THE FUTURE DEVELOPMENT OF ENERGETIC THIN-FILM PROCESSES FOR SPACED BASED DEPOSITIONS

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ABSTRACT

NASA's Lunar-Mars proposal (January 14, 2004) plans to use the Moon as an outpost for future voyages to Mars and beyond. The ability to deposit high performance thin-film coatings in the vacuum of lunar-space will be extremely valuable for executing many aspects of this new mission. Space-based thin-film depositions will enable the future development of flexible large-area space antennae and fixed telescope mirrors for lunar-station observatories. Deployable solar-propulsion concentrator arrays, coated in space, will accelerate the feasibility of human flights to Mars. Energetic deposition processes will be required for the efficient use of space-based thin-film coating technology. Advances in Filtered Cathodic Arc (FCA) technology enables the design and development of a robust system that can be robotically operated for depositing uniform thin films on large area deployed flexible substrates. Metals, especially gold and silver, will play a significant role in the development of advanced large area space deployable optical mirrors. Energetic processes, such as FCA, have terrestrially produced high performance metal, diamond-like-carbon (DLC), and dielectric material coatings that are suitable for space applications.

KEY WORDS: Space/Spacecraft/Satellite; Coatings/Films; Processing/Fabrication Equipment

1. INTRODUCTION

Based on NASA's recent Lunar-Mars proposal (January 14, 2004), the Moon will be used as a temporary rest stop for voyages to Mars and beyond. This new government initiative revitalizes some of the earlier work that was done on "Lightweight Deployable Technologies" for space power and exploration. During the development of "Solar Thermal Propulsion" concepts the use of large-area deployable reflectors and concentrators were required (1). However, one crucial challenge in the development of this technology is the inherent difficulty associated with maintaining the mechanical stability of thin-film coatings after the device deploys from an acute folded state. If the thin-film coating is applied post deployment, then the performance of the film would not be compromised by the environmental insults of an earth launch, or the severe degrading stresses produced by unfolding a large flexible structure.

Returning to the Moon provides NASA with new opportunities and challenges. The author proposes that the ability to deposit high performance thin-film coatings in the vacuum of lunar-space will be extremely valuable in executing this new mission. One immediate requirement for developing space-based thin-film deposition technology is the apparent need for the inhabitants of a lunar station to be protected by a thermally controlled structure and window coatings.

Another exciting application for spaced-based thin-film deposition technology is the coating of large-area space telescope mirrors that could be installed on the dark side of the Moon. If the Hubble Telescope is indeed decommissioned, then an astronomical observatory on the surface of the Moon would be a tremendous asset. Once assembled, the large-area adaptive-optical reflectors can be coated with pure silver, for example, that will not be contaminated, nor degraded, as experienced with earth-based coating technology.

Energetic deposition processes will enable the efficient use of space-based thin-film coating technology. One of the most promising technologies for this application is Filtered Cathodic Arc Deposition (FCAD). More than a century ago Thomas Edison produced coatings using a vacuum arc in a "Process of Duplicating Phonograms" (2). Nevertheless, only in the last decade has arc technology penetrated commercial markets, particularly in the coating of machine tools with metal nitrides. Sanders *et al* published an excellent comprehensive review of the arc technology over decade ago (3). Arc Technology could play a vital role in the future production of high quality thin-films for space-based deposition applications.

Even though a small number of research institutes have investigated filtered cathodic arc deposition for several years, early research work concentrated on the unique material properties of thin-films deposited using this method. Historically, carbon has received most of the research attention while aluminum oxide (Al_2O_3) and other materials, like titanium nitride (TiN), have more recently undergone serious laboratory investigation. The earliest studies found that the Filtered Cathodic Arc Deposition (FCAD) thin-film properties were highly dependent on the ion energy (usually controlled by applying a substrate bias) (4). Additionally, it was found that these films were rendered less useful by the unacceptably high density of particles adhering to the deposited coating. These, so-called, "macro-particles" were generated simultaneously with the FCAD ions, and could not be removed completely by the early filtering system designs (5-6).

Filtering techniques were investigated and the resultant reduction in macro-particles enabled the deposition of coatings that could be used in a number of critical applications. The new filtering designs involved changing the angles of the duct bend, increasing the substrate-to-target distance, and improving the mechanical filters (7-8). One of the most notable recent commercial applications for the FCAD technology is the coating of Gillette razor blades with Diamond-Like-Carbon (DLC) (9).

2. TERRESTIAL PROCESS TECHNOLOGY

Before discussing the space deposition technology, the terrestrial version of the Filtered Cathodic Arc (FCA) system is presented in this section. In the space environment it is envisaged that the FCA technology will be employed without the incorporation of the Ion Assisted Deposition (IAD) technology. The first generation space applications will probably involve simple metal films; however, as the future need grows for more advanced space coatings incorporation of other energetic technology may be required.

2.1 Ion-Assisted Filtered Cathodic Arc Deposition (IFCAD) System

By coupling Ion-Assisted-Deposition (IAD) with FCAD a significant advancement in the deposition of optical thin-films is under development. It is now commonly understood that IAD substantially improves thin-film properties when compared to conventional Physical Vapor Deposition (PVD) (10-11).

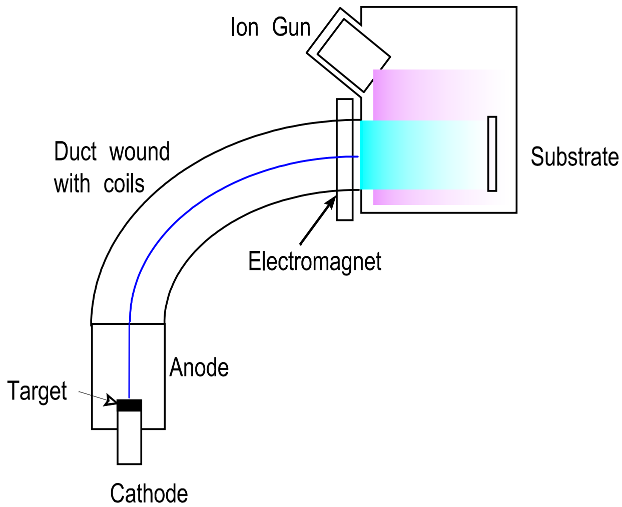


Figure 1: IFCAD System
The above figure schematically represents the terrestrial Ion-assisted Filtered Cathodic Arc Deposition (IFCAD) technology.

The "self-sustaining" arc, produced in the water-cooled cathode block by a conventional arc welding power-supply, vaporizes the target material generating high-energy ions, neutral atoms and particles. Gold (Au^+), Silver (Ag^+), Carbon (C^+), Aluminum (Al^{3+}), or other charged ions are ejected from a metal arc-target and magnetically steered out of the duct, while a mechanical "non-line-of-sight path" filter captures the undesired macro-particles and neutrals. As the ejected ions emerge from the duct, an oscillating electromagnetic field scans (or sweeps) the plasma-beam to provide a uniform deposition over the substrate area. Analogous to brush painting, the ion beam is swept side to side to uniformly coat the substrate. Simultaneously, a beam of gas ions, from an end-Hall ion source, impinges on the arriving arc-generated ions, resulting in dense, well-adhered, stable thin-films. Since the only heat generated by this process resides in the water-cooled cathode assembly (external to the chamber), the substrate remains close to room temperature during the thin-film deposition (12-13).

The Ion-Assisted Filtered Cathodic Arc Deposition (IFCAD) system consists of a cylindrical rotary deposition chamber, orientated horizontally, and two Filtered Cathodic Arc (FCA) sources. One FCA source is associated with an end-Hall gridless Ion-Assisted-Deposition (IAD) ion gun.

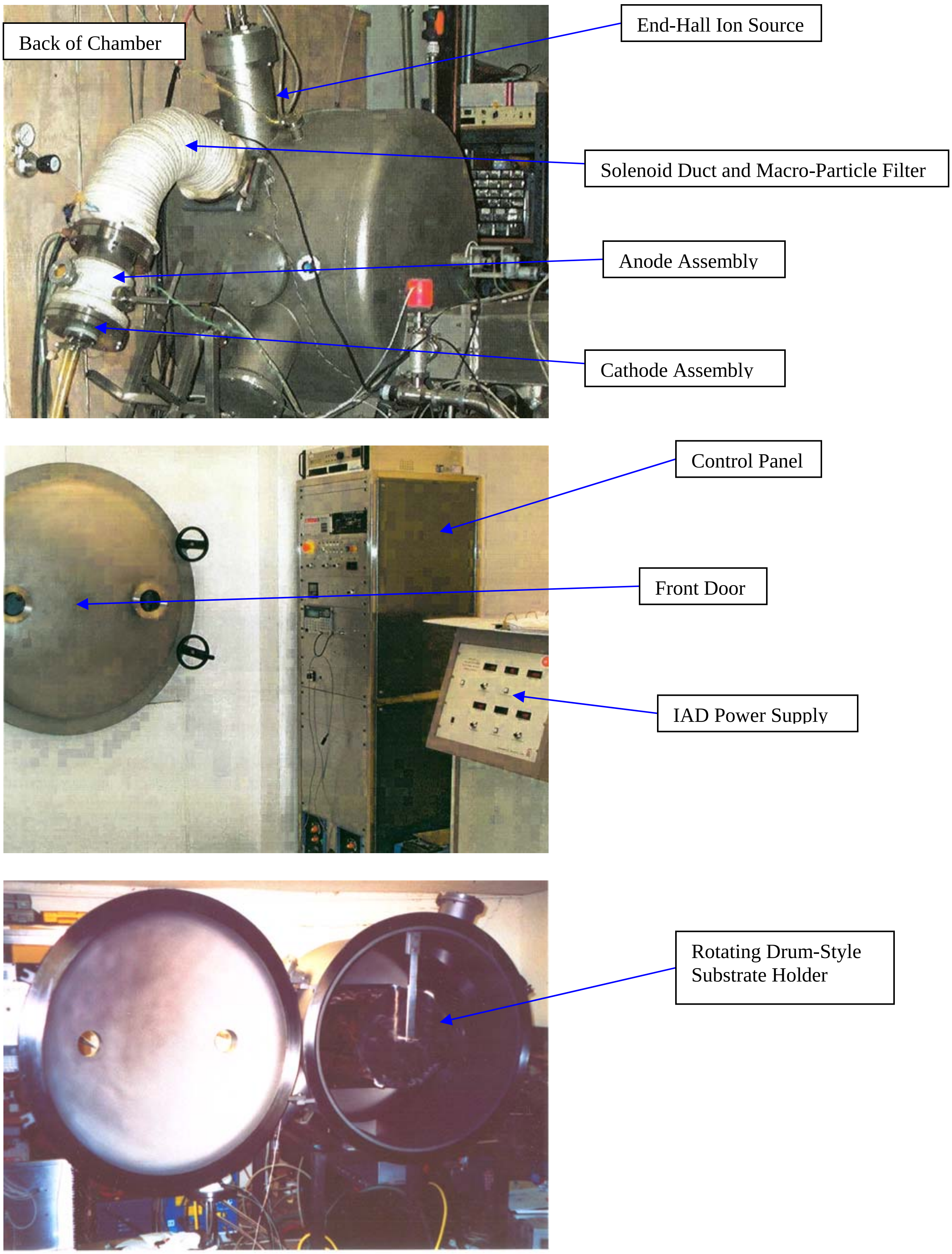


Figure 2: Photographs of Terrestrial IFCAD Chamber

2.2 Ion Assist Deposition (IAD) Technology

The gridless ion source that is incorporated into the FCA process emerged from the pioneering work during the 1960's of the Soviet Union and NASA in the development of ion thrusters for space propulsion, the Kaufman gridded ion generating source was adaptively designed for thin-film depositions (14-16). Early work with a modified gridded ion source proved that lower voltages and higher beam currents were most suitable for Ion Assisted Deposition (IAD) applications (17).

Therefore, an end-Hall ion source, described by Kaufman *et al*, was built for Optical Coating Laboratory Inc. (OCLI) (18). The author had the privilege of being the first engineer to put this source into a production application. Specifically, there was a dramatic need to increase the durability of deposited Zinc Sulfide (ZnS) layers. There are two primary crystal states for ZnS, Wurtzite (hexagonal) and Zinc Blende (cubic). In conventional Physical Vapor Deposition (PVD) substrate temperature is the first order effect for determining the durability of the ZnS layer. With the application of this first end-Hall ion source a ZnS cubic close packing (Zinc Blende) thin-film microstructure was attained. Astonishingly, the revolutionary benefit of this process was that the obtained film performance appeared almost independent of the substrate temperature. This first end-Hall IAD film was an order of magnitude more durable than any conventionally deposited ZnS film produced at OCLI up to that time.

The author had the opportunity to design, develop, and produce the window coatings for the International Space Station (ISS). Due to the large substrate size (29 inches dia.) it was theorized that by placing two ion sources in the chamber a superior coating would result. However, a serious problem ensued. The two sources, in simultaneous operation, arced vigorously, creating destabilizing oscillations in the power supply feed-back control system. By reconfiguring the chamber and the attending process conditions only one ion source was eventually used to successfully complete the required Space Station Window coatings.

Concurrent with the advanced work on the International Space Station (ISS) window coatings an investigation using a new ion source technology was initiated. Motivated by the need for a higher conversion of gas to ions this source was evaluated in a chamber with a similar configuration to the original two ion source set-up used for the ISS window program. The benefits for a higher conversion of gas to ions in the IAD process go beyond the ostensible requirement of placing two ion sources in the same chamber. Developing ion sources that use less operating gas is very beneficial for manufacturing high performance thin-film coatings and will be very important for future space-based IAD technology.

Summarizing generally, it has been demonstrated that bombardment of a growing film with energetic ions enhances the performance of the thin-film properties for optical filter applications. Improved film adhesion is achieved by ionic bombardment of the substrate prior to film deposition. Densification of the film, deposited on either heated or unheated substrates, is achieved with IAD. Other film properties may be positively influenced by this technique, such as: residual stress modification; surface morphology modification (crystal orientation, smoothing, and grain size); enhanced optical performance (stable refractive indices and low-absorption); and durability (10-11).

2.3 Ion-Assisted Filtered Cathodic Arc Deposition (IFCAD)

IFCAD couples Ion-Assisted-Deposition (IAD) with Filtered Cathodic Arc technology to provide a versatile platform for depositing high performance coatings in advancement optical and electro-optical material applications. The IFCAD technology processes produce super hard advanced thin-film materials such as: Amorphous Diamond-Like-Carbon (A-DLC); Aluminum Oxide (Al_2O_3); Aluminum Nitride (AlN); Titanium Nitrite (TiN); Titanium Oxide (TiO_2: Rutile); Indium Tin Oxide (ITO); and many others are now feasible. In addition, the IFCAD system is designed to have the ability to deposit A-DLC, amorphous Al_2O_3, and many other materials in multi-layer thin-film structures suitable for advanced optical applications. The film properties produced by IFCAD technology are superior to those produced using other processes at elevated deposition temperatures, for example: the A-DLC thin-films have a micro-hardness in excess of 50 GPa (Diamond = 100 GPa); and the amorphous Al_2O_3 films have a hardness in excess of 20 GPa (bulk sapphire is 35 GPa). The new IFCAD system is ultimately designed to be an enabling technology for many novel commercial, military, and space applications (12-13).

• Al2O3	**clear film of high hardness**
• Ta2O5	**optical coating material (2.1n)**
• TiO2	**high index optical coating material (>2.6 n)**
• AlN	**purple decorative film**
• TiN	**hard reddish gold wear resistant film**
• TiCN	**dark gray and hard wearing**
• CrN	**dull gray with low coefficient of friction**
• ZrN	**brass colored film with good corrosion resistance**
• ITO	**transparent conductive thin-film**
• C3N3	**material exhibiting extreme hardness (potentially)**

Figure 3: Some of the Advanced IFCAD Thin-Film Materials

2.4 Applications using Terrestrial Ion-Assisted Filtered Cathodic Arc Deposition

There is an enormous number of potential applications for IFCAD technology, including: EUV mirrors; room temperature transparent conductors; thin-film reflectors; MEMS devices; Rugate filters; telecommunication filters; field emission flat panel displays; UV microlithography; scratch resistant ophthalmic lens; protective and barrier coatings; plastic Fresnel lenses; air craft and automobile windows; spacecraft thermal blanket coatings; hydrophobic films; credit card magnetic heads and tape; architectural glass; web and in-line coatings on plastics.

EUV mirrors, as one example, are of particular interest to NASA for space-based astronomical instrumentation. Considerable work has been done in this area at Goddard Space Flight Center (GSFC) where multi-layer coatings with high reflectance in the spectral range of 50 to 121.6nm have been produced and measured (19). Amorphous Diamond-Like-Carbon (A-DLC) deposited by the FCAD technology has shown great promise in this application, measuring a reflection of about 40% at 74nm wavelength.

The following table represents a comparison of the Carbon films produced by difference deposition methods. It should be noted that the FCA technology produces a very hard film at very low deposition temperatures.

Property	**Nat. Diamond**	**CVD DLC**	**DLC (a:CH)**	**FCA (t:aC)**
Hardness GPa	**100**	**80 - 100**	**10 - 50**	**70 - 100**
Density g/cm3	**3.5**	**3.2 – 3.4**	**1.7 – 2.2**	**3.0 – 3.3**
Friction Coeff.	**0.1**	**0.1 (polished)**	**0.1**	**0.1**
Film Roughness	**N/A**	**3μm**	**Optically Smooth**	**Optically Smooth**
Adhesion	**N/A**	**Low**	**Moderate**	**High**
Process T °C	**N/A**	**>600**	**20 – 325**	**20 - 150**
Structure	**Crystalline Sp3**	**Crystalline Sp3**	**Amorphous mostly Sp2**	**Amorphous mostly Sp3**
Reactive Gas	**N/A**	**Yes**	**Yes**	**None**
Transform T °C	**N/A**	**>600**	**250 – 350**	**>500**

Figure 4: Table of diamond-like-carbon produced with IFCAD

4. RELATED SPACE WORK

4.1 Protective Space Coatings

Protective coatings are of prime interest for solar power concentrator arrays and ultra-light inflatable Fresnel lens solar concentrators (20). The author had the opportunity to work on Boeing's program for developing concentrator arrays using silicone Fresnel lenses. Deep Space I, launched on October 24, 1998, used solar concentrator arrays that were based on the architecture developed earlier at The Boeing High Technology Center.

Since silicone degrades in the presence of UV in the space environment the Fresnel concentrator needs protection from this radiation in order to maintain the high efficiency of the lens for the lifetime of the mission. The Deep Space I mission uses silicone Fresnel lenses covered with a thin cerium doped glass to absorb the UV. However, it was demonstrated that silicone Fresnel lenses could be coated with a dielectric thin-film reflector to protect the lens from UV. The major advantage for using a thin-film coating substitute for the glass is significant payload weight savings (21). The thin-film UV blocking design developed by Boeing for the Photovoltaic Array Space Power (PASP) module was deposited directly onto the silicone Fresnel lenses. This concept was successfully tested in space (22).

Work done by the author in 2004, using a specially configured IAD process for this application, is yet to be published. Fresnel silicone lenses (DC93-500) have been successfully coated and tested for UV degradation. As of this publication of this paper the testing is not complete, but the preliminary results to date are excellent. After 1000 ESH (Equivalent Sun Hours) of VUV radiation exposure, the Fresnel lens exhibits negligible change in optical performance. This coated Fresnel lens has also been subjected to 200 thermal cycles (-170^{o} C to +70^{o} C) without any apparent lost of optical or mechanical performance. In the future, the use of concentrators for space power applications could offer a significant technical advantage over conventional flat panel arrays. The coating developed for UV protection of Fresnel silicone lenses could also be applied after deployment in space on other UV radiation sensitive surfaces.

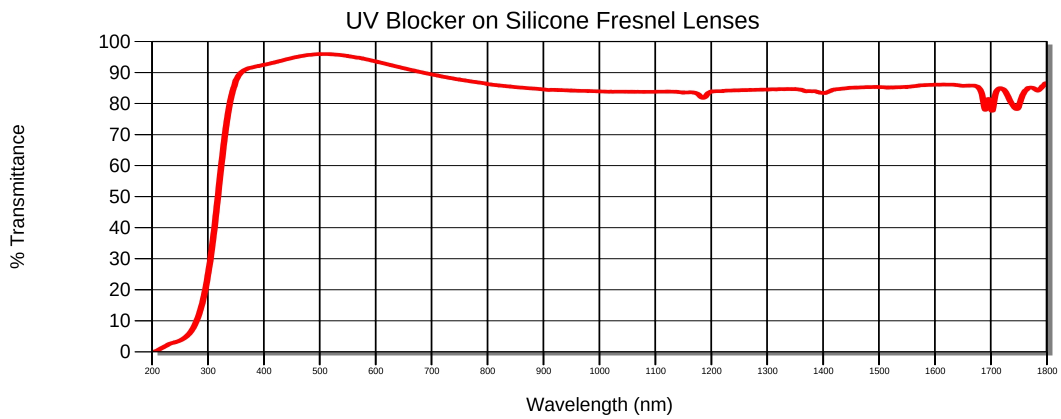


Figure 5: Measured spectrum of silicone (DC93-500) Fresnel lens, providing UV blocking and high transmission

4.2 Thermal Control

Thermal blanket coatings have been used from the beginning of the space program to protect the space vehicle from UV and IR radiation. The author had the opportunity to participate on the Boeing team which investigated the results from the Long Duration Exposure Facility (LDEF). LDEF was a satellite that spent 69 months in space to test a huge assortment of materials and coatings for space applications (23).

Kapton, and silicone were two of many materials exposed to Atomic Oxygen (AO) and UV radiation for the duration of the flight. Coated and uncoated Kapton and silicone samples were evaluated and compared for relative degradation after exposure to the high fluence of UV radiation and AO on the prolonged LDEF space flight. The study was comprehensive, involving a number of research groups examining hundreds of samples, resulting in a voluminous set of documents. Future space-based depositions will play a significant role in thermal control coatings.

5. FCA COATING TECHNOLOGY FOR SPACE APPLICATIONS

5.1 Space Deposition System (Pictures)

The adjoining picture is of a Filtered Cathodic Arc (FCA) source immersed in a vacuum system. A pure of ions is steered through the solenoid coil in this simple mechanical structure. This may be the most efficient (cost, weight, and performance) design for depositing advanced thin-films in a space-based process.

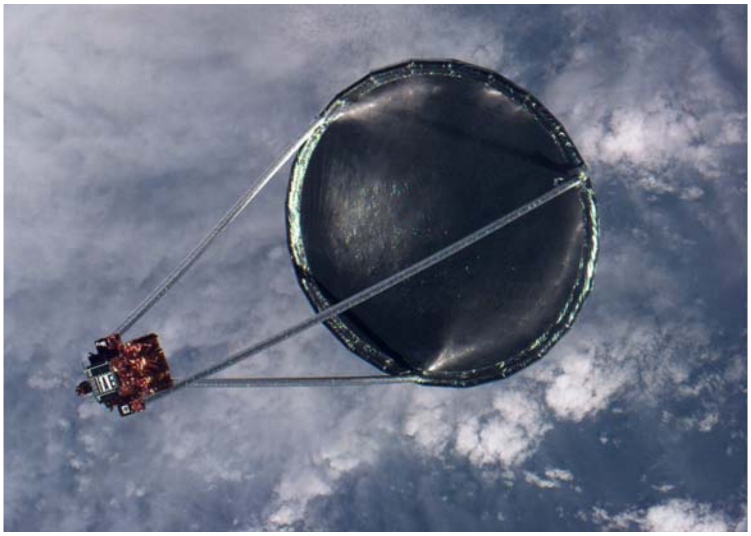
Courtesy of Andre Anders (LBL)

It can be envisaged that the simple FCA source above can be housed inside a space deposition unit pictured here. Laser alignment and computer control will enable this type of FCA source to be mounted on a robotic arm for depositing the thin-films over large area deployed optical structures in the vacuum of space. The FCA source is powered by a simple commercial welding power supply that can be considered a dual-use asset for construction and maintenance of a lunar base.

5.2 Space Antennas

L'Garde Corporation has specialized in the design and deployment of large-area space structures for solar propulsion and antennas (24). In the May 1996 the inflatable antennae experiment (IAE) was launched on Shuttle Mission 77. Antennae reflectors have a stowed volume of the inflatable device that is about one tenth of the deployed structure. This pioneering experiment has opened the way for the development of this technology for a number of applications (25). Thin-film coatings will be required for most of the following future envisaged applications of inflatable structures:

- Sunshades for space telescopes
- Deployment and support for solar arrays
- Planetary rovers
- Pressurized habitats in space or on planetary surfaces
- Extremely light weight solar sails, exploiting photon pressure
- Balloons to operate in planetary atmospheres
- Antenna reflectors
- Solar concentrators
- Precision booms
- Optical telescope mirrors



Actual photograph of the Inflatable Antenna Experiment (IAE) deployed in space in May 1996. The 46 ft. diameter antenna proved the viability of this technology.

Courtesy of L'Garde Inc.

5.3 Space Solar Propulsion

Thin-film reflectors are of particular interest to the solar space propulsion effort, sponsored primarily by the Air Force and NASA. This technology relies on using large area coated polymer structures to reflect and focus concentrated solar energy to a space thruster. The solar thermal thruster is a high performance space vehicle suitable for transferring payloads from low earth orbit (LEO) to geosynchronous orbits (GEO). One vehicle design plans to use large inflatable parabolic concentrators to focus sunlight onto a high temperature absorber (26). This concept would be insured a greater success if the coating was deposited on the reflector after it is deployed.

5.4 Solar Power via Moon

By the year 2050 three to five times more energy will be required provide a prosperous life system for the human population of earth. However, the current means of energy production will be unable to meet this need without substantial negative consequences such as pollution, safety, reliability of supply, and cost. One innovative solution to this problem is collect solar energy on the surface of the moon, convert it to microwave energy and beam it back to the earth to supply electric power to augment other energy production methods (27). Without dwelling on the details of this proposal, suffice it to say that the need for depositing highly reflective coatings on the deployed optical concentrators will be required.

5.5 Solar Power from Space

Solar power from space has been proposed from nearly the beginning of man space flight. In this scheme solar collectors are placed in geosynchronous orbit and the solar energy is converted into a microwave beam that transports the energy back to a receiving station on the earth (28). Generating electrical power by collecting solar energy and beaming it back to the earth is fraught with economic and technical problems. However, with the use of thin-film space-based deposition technology will be an enabling step in the development of either the solar power from the moon or earth orbiting satellites.

5.6 Lunar Astronomical Observation

The establishment of a lunar base will be critical for the providing support for the future human flights to Mars. One of the ancillary benefits to having a lunar base is the ability to set up an astronomical observation facility. It is envisaged that very large-area reflectors, using adaptive optical systems, can be assembled on the lunar landscape. In order to maximize the unobstructed view (from earth's shine) this could be built on the dark-side of the moon. Also, extremely powerful earth observations could be accomplished from setting up an observatory on the surface of the moon.

The lunar environment is particularly favorable for space-based depositions of large-area reflectors for telescopes. Lunar vacuum is on the order of 5.0×10^{-13} Torr. The typical vacuum required to deposit thin-films in a terrestrial chamber is in the 10^{-6} Torr range—seven orders of magnitude less favorable than the lunar surface. In Low Earth Orbit (LEO) metal film depositions would be compromised by oxidation. The LEO atomic oxygen fluence is on the order of 2.3×10^{20} atoms/cm^2. Therefore, on the lunar surface pure silver, for example, could be deposited on the telescope mirrors with out being contaminated, corroded, nor degraded as observed in coatings produced by earth-based technology (29).

6. CONCLUSION

Since space-based deposition technology is not encumbered by a vacuum chamber, then other factors like power consumption, control, efficiency, and reliability must be considered. Filtered Cathodic Arc Deposition (FCAD) has the potential to satisfy theses requirements. The FCAD power is supplied by an arc welding transformer—this power supply would serve the dual function of a conventional arc welder for the lunar station. Simplicity is the central attribute of the FCAD technology; therefore, the source can be mounted on a robotic arm and the beam of deposition ions are applied to the substrate in a "paint brush" manner using laser guided controls to insure coating uniformity.

Space exploration and even colonization appears on the horizon and Filtered Cathodic Arc Deposition technology could play an important role in facilitating this endeavor by providing robotically deposited coatings over enormous space deployed structures for solar power and radiation protection. Spaced-based deposition of advanced materials could open a whole new era in astronomical observation, including large area telescopes on the surface of the moon.

As work progresses with these and other energetic deposition processes, it is the fervent hope of the author that scientists and engineers continuously seek imaginatively beneficial ways to apply their inventions and technology.

7. ACKNOWLEDGEMENTS

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