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IN-SPACE FABRICATION OF THIN-FILM STRUCTURES

by M. E. Lippman

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ASTRO RESEARCH CORPORATION
Santa Barbara, Calif. 93103
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16. Abstract

Vapor deposition of thin films for use as solar sail materials, shadow shields or thermal control coatings, using a revolving substrate and subsequent separation.

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SUMMARY

A conceptual study of physical vapor-deposition processes for in-space fabrication of thin-film structures is presented. Potential advantages of in-space fabrication are improved structural integrity and surface reflectivity of free-standing ultra-thin films and coatings. Free-standing thin-film structures can find use as photon propulsion devices ("solar sails"). Other applications of the concept involve free-standing shadow shields, or thermal control coatings of spacecraft surfaces. Use of expendables (such as booster and interstage structures) as source material for the physical vapor deposition process is considered.

The practicability of producing thin, textured, aluminum films by physical vapor deposition and subsequent separation from a revolving substrate is demonstrated by laboratory experiments. Heating power requirement for the evaporation process is estimated for a specific mission.

CONTENTS

INTRODUCTION

Thin-film structures to provide large functional surface areas of limited weight are required for space missions contemplated for the future. Such structures may be used for reflection of electromagnetic energy, as passive satellites, in communication links, for solar shields, or in utilizing photon pressure for power and control as in the solar-sail concept.

A recent report (Ref. 1) dealing with the "Heliogyro" concept indicates that a thin metal film offers advantages over aluminized polymer film because of an improved (increased) lightness number. The report further indicates that the reflector figure of merit for free-standing aluminum film is an order of magnitude better than the best aluminized polymer thin-film reflector material presently available in quantity.

This report deals briefly with the idea that a thin-film aluminum large-area sail may be produced in space by physical vapor-deposition techniques. The possibility of consuming or converting structural members no longer needed for the mission to thin-film form, suggests a new design discipline involving the optimization of payload-vehicle configuration by materials conversion. Some of the problems involved are discussed.

A variety of applications exist which justify the development of physical vapor deposition techniques for manufacturing thin films in space. These applications are reviewed briefly.

THIN-FILM PRODUCTION ON EARTH AND IN SPACE

Integrity of Earth-Made Thin Films

The total functional integrity of reflective thin-film structures as an earth-made product involves not only the mass properties and optical characteristics of the material, but also its basic strength, uniformity, and degradation due to processing problems, storing, launch, and deployment stresses.

Suppliers of thin gauge metal and metallized polymer films claim that the practical limitations (for thinness) are in part related to the difficulties in winding and unwinding the films in an environment of gravity, electrostatics, air currents, and particulate contaminants. In the case of particulate contaminants, any foreign particles - whether incorporated in the film or clinging to the surface - become more degrading if spooled into a roll. Such a roll, subsequently subjected to normal handling and adverse launch environment, may suffer catastrophic failure during the stresses of deployment and operational use.

Oxidation of the metal surface is expected to occur during manufacture, and to continue through stowing, storage, and the launch sequence. Hence, the reflective degradation of the film commences at "birth" and continues.

Consideration of In-Space Fabrication Factors

Thin-film structures can be automatically produced in space, taking advantage of existing technology in the field of physical vapor deposition (PVD). This PVD system involves the melting and evaporating of a source material such as aluminum in vacuum and then condensing the vapor on a substrate in the form of a thin film.

The infinite "pumping capacity" of space is of course a major attraction, since it eliminates the necessity of vacuum pumping, chambers, and related controls.

It is anticipated that the metal required as a source material for conversion of the thin-film form would be available from a portion of the initial vehicle structure that is no longer required for its initial use, such as booster tankage or interstage structural components.

The system envisioned incorporates a rotating substrate in drum or belt configuration, on which the aluminum vapor condenses to form a thin film. By providing a favorable potential voltage difference from source to substrate, the vaporized aluminum can be "directed" to the substrate and additionally guided by geometric masks, and/or electrostatic fields. Control of the evaporation rate, drum speed, and the other factors will be required to produce the film thickness suitable for the application.

A substrate can be developed which would provide a highly polished surface for the film formation, but will have little or no adhesion to the film. Thus, the film can be formed at the desired deployment rate and be immediately fed into the deployment rollers and payed out as programmed.

In order to evaluate the characteristics of freestanding aluminum film as a solar sail, a direct comparison is made between a 10 000 Å thick aluminum sail and the aluminized-Mylar sail originally proposed by MacNeal in Reference 2.

Sail Material	Approx. Weight
Aluminized Mylar, consisting of 6 micron thick Mylar with a 3000 Å deposition of aluminum	160 kg
Size: 12 000 meters long and 1.5 meters wide	
Free-standing, 10 000 Å thick	49 kg
Size: Same as above	

The use of in-space deposited aluminum film would have a major effect upon voyage travel time because of the increased lightness number and the improvement in propulsive power related to the upgraded reflectance characteristics (Ref. 6).

Substrate Development - Preliminary Experiment

In order to form a large-area aluminum sail in space, it has been suggested that a substrate be used upon which the aluminum is deposited, and from which it can be easily removed (peeled). Two experiments have been conducted to establish some of the basic parameters for this approach.

In the first experiment a polished stainless-steel rigid substrate was chemically cleaned and placed in a vacuum chamber set up for physical vapor deposition of aluminum, utilizing electron-beam melting techniques. The substrate was subjected to thermal degassing and scrubbed by glow discharge using argon. A nominal thickness of aluminum was deposited over the entire substrate area of approximately three by eight inches. A metallic mask was then introduced to shadow an area of approximately two by eight inches, leaving a narrow strip along each side of the substrate still exposed to the aluminum deposition source. The deposition was continued until the edge thickness was approximately twice the central area thickness. The substrate was then removed from the chamber, and the aluminum peeled from it to provide a freestanding film of textured aluminum nominally 0.0005 inch thick with a 0.001-inch thickness along the edges (see Fig. 1). Although this film is considerably thicker than anticipated for sail applications, and therefore easier to peel, it appears that a highly polished metallic cylindrical substrate may be suitable for the application, and stainless steel may be a candidate material.

In a second experiment a two-inch wide by 12-inch long flexible copper ribbon substrate was coated with aluminum in a similar procedure. After removal from the chamber, the copper ribbon was held with moderate tension on a flat horizontal surface and thence drawn vertically down around a bar having a 1/8-inch radius. The aluminum separated continuously from the copper as it passed over the raised bar (see Fig. 2(a) and (b)). A substrate utilizing this separation procedure is envisioned as a continuous belt rotating around rollers, with deposition being accomplished in a flat area between rollers and the freestanding film being removed from the substrate as it rotates over a roller. Figure 3 shows the textured aluminum film formed on a rigid stainless steel substrate. Figure 4 shows the flexible copper substrate from which the deposited aluminum film is partially separated.

It was observed during these laboratory experiments that the aluminum film started to separate from the substrate slightly while still in the vacuum chamber at low pressure (10^{-6} torr range). When the chamber was returned to atmospheric pressure, the separation continued at a slightly accelerated rate suggesting that stress, as well as chemical conditions, may contribute to the self-induced separation. Separation was completed manually. Some small cracks appeared on the film which was peeled from the rigid substrate; they were observed at locations where the substrate had visible surface scratches. Cracks did not appear in the aluminum peeled from the flexible substrate. The proposed concept could be enhanced by the use of aluminum on aluminum in a textured form. Such a film would incorporate a number of longitudinal and transverse aluminum ribbons of reasonable thickness, overcoated with a thinner film of the same aluminum. This enhances the structural integrity of the sail and provides protection against catastrophic tears in the material.

Melting Aluminum In Space

In considering the proposed process, the initial task of melting the aluminum to be converted from bulk form to thin-film textured form must be reviewed. In a gravity free environment the melt will tend to form a spherical ball, and its position with relation to the heat source and the substrate must be controlled, for instance by electroinductive "levitation". In a rotating spacecraft, a melt container may be used. The obvious approach would be to provide a suitable container and heat shield for the aluminum and to incorporate electrically operated heating elements capable of melting the desired amount of aluminum at the required rate. Other sources of heat such as from solar concentrators or electron beams should also be considered.

Estimate of Required Heating Power

If, for instance, a two bladed Heliogyro is assumed, as suggested by MacNeal (Ref. 2), with a 1.5-meter width, 6000 meter length (per blade), and a nominal aluminum thickness of 10 000 Å, the total sail weight would be 49 kg. MacNeal suggests an estimated deployment period of 14 days. Accordingly the rate of deposition would be approximately 0.2 kg per hour. This may be accomplished at an assumed deposition efficiency of 75%. If we assume a power demand of 6 kw per pound per hour (Ref. 3), a beam power supply of 2640 watts will be required to produce the film at the desired deployment rate. Some modifications to this figure will be needed to accommodate the specific geometry of the proposed system, considering total area, thickness, and texturing details.

The bulk aluminum material to be converted to film could be in the form of powder, wire, rod, pellets, or ingots. In the system envisioned, it may be in chunk form as cut from the booster tankage or some other structural members no longer needed for mission objectives. In the case of manned system applications, the metal may be melted inside the space vehicle at vehicle pressure and then siphoned outside into the vacuum environment for deposition, or the entire melt could be accomplished outside the space vehicle.

If booster tankage or other aluminum structural material is to be converted for thin-film use, additional equipment will be required to cut the material into a practical size for melting. Forms such as angles, rods, bars, or tubes may be conveniently introduced to the melt with a minimum amount of intermediate work.

Fabrication Technique in Space

A design concept for an experimental two-blade Heliogyro has been described in Reference 2. Figure 5 illustrates a modified vehicle incorporating the equipment to form textured aluminum rotary wings which will be stiffened in flight by centrifugal force and capable of being pitched. Two melt crucibles provide vaporized aluminum to two regenerative rotating cylindrical substrates. The aluminum condenses on the substrate, forming a thin textured film which separates from the substrate where it enters the rotating deployment rollers. The process is started initially by pre-prepared leader film which is threaded through the equipment and is deployed slowly as new film is formed. The longitudinal strengthening ribbons are formed by the creation of an intermittent dwell in the substrate rotation which permits the aluminum thickness to build up in selected areas.

Deployment Sequence

MacNeal's plan is used for the proposed deployment sequence, which is illustrated in Figure 6.

The rocket motor ignites, initiating spin-up, and producing sufficient angular velocity to provide initial tension to the leader film. As deployment starts, new film is deposited and deployed continually from the pre-melted aluminum supply. After deployment of about 100 meters in length, the deployment rollers are collectively pitched, as in a helicopter. The rotary wing blades are then driven like a windmill by the pressure of photons from the sun. The film formation and deployment sequence are continued, and the angular momentum increases. Estimated time for total deployment is approximately 14 days.

The use of cyclic and collective pitch techniques to induce control forces and moments to the Heliogyro in flight are described in detail in numerous texts dealing with rotary wing systems (e.g., Refs. 1, 2, 4, 5) and will therefore not be discussed in this report.

OTHER APPLICATIONS OF IN-SPACE FABRICATED THIN FILMS

Space Station Surface Coatings

Among the applications which may warrant further development of in-space physical vapor-deposition techniques is the necessity of repairing or renewing thermal control coatings on spacecraft surfaces. Degradation rates of existing coatings are not considered to be consistent with the life requirements of long missions. An aluminum or other thermal-control coating could be renewed in selective areas or on entire spacecraft surfaces, by utilizing vapor-deposition techniques.

The operation is envisioned as being accomplished manually by a space-station maintenance crew member, utilizing portable deposition equipment to re-coat a degraded surface area. The unit shown in Figure 7 would coat approximately a square meter in a few minutes to a pre-set thickness of about 3000 Å.

In the proposed coating system, a manually held unit provides a supply of source material such as aluminum, which is vaporized inside a lightweight shroud at space ambient pressure. The vaporized material is allowed to condense on the spacecraft surface to restore the high IR reflectance of the coating, or to attain desired thermal control conditions.

Articulating Solar Shade for Space Stations

The possibility of providing a large-area, lightweight, highly reflective "shade" as part of a thermal control system for a space station can be envisioned in conjunction with the in-space capability of producing the film.

Such a "shade" could span an articulating frame mounted or tethered to the space station and controlled to provide a shadow on the station on a programmed basis. The controlled shade would be integrated into the total thermal control system.

CONCLUSIONS

The application of existing physical vapor-deposition techniques to produce lightweight, thin-film, large-area structures in space - for space use - is considered to be practicable and may warrant serious consideration.

The possibility of converting material from its initial use form to one which is useful for later mission requirements is attractive. An aluminum bar one inch square and one foot long will produce approximately 8000 square feet of film having a thickness of 10^{-6} inch.

The general idea of thin-film production in space for space end use, together with the possibilities of utilizing solar concentrators to melt materials to be vaporized, providing a means of applying fresh thermal control coatings to space station surfaces, providing solar shades to aid in the thermal control of space stations, and the unexplored possibility of providing thermal barriers for cryogenic storage facilities appear to justify a limited-scale exploratory program.

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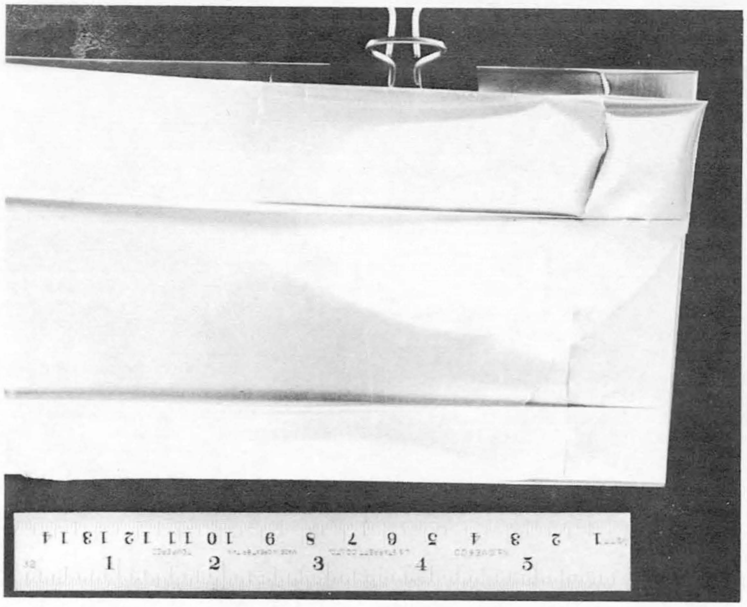
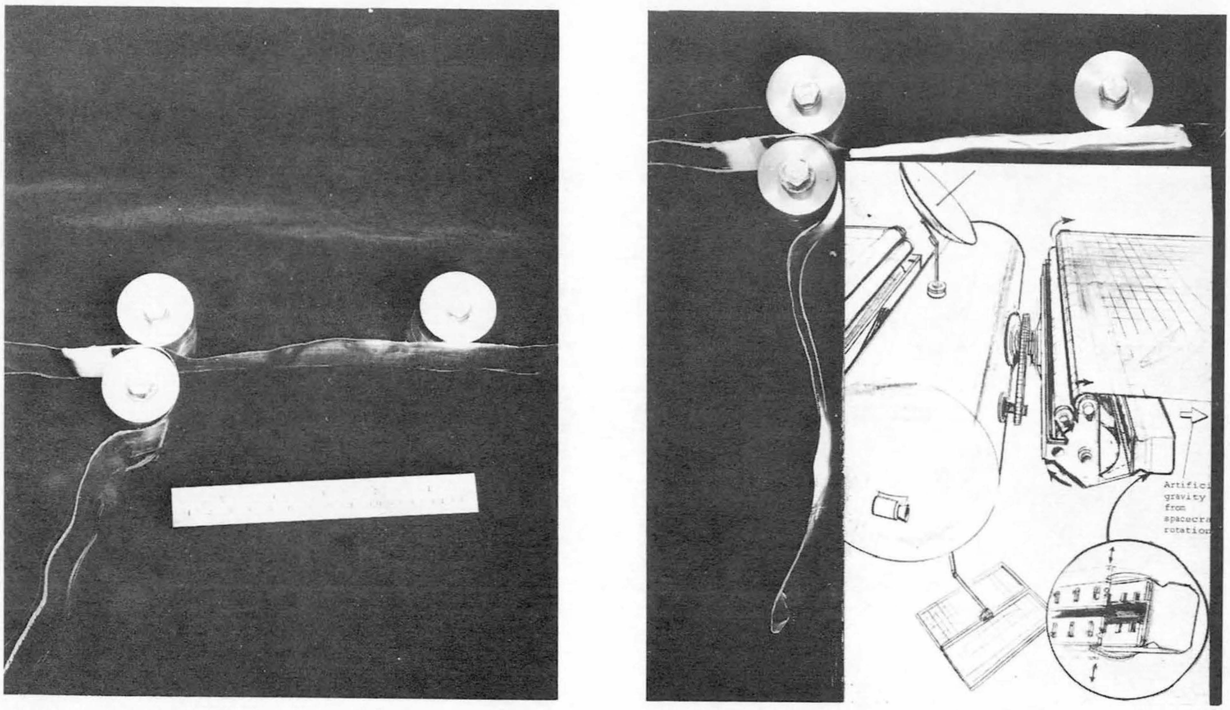


Figure 1. Textured Aluminum Film Being Separated From a Rigid Polished Stainless Steel Substrate



(a) (b)

Figure 2. Aluminum Film Being Separated From a Flexible Copper Substrate

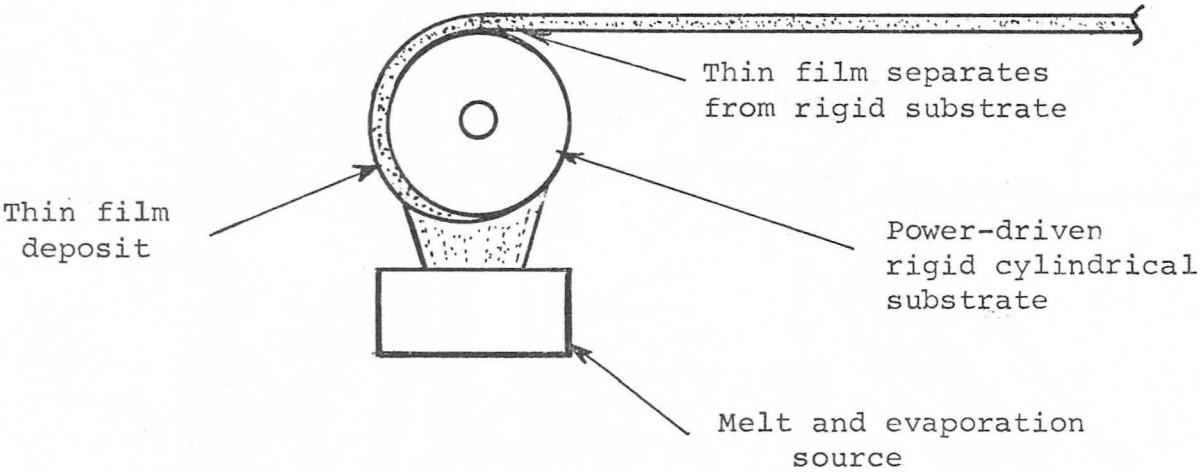


Figure 3. Textured Aluminum Film Deposited and Removed from Rigid Substrate

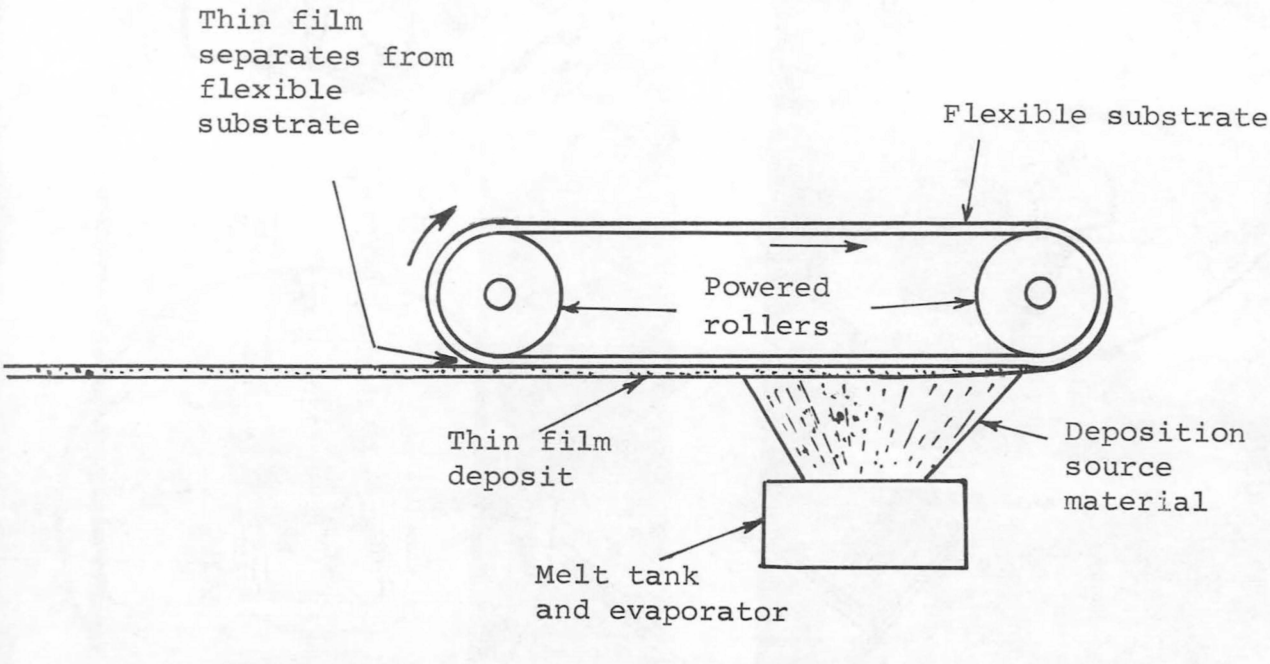


Figure 4. Aluminum Film Deposited and Removed from Flexible Substrate

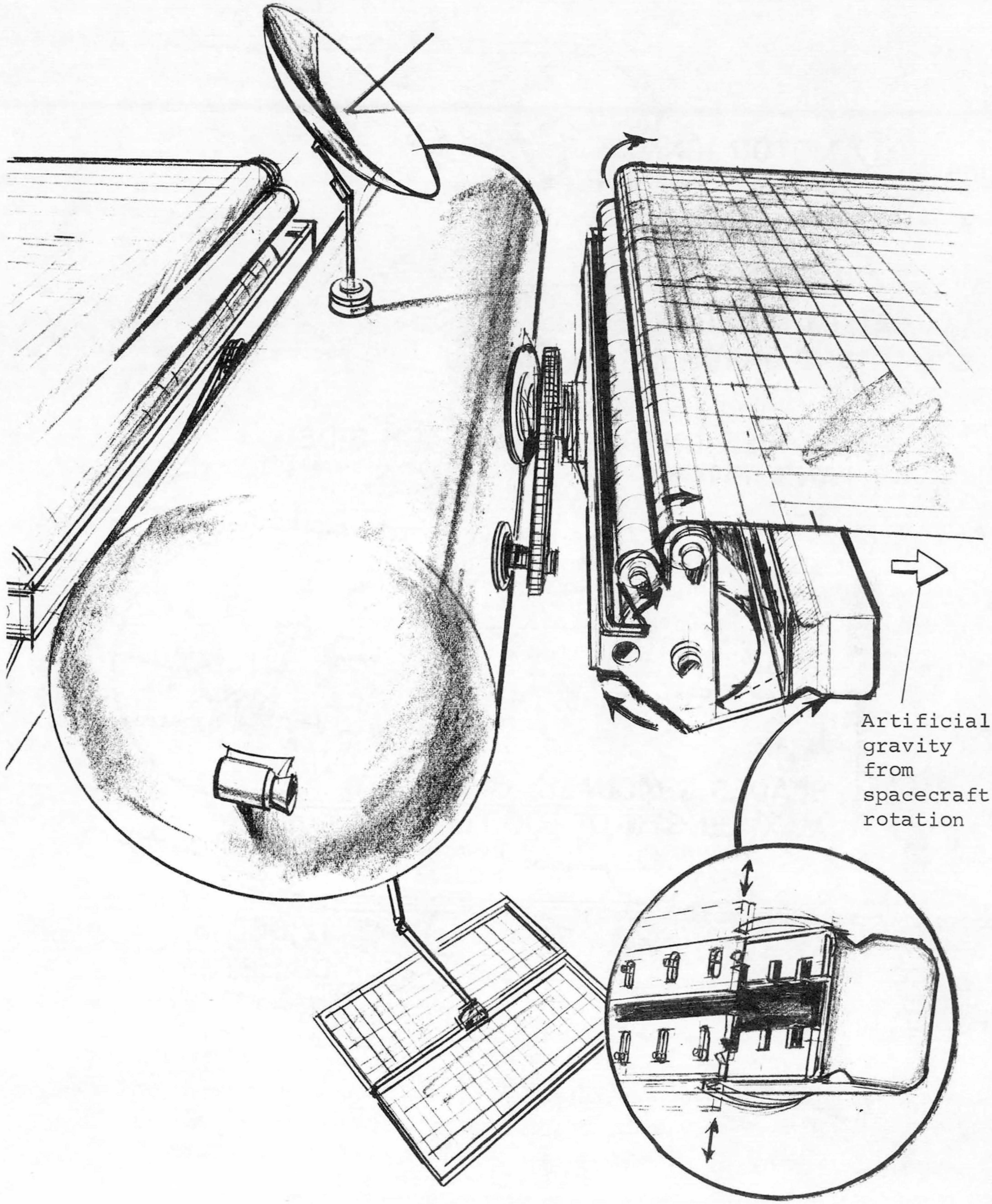


Figure 5. Heliogyro with Textured Aluminum on Aluminum Sails
Deployed as Deposited in Space

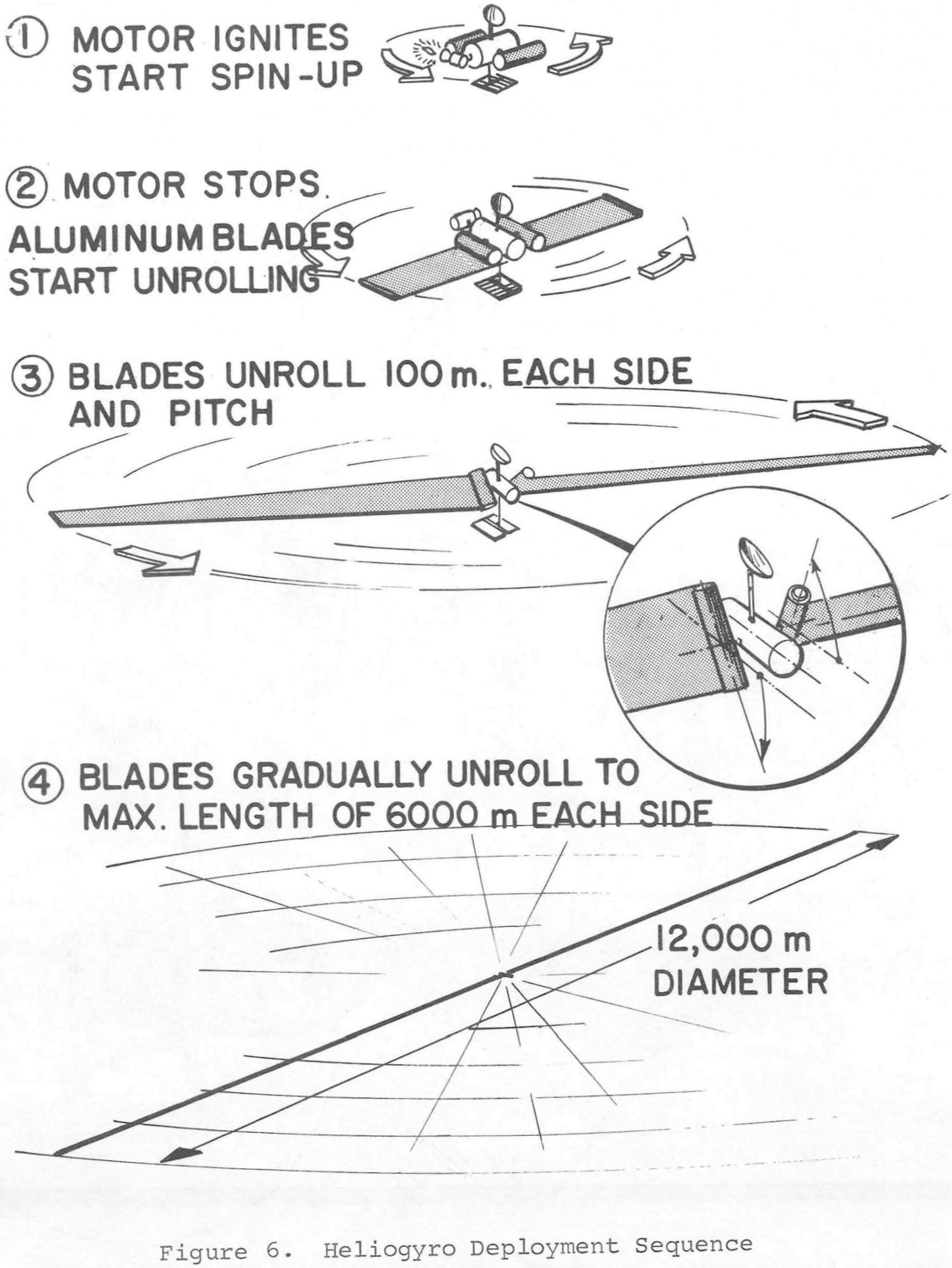


Figure 6. Heliogyro Deployment Sequence

Figure 7. Space-Station Surface Re-coating Maintenance by Thin Film Deposition in Space