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Thin Film Coatings for Space Electrical Power System Applications

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SPACE ELECTRICAL POWER SYSTEM APPLICATIONS
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THIN FILM COATINGS FOR SPACE ELECTRICAL POWER SYSTEM APPLICATIONS

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SUMMARY

This paper examines some of the ways in which thin film coatings can play a role in aerospace applications. Space systems discussed include photovoltaic and solar dynamic electric power generation systems, including applications in environmental protection, thermal energy storage, and radiator emittance enhancement. Potential applications of diamondlike films to both atmospheric and space based systems are examined. Also, potential uses of thin films of the recently discovered high temperature superconductive materials are discussed.

INTRODUCTION

Thin film coatings play a significant role in space station and other space system applications. Thin films can be used to change substrate physical properties, to protect substrates against damage from natural or man-made environmental hazards, and as electronic materials in device applications. This paper will summarize some of the potential uses of thin films in spacecraft electrical power systems.

SOLAR ELECTRIC POWER GENERATION

Electric power generation on space station is ultimately envisioned to be accomplished by two means. The initial operating configuration calls for four 18.75 kW photovoltaic modules providing a total of 75 kW of electricity (fig. 1, ref. 1). These will generate power by use of traditional silicon solar cells. Subsequently, two solar dynamic power modules (25 kW each) will be added (fig. 2), and these will generate electricity by focusing the sun's energy onto the receivers of Rankine cycle heat engines. In both cases, thin film coatings are used to enhance system performance and/or protect against environmental degradation.

Photovoltaic Power System Applications

On the photovoltaic power modules, silicon solar cells will be mounted to a blanket made of DuPont Kapton polyimide (ref. 1). This material finds extensive use in space applications because of its good thermal, optical, and mechanical properties. Flexibility is also needed because the array blankets are folded and stored in a canister for launch and retrieval (fig. 3). Once

on orbit, the arrays are unfolded from the canister. One option under consideration to protect against environmental oxidation is the application of thin films of silicon dioxide. Thin films of SiO_2 have adequate flexibility for most portions of the array blanket. Increased flexibility is needed only at the hinge areas. The addition of a small amount (≈ 8 percent) of fluoropolymer (e.g., PTFE Teflon) to the SiO_2 can be used to give the coating additional flexibility while maintaining oxidation protection (figs. 4 and 5) (refs. 3 and 4). This coating is generally applied by ion beam cosputtering, where a small wedge of PTFE Teflon is placed in front of the SiO_2 target during deposition (fig. 6). The size of the wedge determines the percentage of fluoropolymer incorporated in the coating. The Teflon is not actually chemically bonded to the SiO_2 , but rather is uniformly mixed into the film. Both SiO_2 and 8 percent PTFE- SiO_2 thin film coatings on Kapton are under evaluation for array blanket protection.

Solar Dynamic Power System Applications

Solar dynamic power systems generate electricity by reflection (or refraction) and concentration of sunlight into a cavity containing a thermal energy storage material acting as the receiver of a heat engine (ref. 5). The storage material drives the heat engine during earth eclipse, and is typically a salt such as lithium fluoride. Waste heat is rejected to space with a radiator system. Thin film coatings are used extensively in the concentrator (mirror) portion of the system, and they have potential use in the receiver portion as well.

Concentrator. - Silver has the highest reflectance of any metal, and hence it is the desired material for use as the reflective medium on the concentrator. Silver is, however, highly susceptible to oxidation by low earth orbit atomic oxygen, and thus a protective coating is required if silver is to be used (refs. 6 to 8). The concentrator substrate material is graphite-epoxy composite, which is low in cost, light weight, and mechanically stiff. A four-layer coating system has been developed (ref. 9) which both protects the silver from oxidation and preserves its desirable reflectance properties (fig. 7). The layers from the substrate up consist of copper (≈ 25 Å thick), silver (2000 Å), aluminum oxide (300 Å), and finally silicon dioxide (700 Å). The copper promotes adhesion of the silver to the graphite-epoxy. The combined oxides provide protection against both moisture and atomic oxygen and minimize the number of coating defects which might extend completely through from the outer surface of the SiO_2 to the $\text{Al}_2\text{O}_3/\text{Ag}$ interface.

The concentrator surface is comprised of triangular facets one meter on a side. Twenty-four of these are assembled into each of 19 hexagonal elements which then comprise one concentrator (fig. 8) (ref. 10). Since two concentrators are to be used on space station, a total of 912 (= 24 by 19 by 2) facets are needed. An industrial coating facility has been designed and built to accomplish the task of applying these coatings to the facets (fig. 9). The films are deposited by electron-beam evaporation from a four-pocket electron-beam gun. Thus, all four layers can be deposited during one pumpdown, which results in both purer films and reduced coating time and cost. The facet is attached to a mount which holds it at the required angle and rotates it during deposition to achieve the required uniformity.

Heat engine. - As stated above, the heat engine receiver cavity contains a thermal energy storage (TES) material (ref. 11). This material is melted during that portion of the orbit when the space station is exposed to the sun. During periods of solar eclipse, the TES material is cooled, and the latent heat extracted is used to power the heat engine. The TES material should have a high thermal conductivity to maximize the rate of melting and freezing. Typical TES materials under consideration are fluoride salts such as LiF and NaF as well as metals such as gallium. Metals generally have high thermal conductivities, but low latent heats. Conversely, salts have higher latent heats, but low thermal conductivities. A possible technique for increasing the thermal conductivity is to mix into the salt graphite fibers, which are high in thermal conductivity (ref. 11). To obtain the highest heat transfer rate from this technique, the molten salt must wet the fibers, and here is where a thin film coating can possibly play a role. Several materials have been identified which, when applied to the fibers, improve fiber wettability by the molten salt. These materials include oxides, such as Al_2O_3 and MoO_3 , and metals such as platinum and aluminum. Problems, such as obtaining good adhesion of the film to the fiber, exist in the use of thin films for this purpose, but the work is ongoing.

HIGH TEMPERATURE SPACE RADIATORS

Advanced power generation systems for use on unmanned spacecraft to the outer planets, manned missions to Mars, and Earth orbit missions requiring large amounts of power will undoubtedly make significant use of nuclear power generation systems. An ambitious effort, called SP-100 (for Space Power-100), is currently underway through a joint effort between NASA, the Department of Energy, and the Air Force to develop space nuclear power generation systems (fig. 10). Due to the high temperatures at which such power systems operate, special radiators are required to eject waste heat safely and efficiently (ref. 12).

The operating temperature of thermo-electric power system radiators will be in the range of 700 to 900 K, which requires the use of special materials in the radiator construction. Several materials have been under consideration, and these include copper, beryllium, carbon-carbon composites, 304 stainless steel, a titanium alloy containing 6 percent aluminum and 4 percent vanadium (referred to as Ti-6 percent Al-4 percent V), and a niobium alloy containing 1 percent zirconium (referred to as Nb-1 percent Zr). Efficient rejection of waste heat requires that the radiator surface be modified to emit efficiently at these temperatures. In addition, for any applications of the system in low earth orbit, atomic oxygen durability is required.

There are three ways to approach the problem of obtaining both high thermal emittance and atomic oxygen durability. These are texturing, or physical modification of the metal surface (ref. 13), etching, or chemical modification of the surface (ref. 12), and the application of thin film coatings. Only surface modification has been performed at NASA Lewis to date. A variety of treatments, including acid etching, arc, seed, and discharge chamber texturing, abrasion, heating, electrochemical treatment, and various combinations of these have been tried. An example of the surface morphology that can be obtained is shown in figure 11. The best emittance enhancement results obtained to date are summarized in table I. These measurements were made at room temperature at a wavelength of 2.5μ , which corresponds to a temperature of 1159 K. It is interesting to note that in some instances, exposure to an

atomic oxygen environment actually improved the emittance, which was most likely due to the formation of an oxide layer.

DIAMONDLIKE CARBON FILMS

Preparation and Properties

Carbon films have potential applications in several space systems. Such films have been prepared by many techniques, including ion beam sputtering from a carbon target (ref. 14), rf plasma decomposition of methane gas (refs. 15 to 18), and direct carbon ion beam deposition using argon and hydrocarbon scission fragments (refs. 19 to 22).

What distinguishes "diamond" films from "diamondlike" films is that diamond films are crystalline and contain little or no hydrogen, while diamondlike carbon (DLC) films are amorphous and contain up to 50 percent hydrogen, only 4 percent of which is actually bonded to the carbon. The remainder is interstitially trapped and does not diffuse out of the film over time.

DLC films are characterized by high electrical resistivity, hardness, high index of refraction, high optical absorption, and a density intermediate between that of the starting material and that of diamond. Table II summarizes some of the properties of carbon films prepared by various techniques. Of course, the properties obtained are strongly dependent on the operating parameters during deposition, as described in the original reference.

Applications

Hard coatings. - The hardness of carbon films suggests their use in applications where protection from particle erosion is necessary. For example, zinc sulfide and zinc selenide are materials with good transmittance in the infrared. As such, they find wide use as IR transmitting windows for satellite surveillance applications. These materials are soft, and hence susceptible to erosion from rain and atmospheric particulates (dust, sand). DLC films have been deposited on these materials by dual beam techniques and have successfully protected them from particulate and rain erosion (fig. 12) (refs. 23 to 25). The studies revealed that adhesion of the DL films to ZnS and ZnSe was poor, and it was found that by depositing a layer (500 Å) of germanium (by ion beam sputtering from a Ge target) prior to the application of the DL film, adherence could be greatly improved. The effect of the Ge layer on transmittance was very small, being a maximum of 8 percent at 2.5 μm and decreasing to 1 percent at 10 μm.

IGFET Gate Insulator. - The feasibility of using a DL film as a gate dielectric for very high speed (1 to 10 GHz) integrated circuits has been investigated (ref. 26). DLC films were deposited on InP, GaAs, and Si substrates, and then ohmic contacts were applied to create metal-insulator-semiconductor (MIS) configurations.

Fixed insulator charge density and interface state density, important parameters whose values must be precisely controlled, were measured as a function of energy of the ion beam. In all instances, higher beam energies

resulted in higher fixed insulator charge and interface state density (figs. 13 and 14). The results as a whole indicated that ion beam-deposited DLC films are probably not a good material for this application.

HIGH TEMPERATURE SUPERCONDUCTIVITY

The Lewis Research Center is investigating the feasibility of preparing some of the recently discovered high temperature superconductor materials in thin film form. In particular, thin films of $Ba_2YCu_3O_{7-x}$ have been laid down stoichiometrically by ion beam sputtering from a target of the same superconducting material (ref. 27). Such ion beam sputter deposited films have very low intrinsic stresses, thus allowing the films to be deposited to thicknesses an order of magnitude larger than other typical high stress films. An example x-ray diffraction pattern obtained for such a film deposited on a $SrTiO_3$ substrate is shown in figure 15. To date, the films have not been found to be superconducting. The problem is thought to lie in the annealing portion of the preparation process, but at this time the data are preliminary, and the work is ongoing.

The ease with which relatively low temperatures can be obtained in space (in many instances, 77 K is "room temperature") suggests that high temperature superconductors may be particularly well-suited for use in this environment. Several applications of thin film superconductors to space electrical power distribution have been proposed, and these include transformers, capacitors, and simple current-carrying media (wires or circuit interconnects) (ref. 28). Before any of these are realized, however, the goal of successfully and reproducibly depositing thin films which exhibit high temperature superconductivity must be attained.

CONCLUDING REMARKS

There are several areas in which thin films can or will play a role in aerospace components or systems. Thin films are used because of their mechanical properties to offer protection against the corrosive effects of the aerospace environment, because of their physical and chemical properties to enhance or modify the properties of the substrate, and because of their electrical properties as conductors or insulators. Thin films can be prepared in a variety of ways, depending on the material to be deposited, the size and shape of the substrate, and the properties desired in the particular thin film. Many new applications of thin films in space power applications will undoubtedly be forthcoming.

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TABLE I. - SUMMARY OF EMITTANCE ENHANCEMENT RESULTS^a

Material	Emittance before texturing	Emittance after texturing	Emittance after texturing and ashing	Surface treatment
304 Stainless steel	0.47±0.02	0.93±0.02	0.93±0.02 (ashed ≈72 hr)	HCl etching then furnace heating
Copper	.28±.02	.88±.02	.92±.02 (ashed ≈72 hr)	Discharge chamber sputter etching
Ti-6%Al-4%V	.52±.02	.83±.02	.81±.02 (ashed ≈160 hr)	Sand blasting, then furnace heating
Nb-1%Zr	.46±.02	.91±.02	.79±.02 (ashed ≈24 hr)	Arc texturing (in Ar + N ₂)

^aAll emittance measurements taken at 2.5 μm, which corresponds to 1159 K.

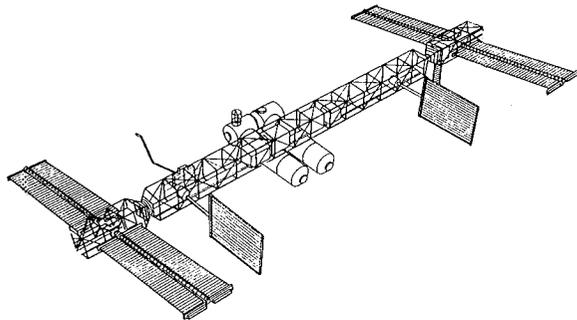
TABLE II. - COMPOSITION OF SEVERAL OF THE PROPERTIES OF DIAMONDLIKE CARBON FILMS
PREPARED BY ION BEAM SPUTTERING, DUAL ION BEAM, AND RF DISCHARGE TECHNIQUES.

Parameter/ property	Deposition technique			For comparison		
	Ion beam sputtering ^a	Dual beam ^b		RF discharge ^c	Graphite	Diamond
		CH ₄ /Ar	CH ₄ /Ar + Ar			
Beam energy, eV	1000	100 to 250	200 to 600	-----	-----	-----
Beam current density, mA/cm ²	1 to 2	0.001	0.025	-----	-----	-----
Deposition rate, Å/min	≈16	≤70	≤70	≈50	-----	-----
Resistivity, Ω·cm	>10 ¹¹	8.7×10 ⁶	3.4×10 ⁶	-----	0.017	≈10 ¹⁴
Density, gm/cm ³	2.1 to 2.2	-----	-----	1.7 to 1.8	1.9 to 2.3	3.2 to 3.5
Absorption coefficient, cm ⁻¹	6.7×10 ⁴ (at 555 nm)	5.2×10 ⁴ (at 500 nm)	4.3×10 ⁴ (at 500 nm)	-----	-----	-----
Index of refraction	-----	2.0	2.46	-----	2.04	2.42
Optical band gap, eV	-----	0.382	0.343	-----	5.0	-----

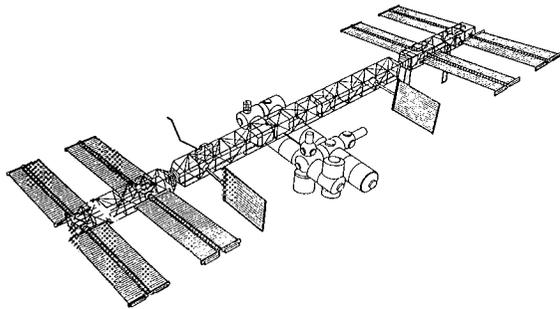
^aRef. 14

^bRef. 19

^cRef. 29

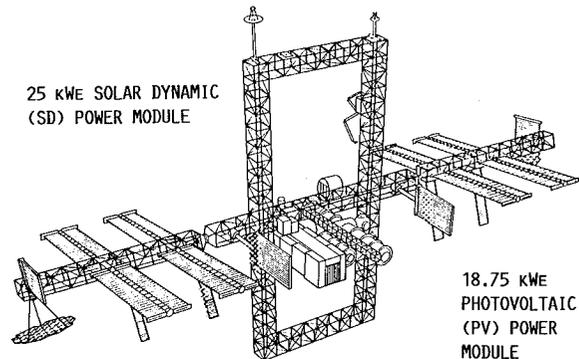


37.5 kWe PV EPS (INITIAL DEPLOYMENT)



75 kWe EPS (INITIAL OPERATING CONFIGURATION) - PHASE I
DEPLOYMENT COMPLETED

FIGURE 1. - DEPLOYMENT SEQUENCE OF THE FOUR 18.75 kW PHOTOVOLTIC POWER MODULES (75 kW TOTAL POWER OUTPUT) WHICH COMPRISE THE INITIAL OPERATING CONFIGURATION OF THE SPACE STATION ELECTRICAL POWER SYSTEM.



25 kWe SOLAR DYNAMIC
(SD) POWER MODULE

18.75 kWe
PHOTOVOLTIC
(PV) POWER
MODULE

FIGURE 2. - FINAL CONFIGURATION OF THE SPACE STATION ELECTRICAL POWER SYSTEM INCLUDES FOUR 18.75 kW PHOTOVOLTIC POWER MODULES AND TWO 25 kW SOLAR DYNAMIC POWER MODULES.

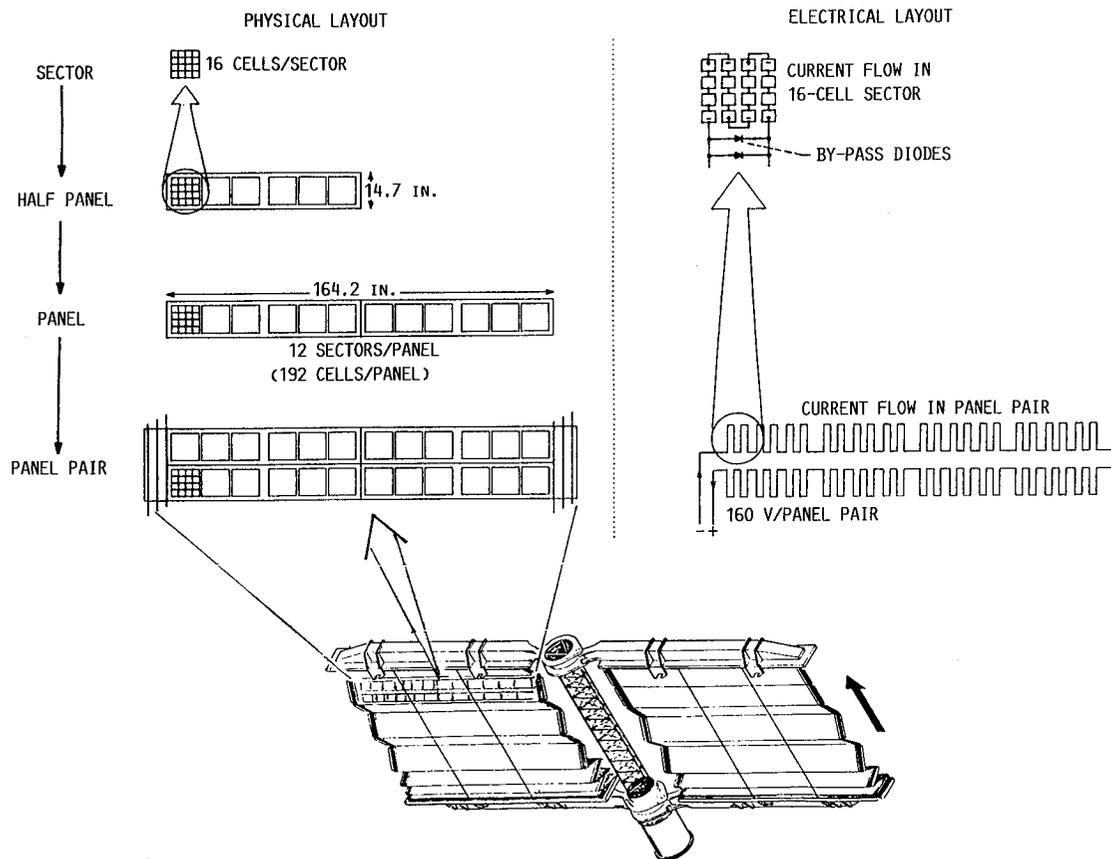


FIGURE 3. - SOLAR ARRAY ASSEMBLY MAST AND CANISTER.

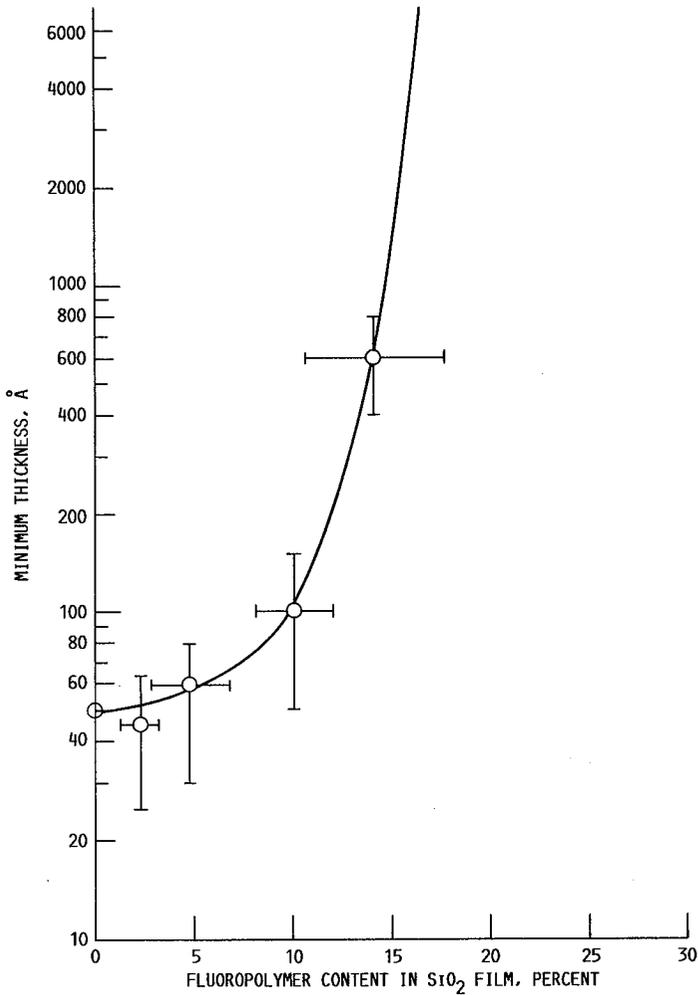


FIGURE 4. - MINIMUM FILM THICKNESS FOR PERMANENT OXIDATION PROTECTION OF A DIAMOND-LIKE CARBON FILM USING A MIXED FLUOROPOLYMER/SiO₂ FILM.

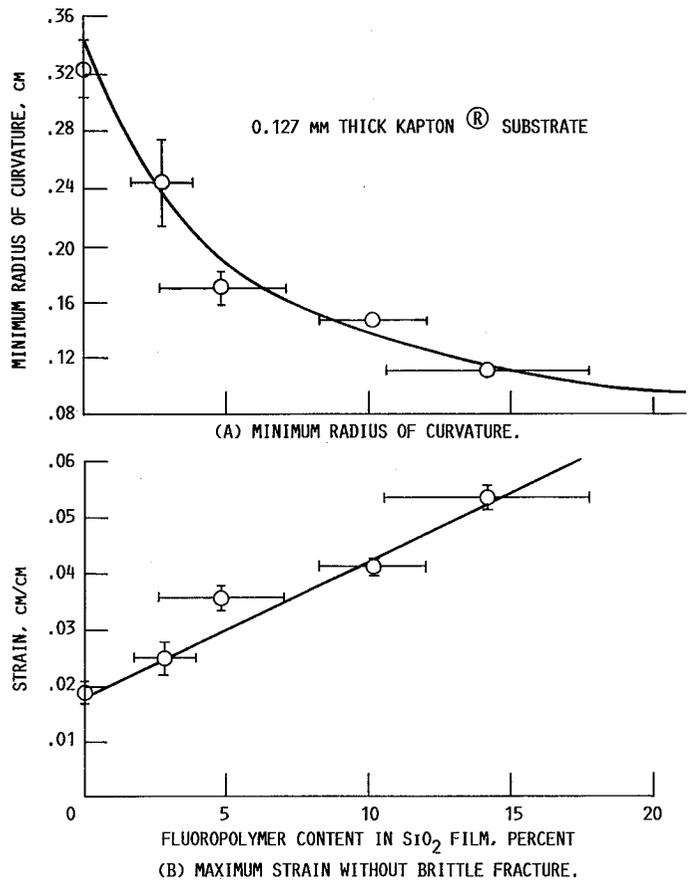


FIGURE 5. - MINIMUM RADIUS OF CURVATURE AND MAXIMUM STRAIN THAT A CO-DEPOSITED SiO₂-FLUOROPOLYMER FILM (1000 Å THICK) CAN SURVIVE WITHOUT BRITTLE FAILURE.

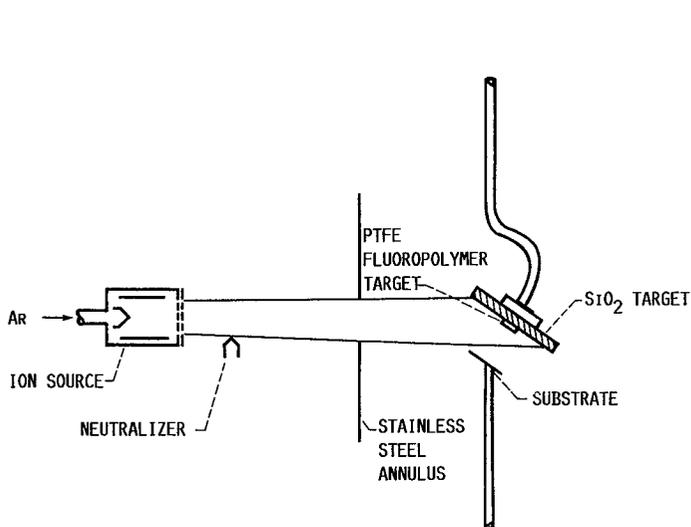


FIGURE 6. - ION BEAM SPUTTERING SYSTEM FOR PREPARATION OF SiO_2 -FLUOROPOLYMER PROTECTIVE FILMS FOR LABORATORY EVALUATION.

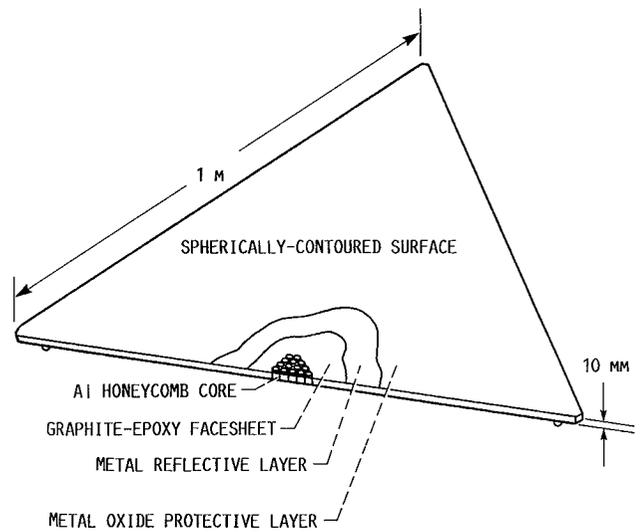


FIGURE 7. - SCHEMATIC REPRESENTATION OF THE MULTI-LAYER SYSTEM WHICH COMPRISES A CONCENTRATOR FACET. IN THIS PARTICULAR CASE, THE METAL REFLECTIVE LAYER (SILVER) IS DEPOSITED ONTO A LAYER OF COPPER (NOT SHOWN). THE METAL OXIDE PROTECTIVE LAYER CONSISTS OF A LAYER OF Al_2O_3 FOLLOWED BY A LAYER OF SiO_2 .

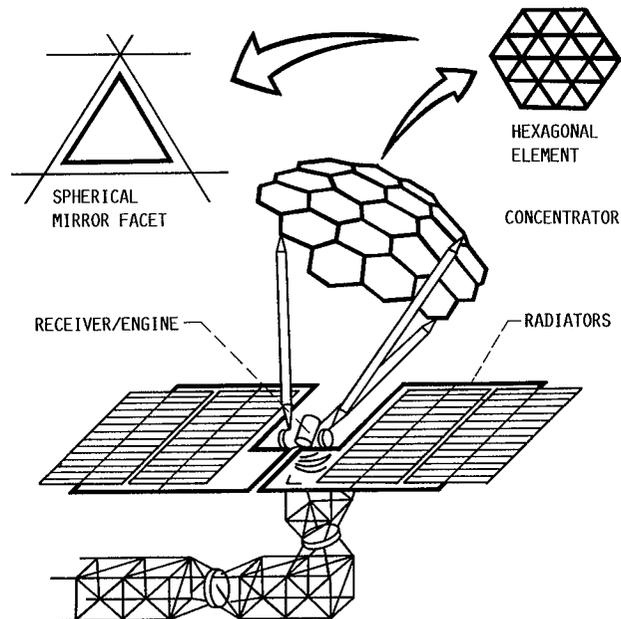


FIGURE 8. - SCHEMATIC DIAGRAM OF A SOLAR DYNAMIC POWER MODULE WHICH INCLUDES A CONCENTRATOR MADE UP OF HEXAGONAL ELEMENTS, EACH OF WHICH IS COMPRISED OF SPHERICALLY CONTOURED TRIANGULAR FACETS. ALSO SHOWN ARE THE RECEIVER/HEAT ENGINE AND RADIATOR.

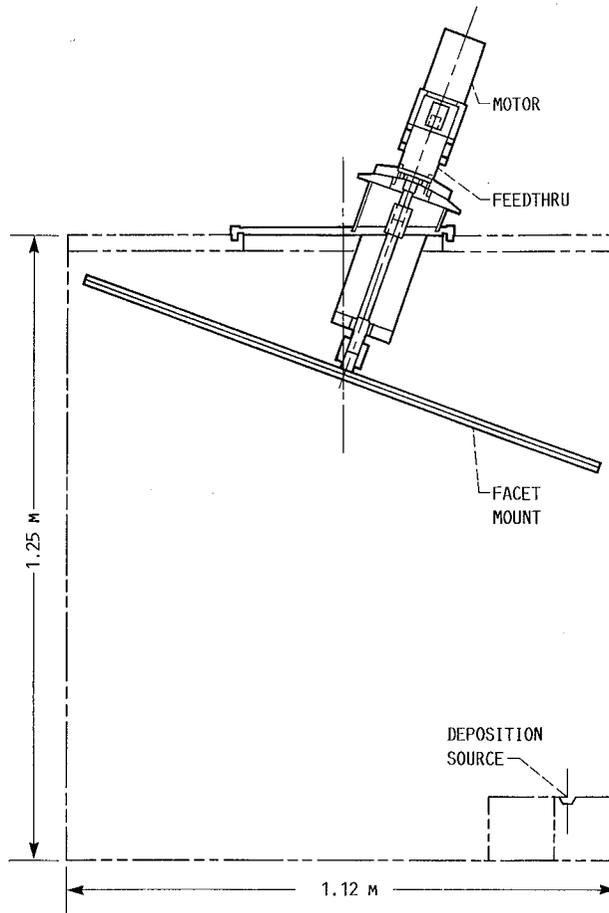


FIGURE 9. - SCHEMATIC REPRESENTATION OF THE FACET COATING VACUUM CHAMBER. THE FACET IS ATTACHED TO THE FACET MOUNT, WHICH IS ROTATED WHILE HELD AT A 20° ANGLE BY AN OFFSET, MOTOR-DRIVEN FEED-THRU MOUNTED IN THE TOP OF THE CHAMBER. MATERIAL IS EVAPORATED AT AN ELECTRON-BEAM SOURCE LOCATED IN THE BOTTOM OF THE CHAMBER AT ONE SIDE.

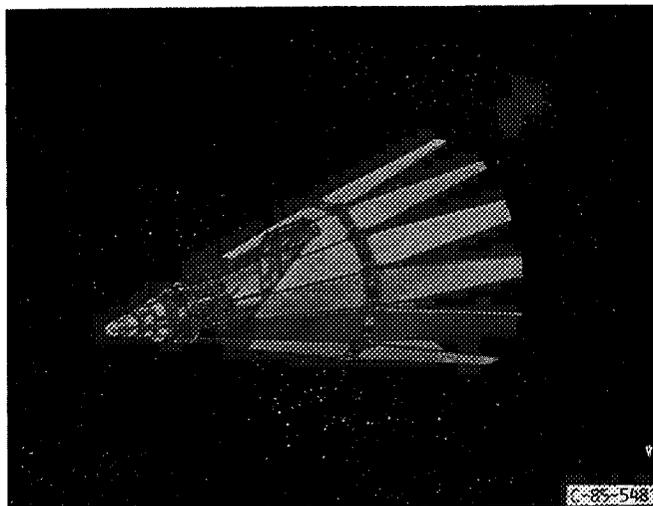
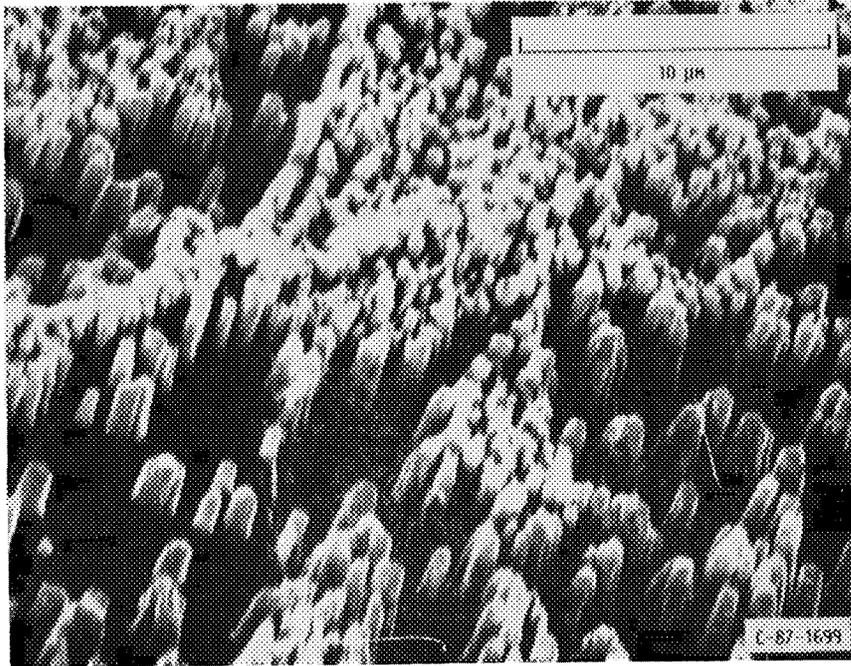
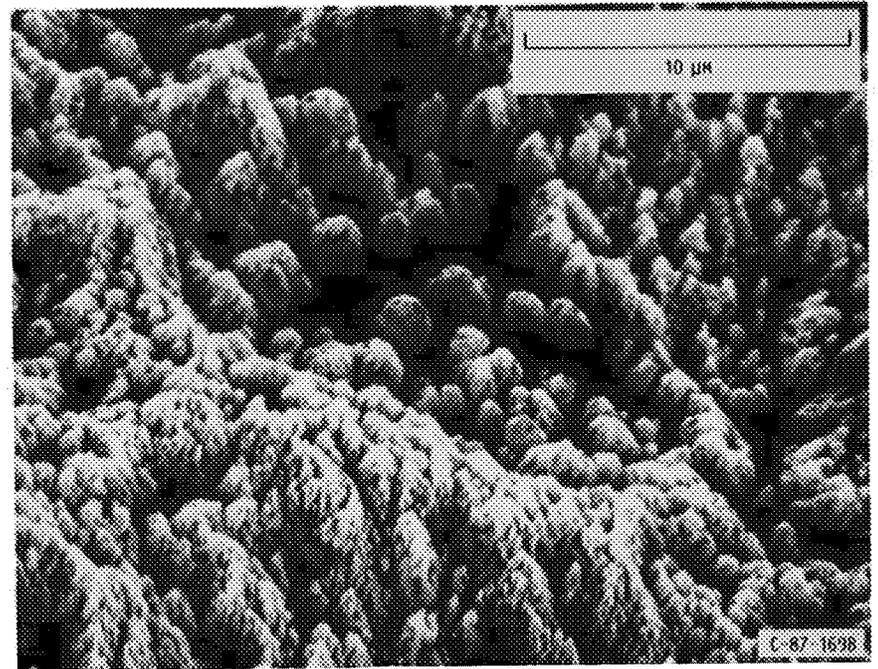


FIGURE 10. - SP-100 POWER SYSTEM.

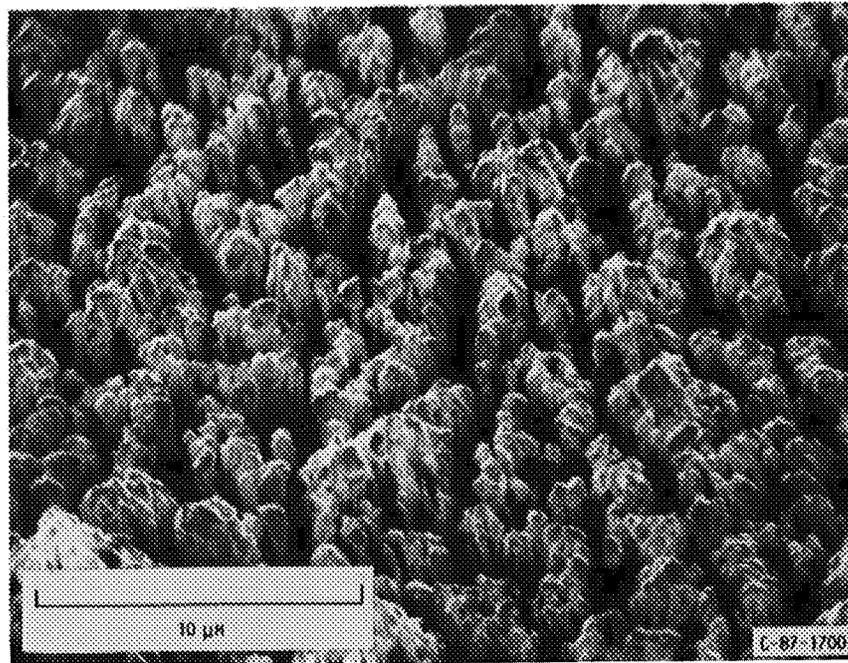
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(A) Cu 1/2 HR.



(B) Cu 1 HR.



(C) Cu 2 HR.

FIGURE 11. - DEVELOPMENT OF THE MORPHOLOGY OF A COPPER SPECIMEN EXPOSED FOR 0.5, 1, AND 2 HR TO 1500 eV ARGON IONS USING TANTALUM AS A SEED MATERIAL.

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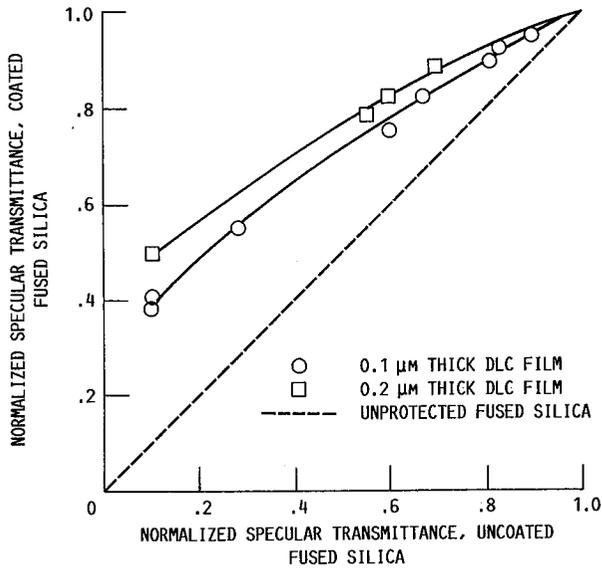


FIGURE 12. - NORMALIZED SPECULAR TRANSMITTANCE OF PROTECTED WITH 0.1 μm AND 0.2 μm THICK DIAMOND-LIKE CARBON FILMS VERSUS NORMALIZED SPECULAR TRANSMITTANCE OF UNCOATED FUSED SILICA AFTER BOTH TYPES OF SAMPLES WERE EXPOSED TO 100 μm SILICA PARTICLES ACCELERATED TO 27 M/SEC. THE DLC FILMS WERE PREPARED USING A SINGLE ION BEAM SOURCE OPERATED WITH METHANE. POINTS FALLING ABOVE THE DOTTED LINE INDICATE THAT THE DLC FILM PROTECTED THE FUSED SILICA SUBSTRATE.

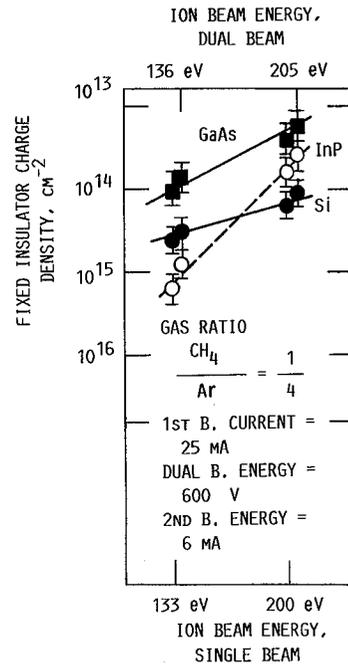


FIGURE 13. - VARIATION OF THE FIXED INSULATOR CHARGE NUMBER DENSITY AS A FUNCTION OF ION BEAM ENERGY OF THE DEPOSITION SOURCE FOR METAL-INSULATOR-SEMI-CONDUCTOR STRUCTURES ON GaAs, InP, AND Si SUBSTRATES.

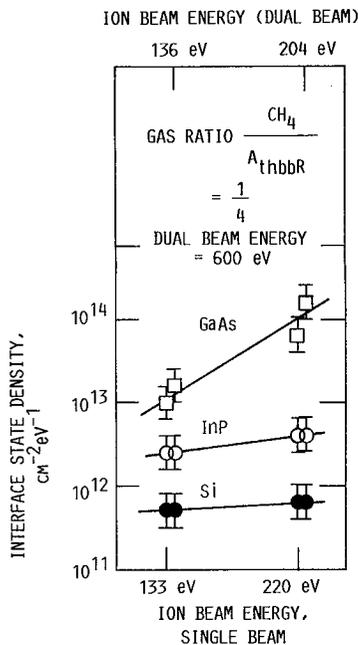


FIGURE 14. - VARIATION OF THE INTERFACE STATE DENSITY AS A FUNCTION OF ION BEAM ENERGY OF THE DEPOSITION SOURCE FOR METAL-INSULATOR-SEMI-CONDUCTOR STRUCTURES ON GaAs, InP, AND Si SUBSTRATES.

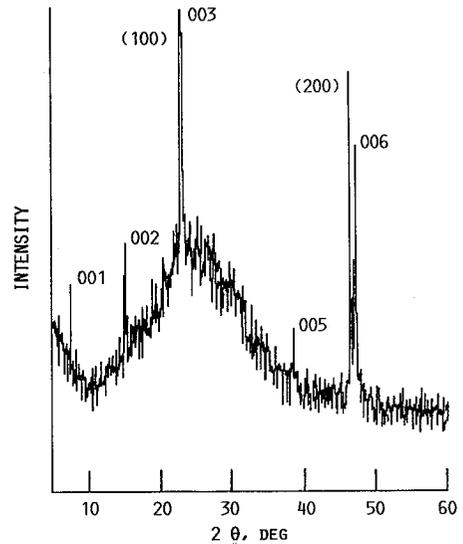


FIGURE 15. - X-RAY DIFFRACTION PATTERN OF $\text{Ba}_2\text{YCu}_3\text{O}_7$ THIN FILM ON STRONTIUM TITANATE SUBSTRATE. THE SPECTRUM INDICATES A HIGH DEGREE OF C-AXIS ALIGNMENT, SHOWING THAT THE FILM IS CRYSTALLINE.

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16. Abstract This paper examines some of the ways in which thin film coatings can play a role in aerospace applications. Space systems discussed include photovoltaic and solar dynamic electric power generation systems, including applications in environmental protection, thermal energy storage, and radiator emittance enhancement. Potential applications of diamondlike films to both atmospheric and space based systems are examined. Also, potential uses of thin films of the recently discovered high temperature superconductive materials are discussed.					
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