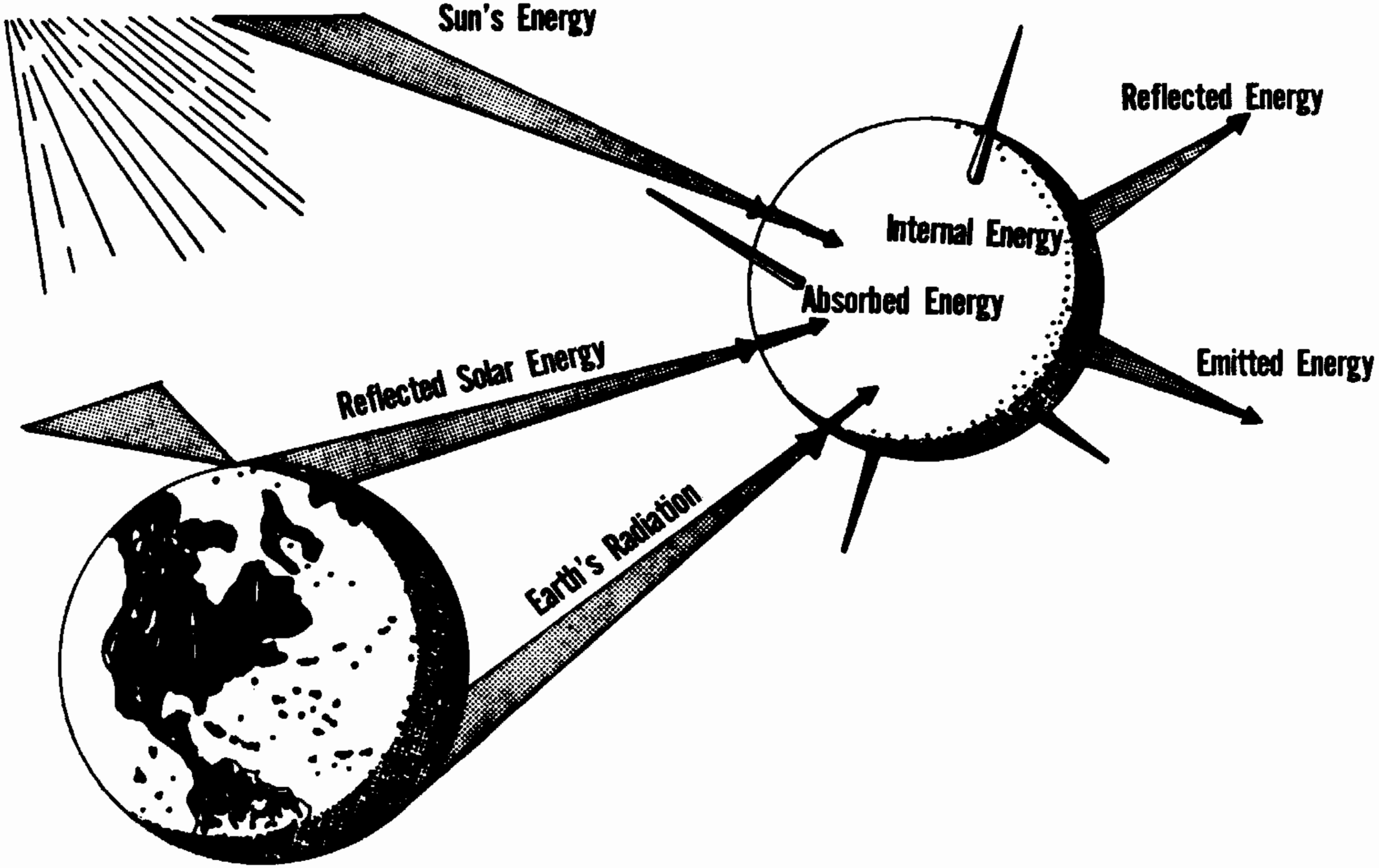

Figure 1.

THIN FILMS vs. HEAVY INSULATING MATERIAL

24" DIAMETER SPHERE

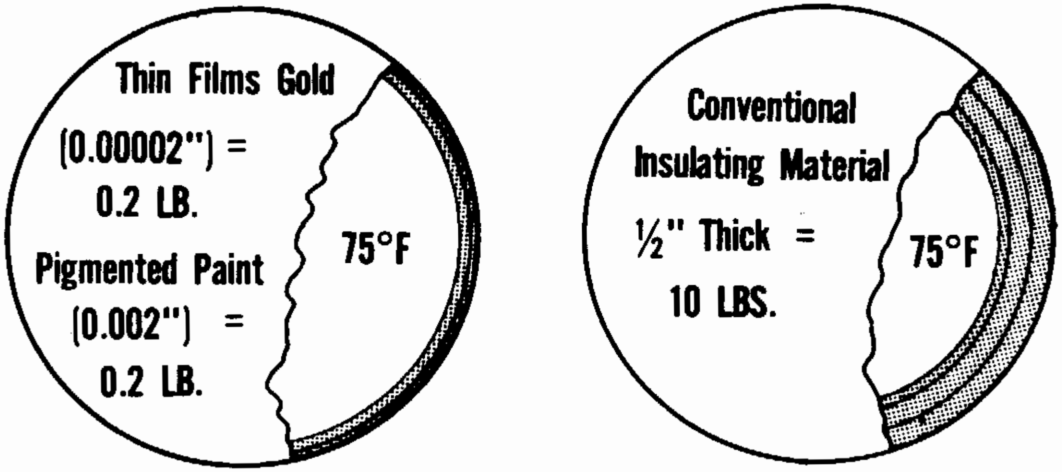

Figure 2.

COATING	SOLAR			TEMPERATURE °F	
	REFLECTION	ABSORPTION	EMITTANCE	SPHERE	STRIPED SPHERE
WHITE	0.82	0.18	0.95	-135	-20
WHITE PLUS CARBON BLACK	0.47	0.53	0.95	-30	32
FLAT BLACK	0.03	0.97	0.95	45	85
FLAT BLACK PLUS ALUMINUM	0.05	0.95	0.80	65	120

Figure 3. Vehicle Temperature Control

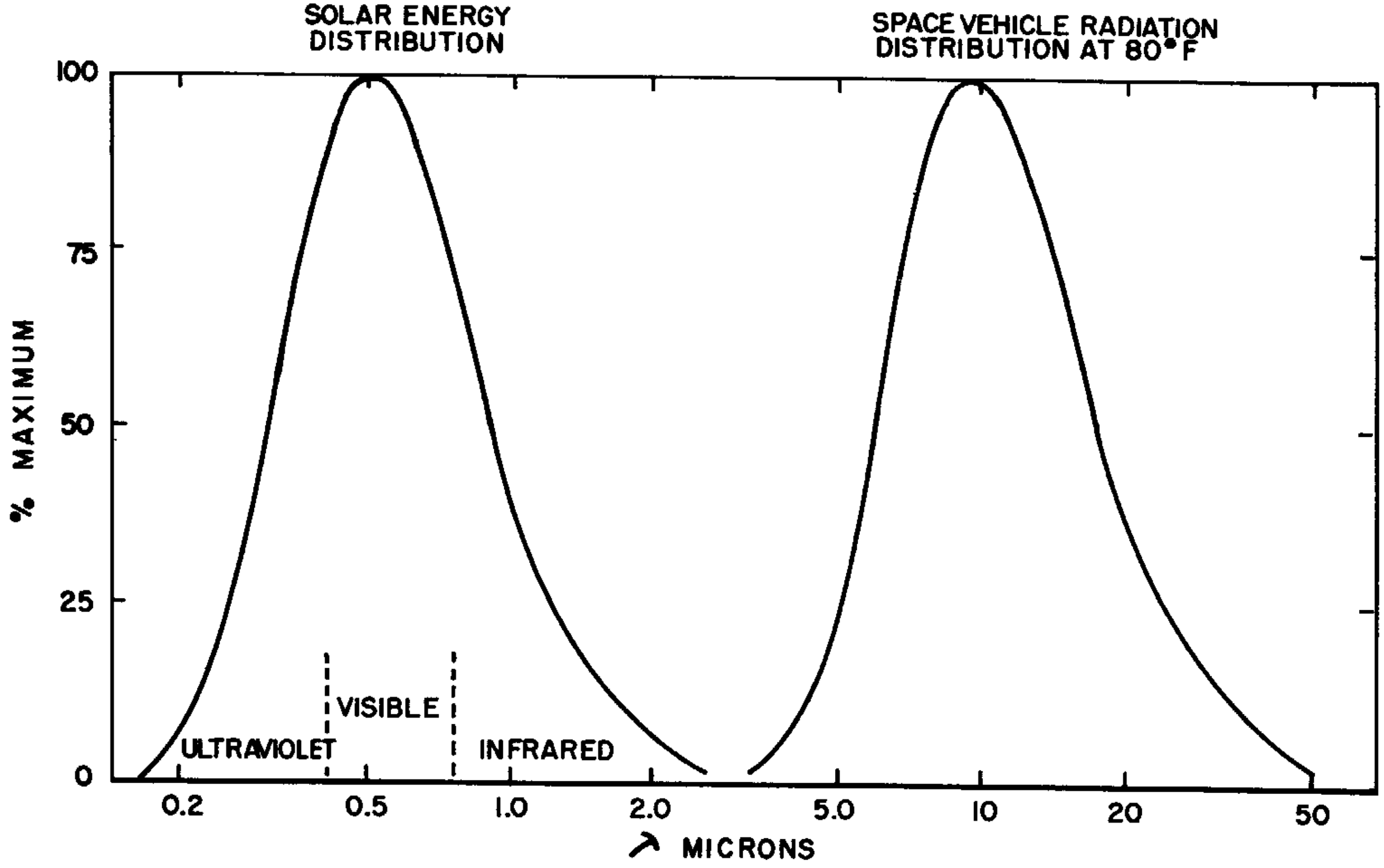

Figure 4. Relative Spectral Distribution of Heat from Sun and Space Vehicle

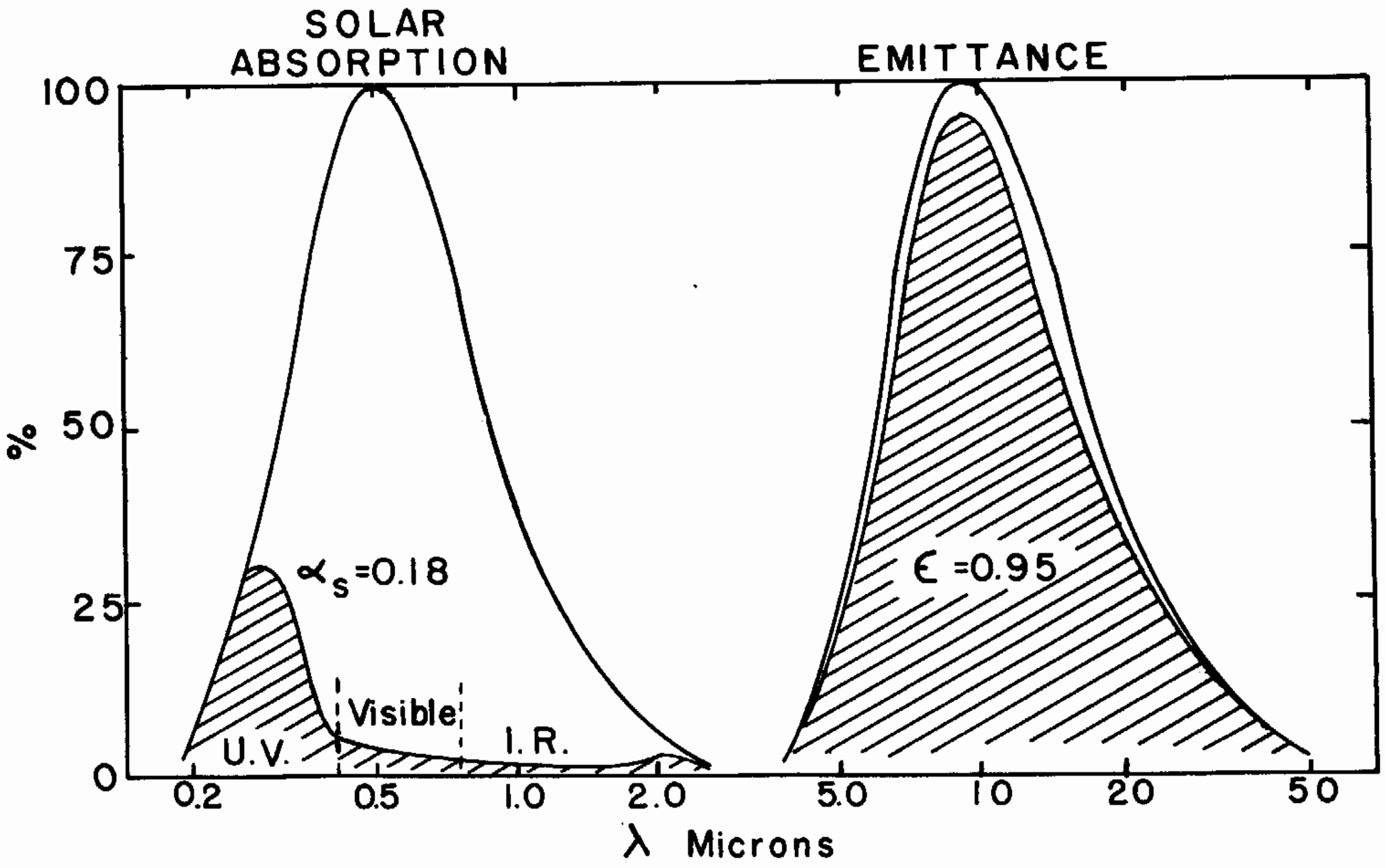

Figure 5. A Graphical Representation of a White Organic Coating Designed for Maximum Cooling

COATING	α / ε	TEMPERATURE °F
ALUMINUM	4.0	250
STAINLESS STEEL	2.5	170
ALUMINIZED SILICONE	1.3	60
ALUMINUM + CLEAR LACQUER	1.0	40
WHITE ORGANIC PAINT	0.2	125

Figure 6. Equilibrium Temperature of Spherical Space Probes with Various Coatings

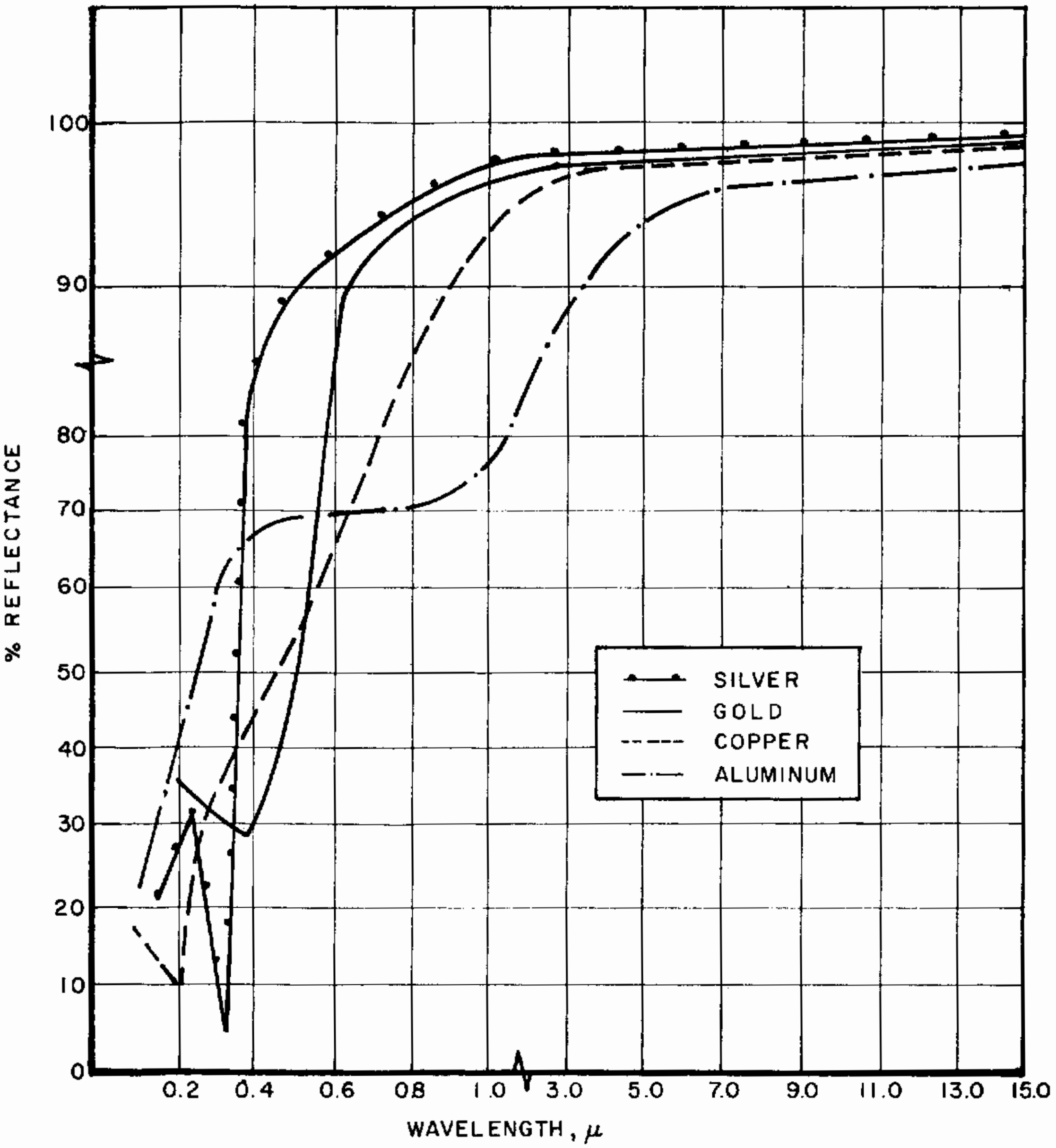

Figure 7. Metallic Surfaces

ORGANIC MATERIAL	α	ϵ	α/ϵ RATIO
White (30% PV Zinc Sulfide) Silicone	0.31	0.77	0.40
Grey Silicone	0.53	0.95	0.55
Leafing Aluminum in Silicone	0.32	0.33	0.98
White Lead Carbonate (30% PV) Silicone	0.46	0.46	1.0
Dull Black (Vinyl Phenolic)	0.93	0.84	1.1

Figure 8. Organic Material Radiative Properties

PROBLEM AREAS, SUMMARY

Evaporation

Vacuum

Temperature Stability

UltraViolet Radiation

Oxidation

Diffusion

Cleaning Techniques

Application Techniques

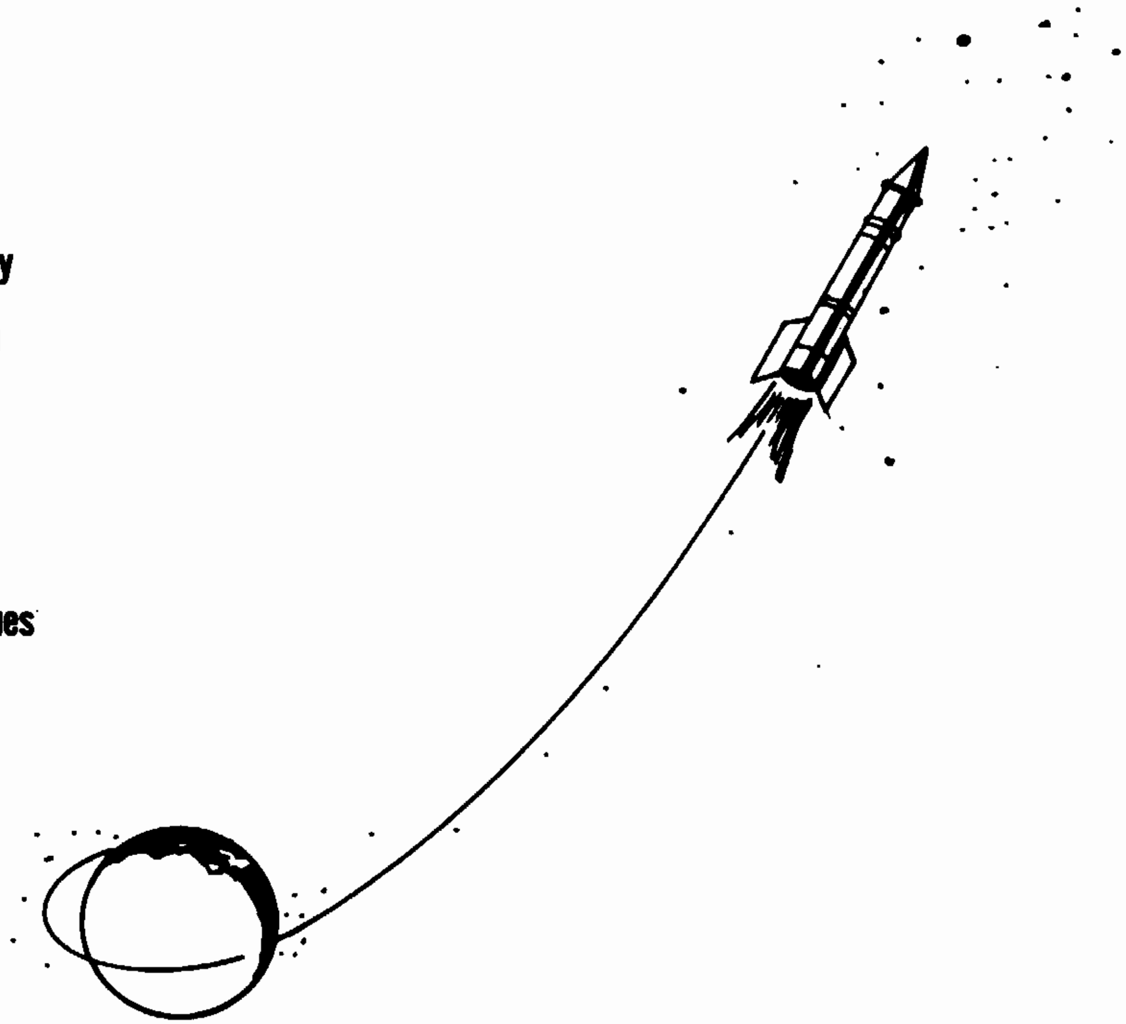

Figure 9.