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Space Station Solar Concentrator Materials Research

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SPACE STATION SOLAR CONCENTRATOR MATERIALS RESEARCH

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ABSTRACT

The Space Station will represent the first time that a solar dynamic power system will be used to generate electrical power in space. In a system such as this, sunlight is collected and focused by a solar concentrator onto the receiver of a heat engine, which converts the energy into electricity. The concentrator must be capable of collecting and focusing as much of the incident sunlight as possible, and it must also withstand the atomic oxygen bombardment which occurs in low-earth-orbit (LEO). This has led to the development of a system of thin film coatings applied to the concentrator facet surface in a chamber designed especially for this purpose. The system of thin film coatings employed gives both the necessary degree of reflectance and the required protection from the LEO atomic oxygen environment.

INTRODUCTION

Concept

Electrical power generation on the U.S. Space Station is ultimately intended to be accomplished by two different systems. Traditional silicon photovoltaic (PV) cells will provide approximately 75 kW of electricity for the station's initial operating configuration (IOC). Subsequently, two 25 kW solar dynamic power system (SDPS) modules will be added to the station approximately 2 years after IOC has been achieved.

A solar dynamic power system generates electricity by focusing sunlight onto the receiver of a heat engine, such as a closed cycle Brayton system.

Focusing of the sunlight into the receiver may be accomplished by either reflective or refractive techniques. Such systems have the potential to generate electricity with a four-fold increase in efficiency over an equivalent PV system on the basis of power-per-unit collector surface area. This can result in a significant savings over the life of the station in terms of fuel required for periodic reboosts as its orbit decays due to atmospheric drag.

Solar dynamic power modules are comprised of several parts, which include the concentrator, receiver, power conversion unit (the heat engine), and radiator (Fig. 1). The designs of each of these has required the development of new materials and procedures in order for the system to both meet performance requirements and survive in the low-earth-orbit space environment. A reflective system, rather than a refractive lens system, has been chosen for the initial solar dynamic power module configuration. This article is concerned primarily with materials research and selection for the concentrator optics.

The function of the concentrator is to collect sunlight and focus it through an aperture and onto the receiver of the heat engine. Any sunlight which falls outside of the aperture is wasted; hence, it is desirable that the concentrator surface has a high value of solar specular reflectance. Solar specular reflectance is defined as the percentage of incident solar energy reflected through an aperture of a given solid angle, which in this case is defined by the diameter of the receiving aperture and distance from the concentrator to the receiver. The respective sizes of these components have placed a lower limit on the acceptable value of the solar specular reflectance of the concentrator surface. This value has been determined to be 0.88

through an aperture of 7.5 mrad full cone angle (4.4×10^{-5} steradian solid angle).

There are two principal ways of achieving high solar specular reflectance. The first is to make the concentrator surface as smooth as possible. This minimizes the degree of scattered or diffusely reflected light. The second is to use a material with a high reflectance over the solar wavelengths of interest (generally 250 to 2500 nm) as the reflective medium. Silver and aluminum each have high reflectances over this range (Fig. 2), with silver better at wavelengths where the solar spectrum peaks (≈500 nm). The integrated solar hemispherical reflectances for these metals (calculated by convolution of their respective reflectance spectra in to the air-mass-zero solar spectrum) (Ref. 1) are nearly identical, with aluminum a percentage point or so higher (93 versus 92 percent).

In addition to high reflectance, the concentrator must meet a number of additional requirements. It must be low cost, lightweight, easily stowed for transport in the shuttle cargo bay, easily deployed, and durable in the natural space environment. Accomplishing this last requirement has required the expenditure of a great deal of time and effort to identify suitable materials and techniques.

The Low Earth Orbit Environment

The region between 200 and 800 km above the earth's surface is characterized by a number of factors potentially harmful to spacecraft component materials. The predominant hazard is oxidation by neutral atomic oxygen (Ref 2) which arises from the photodissociation of upper atmosphere molecular oxygen (Fig. 3). This oxygen impacts spacecraft surfaces in the ram direction with an energy of about 4 eV, due to the relative velocity of the orbiting spacecraft. Other hazards include ultraviolet radiation (especially at wavelengths below 200 nm), particulate impact from micrometeoroids and space debris, energetic charged particle impact, and thermal cycling resulting from repeated excursions through the earth's shadow during orbit. Although all of the above hazards have been and are being investigated, this article will be concerned only with the problem of atomic oxygen.

Early shuttle flights exhibited degradation of a number of spacecraft component materials due to oxidation by ram-impact atomic oxygen (Refs. 3 to 6). In particular, many organic polymer materials were severely degraded after only 40 hr of exposure (Refs. 5 and 6). This degradation consisted of both mass loss and surface texturing, with concomitant changes in optical properties. Most metallic materials were considerably less affected, with mass loss generally too small to be measured. Silver was an important exception and was readily oxidized in LEO. If silver is to be used as the concentrator reflective medium, some form of protection, probably in the form of a thin film coating, is required.

Concentrator Materials and Construction

As currently designed, one complete concentrator unit (or module) will consist of 456 triangular facets, each 1 m on a side. These will be arranged into 19 hexagonal elements, each composed of 24 facets. Each of these facets is composed of 0.19 mm (7.5 mil) thick graphite-epoxy composite bonded to a 6.4 mm (0.25 in.) thick aluminum honeycomb core. The composite is fabricated by pressing 193P/3501-6 prepreg graphite cloth into 0.038 mm (1.5 mil) thick epoxy resin (Ref. 7). This construction gives the facets rigidity while maintaining light weight. This size of facet allows for both efficient packaging into the shuttle cargo bay and ease of handling and deployment once on orbit. Coating of these facets requires a deposition chamber large enough to contain the facet and apply the necessary coatings to the required thickness completely and uniformly, but small enough to allow for rapid turn around because of the large number of facets.

A variety of scenarios are possible for the coating system. Silver and aluminum have nearly identical solar reflectances (≈0.93) which are higher than any other metal. Silver is easily oxidized, and would thus require protection. Aluminum, however, forms a transparent, passivating oxide which would be expected to protect it against further oxidation by LEO atomic oxygen. Recent studies, however, have indicated that aluminum is not completely passivated; it has been observed that the surface continues to oxidize, albeit very slowly, in the presence of a simulated LEO atomic oxygen environment (Ref. 8). Furthermore, calculations predict that the reflectance of aluminum is reduced significantly by dielectric coatings (such as metal oxides) a few hundreds of Angstroms thick, especially at angles of incidence other than the normal (Ref. 9). Because of these findings, silver remains under prime consideration as the reflecting medium.

Because of the adverse effect of LEO atomic oxygen observed on organic polymers, most commercially available silvered films, such as Silverlux (3M), are effectively ruled out unless an additional atomic oxygen protective coating is applied to the surface. Several thin film dielectric coatings, however, have been identified as suitable for protection of silver in an oxidizing environment. In general, the protective coating must be transparent to the solar wavelengths of interest in order that it not interfere with the reflected light. Dielectric materials, such as silicon dioxide, magnesium fluoride, and aluminum oxide, have been found to offer adequate protection to silver (Refs. 10 and 11). Typical reflectance data for several reflective metal/protective coating systems are shown in Fig. 4. In addition to environmental and performance suitability, there are a number of other factors to be considered in selecting a particular system of materials. Among these are cost, availability, ease of deposition, compatibility, and durability from damage that could be induced through normal handling and transport.

METHODS OF COATING PREPARATION AND CHARACTERIZATION

Deposition Techniques

A number of methods are available to deposit the various coatings onto the facet surfaces. Two techniques which have been extensively studied in relation to this application are ion-beam sputtering and electron-beam evaporation. The NASA Lewis Research Center has a long history in the study of ion thrusters for spacecraft propulsion and in the application of this technology to a variety of different uses (Ref. 12). Among these is the sputter deposition of target materials to prepare thin film coatings (Refs. 13 and 14). A major advantage of this technique is that, if the system is configured properly, the substrate surface can be cleaned in situ by ion beam sputtering prior to deposition, which greatly improves film-substrate adherence. The major drawback to the technique is that it is generally limited to relatively small substrates (a few inches square), unless a large beam and target are used, or the source and target are rastered over the surface of the substrate. It is not cost effective to build a large scale ion-beam deposition system for an application such as this since other techniques are available which can provide the required coatings on substrates of this size.

Evaporation techniques are available which can provide acceptable coatings over large surface areas. Electron-beam evaporation offers several advantages including rapid deposition rates, thickness uniformity, multiple depositions under a single pumpdown, low cost, and the ability to evaporate a wide variety of materials (including all the materials required for the concentrator facets). A deposition chamber, which makes use of an electron-beam evaporator, has been designed and outfitted (Fig. 5) to coat the facets with the required coatings to achieve the required reflectance and atomic oxygen durability.

Materials Compatibility

The preparation of a facet, which will successfully withstand an atomic oxygen environment, requires consideration of the interactions of the various required materials. The reflective system, as currently proposed, will be based on silver and will consist of four layers (Ref. 9) (Fig. 6). A layer of copper a few tens of Angstrom thick is first deposited onto the graphite-epoxy substrate. The purpose of the copper is to promote the adhesion of silver which is deposited onto the copper to a thickness of about 2000 Å. The final two layers, present for the purpose of protecting the silver, are aluminum oxide (about 300 Å) and silicon dioxide (about 700 Å).

There are several reasons for this choice of protective layers. Aluminum oxide adheres well to silver and provides an effective barrier to atomic oxygen. It is not, however, impervious to moisture, and since the reflective surface will have to withstand ground level atmospheric conditions prior to launch, it is desirable to place a second, moisture-resistant barrier over the Al_2O_3. The addition of a second layer also acts to cover any surface-defect induced pinholes in the first layer. Defects such as these are sites for oxidation of the silver layer, and it has been observed that oxidative damage at such sites can spread to cover an area many times larger than that of the pinhole itself (Refs. 15 and 16). This is due to the fact that the graphite-epoxy substrate is highly susceptible to oxidation, and it thus can also be oxidized through the pinhole (Fig. 7).

In summary, the series of four coatings (SiO_2, Al_2O_3, Ag, and Cu) are easily applied, adherent, transparent, inexpensive, and readily available.

The combined multilayer coating is hard, resistant to atomic oxygen, and reasonably resistant to damage that might occur from ordinary handling during transport and deployment. Of course, given a sufficiently energetic impact, damage sufficient to pierce the protective coating can occur. The likelihood of damage due to handling and deployment must be kept to a minimum.

OTHER CONSIDERATIONS

This article has been primarily concerned with the preparation of a solar concentrator reflective surface capable of both meeting the required degree of reflectance and surviving in the low-earth-orbit environment. There are other factors to be considered in the successful deployment of a solar concentrator. As mentioned earlier, other hazards exist such as ultraviolet radiation, thermal cycling, and micrometeoroid/debris impact. Investigation of the durability of these mirrors to hazards such as these is ongoing at NASA Lewis.

It is also important to realize that this protective coating system only protects the front side of the facets. The back side and edges, as well as much of the rest of the Space Station structure, will be fabricated from graphite-expoxy composite and will need protection from atomic oxygen. This subject is beyond the scope of this article, but it must be remembered that the problem of low-earth-orbit durability exists for other parts of the concentrator and Space Station as well.

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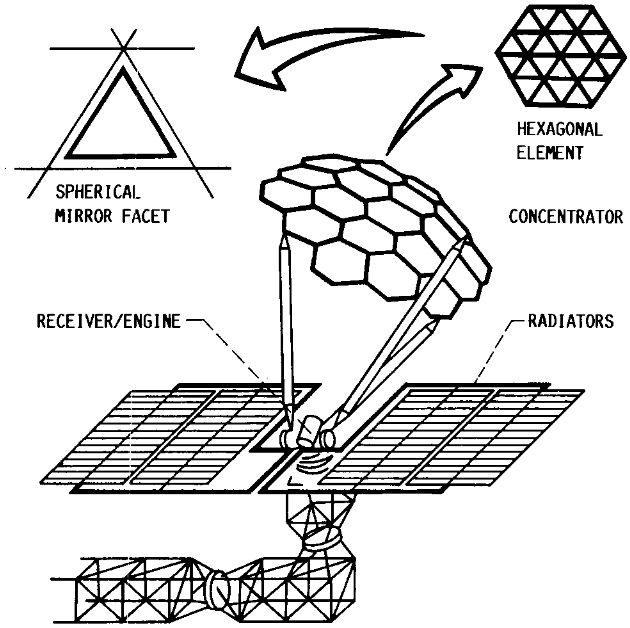

FIGURE 1. - SCHEMATIC DIAGRAM OF A SOLAR DYNAMIC POWER MODULE WHICH INCLUDES A CONCENTRATOR MADE UP OF HEXAGONAL ELEMENTS, EACH OF WHICH IS COMPRISED OF SPHERICALLY CONTOURED TRIANGULAR FACETS. ALSO SHOWN ARE THE RECEIVER/HEAT ENGINE AND RADIATOR.

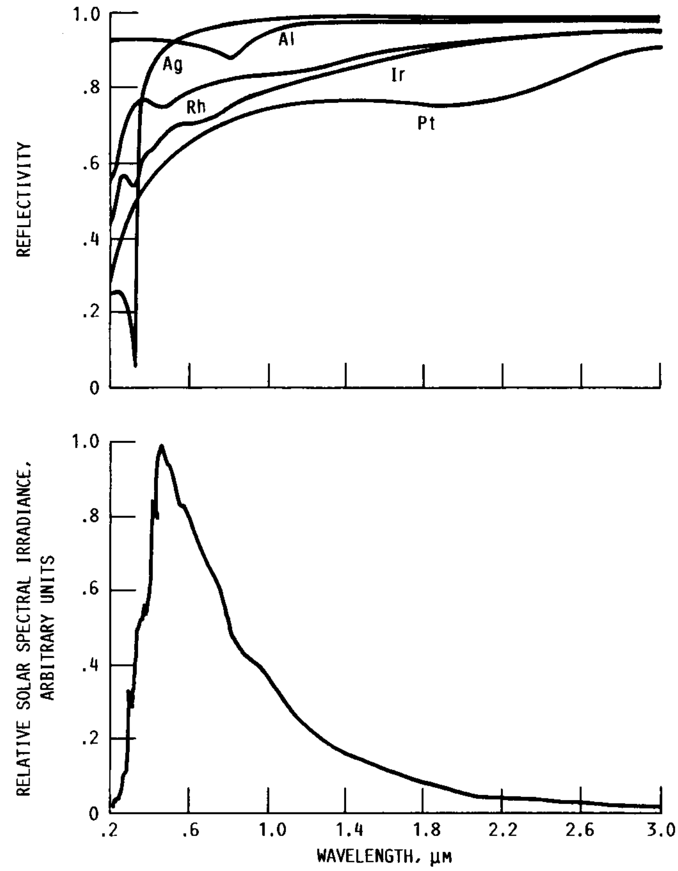

FIGURE 2. - REFLECTANCE VERSUS WAVELENGTH FOR SEVERAL METALS (TOP), AND RELATIVE SOLAR SPECTRAL IRRADIANCE VERSUS WAVELENGHT AT AIR-MASS-ZERO (BOTTOM).

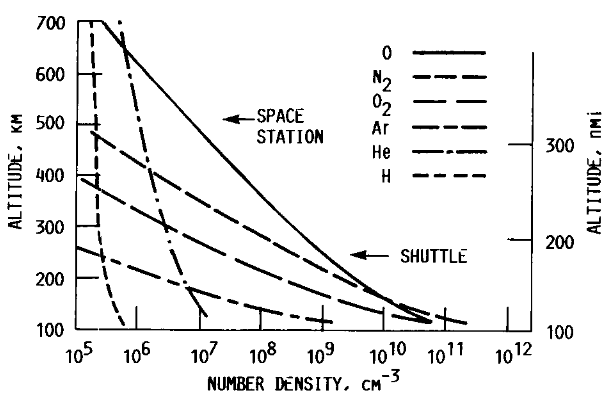

FIGURE 3.- ATMOSPHERIC COMPOSITION AS A FUNCTION OF ALTITUDE. THE TYPICAL SHUTTLE ORBIT AND PROPOSED SPACE STATION ORBIT ARE SHOWN.

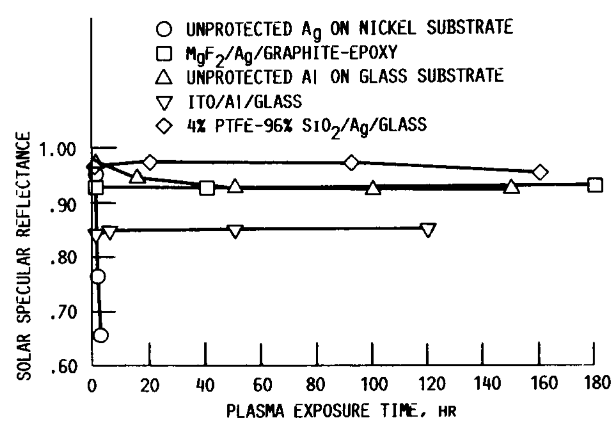

FIGURE 4. - INTEGRATED SOLAR SPECULAR REFLECTANCE AS A FUNCTION OF OXYGEN PLASMA EXPOSURE TIME FOR SEVERAL REFLECTOR SYSTEMS.

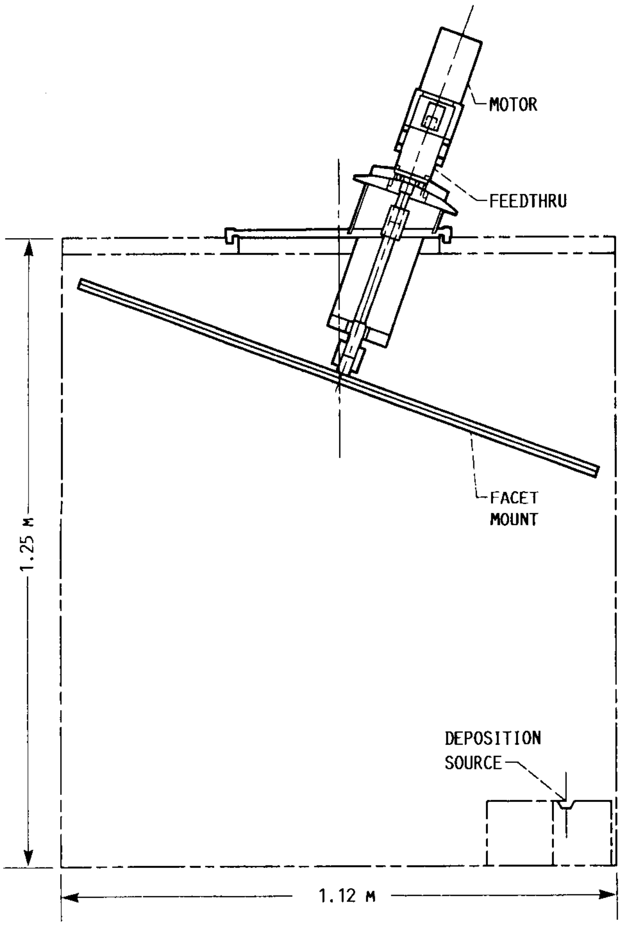

FIGURE 5. - SCHEMATIC REPRESENTATION OF THE FACET COATING CHAMBER. THE FACET IS ATTACHED TO THE FACET MOUNT, WHICH IS ROTATED WHILE HELD AT A 21° ANGLE BY AN OFFSET, MOTOR-DRIVEN FEEDTHRU MOUNTED IN THE TOP OF THE CHAMBER. MATERIAL IS EVAPORATED AT AN ELECTRON-BEAM SOURCE LOCATED IN THE BOTTOM OF THE CHAMBER AT ONE SIDE.

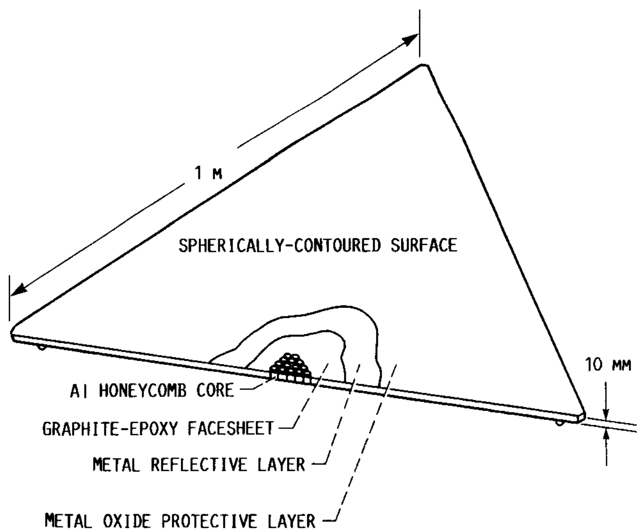

FIGURE 6. - SCHEMATIC REPRESENTATION OF THE MULTILAYER SYSTEM WHICH COMPRISES THE FACET. IN THIS PARTICULAR CASE, THE METAL REFLECTIVE LAYER (SILVER) IS DEPOSITED ONTO A LAYER OF Cu (NOT SHOWN) THE METAL OXIDE PROTECTIVE LAYER CONSISTS OF A LAYER OF Al_2O_3 FOLLOWED BY A LAYER OF SiO_2.

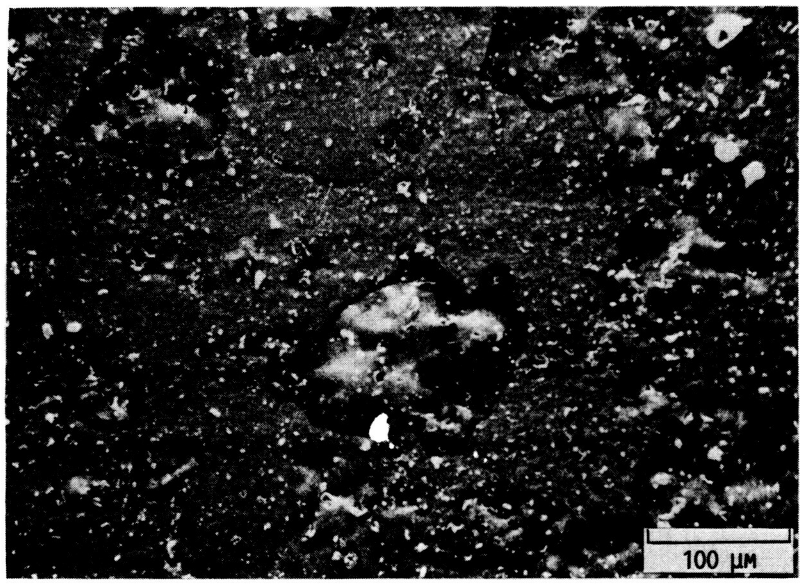

FIGURE 7. - SCANNING ELECTRON MICROGRAPH OF A MIRROR SURFACE WITH PINHOLE DEFECTS AFTER 240 HOURS OF OXYGEN PLASMA EXPOSURE. THE MIRROR CONSISTED OF: GRAPHITE-EPOXY SUBSTRATE/AG(1000Å)/ AL_2O_3(700Å)/SIO_2(2200Å). THE DARK PATCHES ARE OXIDATIVE UNDERCUTTING THROUGH THE DEFECT SITES (SMALL HOLE ROUGHLY IN THE CENTER OF EACH PATCH).

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15. Supplementary Notes

16. Abstract

The Space Station will represent the first time that a solar dynamic power system will be used to generate electrical power in space. In a system such as this, sunlight is collected and focused by a solar concentrator onto the receiver of a heat engine which converts the energy into electricity. The concentrator must be capable of collecting and focusing as much of the incident sunlight as possible, and it must also withstand the atomic oxygen bombardment which occurs in low-earth-orbit (LEO). This has led to the development of a system of thin film coatings applied to the concentrator facet surface in a chamber designed especially for this purpose. The system of thin film coatings employed gives both the necessary degree of reflectance and the required protection from the LEO atomic oxygen environment.

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